Unitarity, information, black holes and fuzzballs

Andrea Puhm

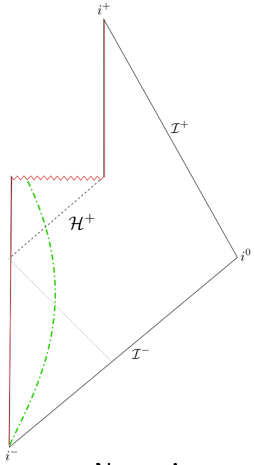
IPhT, CEA/Saclay

based on

1210.6996	with S. G. Avery, B. C. Chowdhury
1208.2026	with B. C. Chowdhury
1208.3468 and 1109.5180	with I. Bena and B. Vercnocke

Vienna Central European Seminar 2012

Information paradox versus infall problem



Semiclassical gravity:

A black hole forms by gravitational collapse and evaporates via Hawking pair production.

Bob is collecting the radiation quanta at infinity.

Information paradox:

When and how does the information come out?

Alice is traveling towards the black hole to jump in.

Infall problem:

Is Alice burning of fuzzing?

Note: Answers to information and infall question are in tension.

A stop-gap: black hole complementarity [Susskind, Thorlacius, Uglum]

Motivation: Reconciliation of unitary evaporation and free infall.

*I*dea: Experience of asymptotic and infalling observer are different.

Postulates:

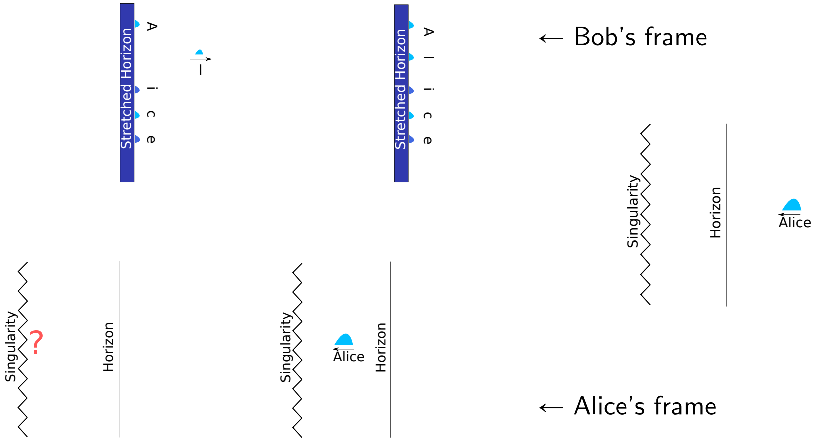
1. Black hole evolution via unitary S-matrix for *outside* observer.
2. Semi-classical physics valid outside stretched horizon.
3. To distant observer black hole appears as a *membrane*.
4. An *infalling* observer falls freely through horizon of large black hole.

Note:

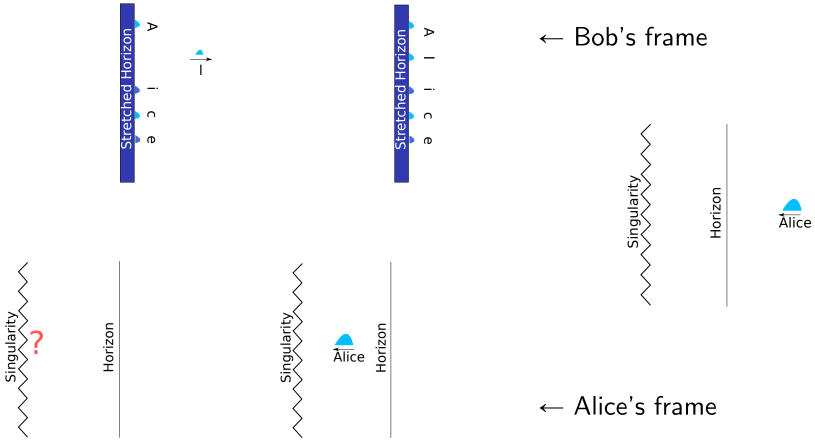
Tension between postulates 1 and 4.

There is *no mechanism* for the membrane!

A stop-gap: black hole complementarity [Susskind, Thorlacius, Uglum]



A stop-gap: black hole complementarity [Susskind, Thorlacius, Uglum]



BHC has recently been argued to be inconsistent.

[Almheiri, Marolf, Polchinski, Sully]

Unitary evaporation [Page]

If the **black hole** in a typical pure state and *assume* unitary evaporation:

typical: each small subsystem is almost maximally entangled with the remaining (larger) subsystem.

pure: $S_{rad} = \mathrm{Tr}_{BH}|\Psi\rangle\langle\Psi|$.

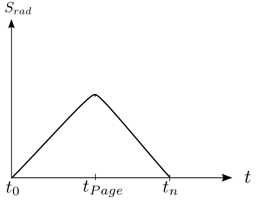


Figure: *Unitary evaporation.*

As long as radiation smaller part S_{rad} grows.

When black hole is smaller part S_{rad} falls.

For *purity* of final state: $S_{rad}(t_n) = 0$!

Unitary evaporation [Page]

If the **black hole** in a typical pure state and *assume* unitary evaporation:

typical: each small subsystem is almost maximally entangled with the remaining (larger) subsystem.

pure: $S_{rad} = \mathrm{Tr}_{BH}|\Psi\rangle\langle\Psi|$.

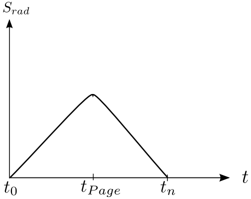


Figure: *Unitary evaporation.*

As long as radiation smaller part S_{rad} grows.

When black hole is smaller part S_{rad} falls.

For *purity* of final state: $S_{rad}(t_n) = 0$!

A black hole does not behave like that! [Mathur]

Hawking radiation

[Mathur]

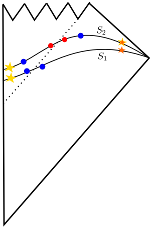
(ss) **Strong subadditivity**:

$$S_{AB} + S_{BC} \geqslant S_B + S_{ABC}$$

If evaporation via Hawking-pair production:

BC maximally entangled: $S_{BC} = 0$

$$\rightarrow \quad S_{AB} \geqslant S_B + S_A$$



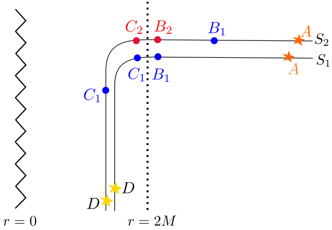


Figure: *Hawking pair creation.*

Hawking radiation

[Mathur]

(ss) **Strong subadditivity**:

$$S_{AB} + S_{BC} \geqslant S_B + S_{ABC}$$

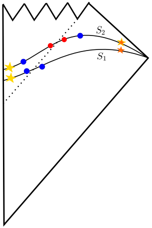
If evaporation via Hawking-pair production:

BC maximally entangled: $S_{BC} = 0$

$$\rightarrow \quad S_{AB} \geqslant S_B + S_A$$

(s) **Subadditivity**:

$$S_{AB} \leqslant S_A + S_B$$



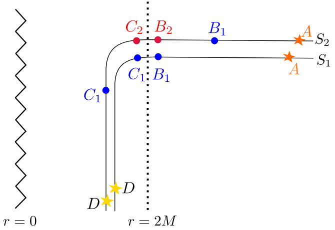


Figure: *Hawking pair creation.*

Hawking radiation

[Mathur]

(ss) **Strong subadditivity**:

$$S_{AB} + S_{BC} \geqslant S_B + S_{ABC}$$

If evaporation via Hawking-pair production:

BC maximally entangled: $S_{BC} = 0$

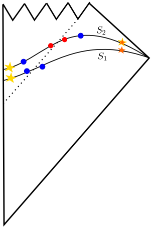
$$\rightarrow \quad S_{AB} \geqslant S_B + S_A$$

(s) **Subadditivity**:

$$S_{AB} \leqslant S_A + S_B$$

(ss) + (s) : $S_{AB} = S_A + S_B$

A and B are not correlated!



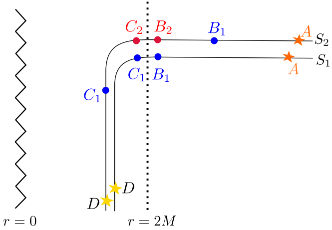


Figure: *Hawking pair creation.*

Hawking radiation [Mathur]

(ss) **Strong subadditivity**:

$$S_{AB} + S_{BC} \geqslant S_B + S_{ABC}$$

If evaporation via Hawking-pair production:

BC maximally entangled: $S_{BC} = 0$

$$\rightarrow \quad S_{AB} \geqslant S_B + S_A$$

(s) **Subadditivity**:

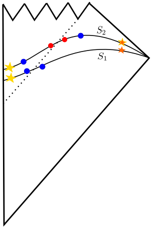
$$S_{AB} \leqslant S_A + S_B$$

(ss) + (s) : $S_{AB} = S_A + S_B$

A and B are not correlated!

$$S_{AB} \geqslant S_A$$

Entropy of radiation via Hawking pair creation never decreases!



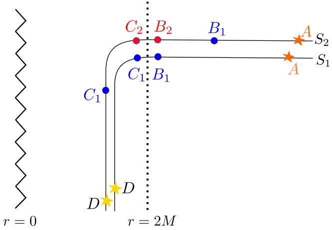


Figure: *Hawking pair creation.*

The need for large corrections [Mathur; Avery]

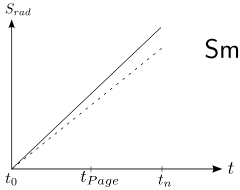


Figure: *Black hole evaporation.*

Small corrections cannot bend the entropy curve!

For *purity* of the final radiation state:

Large corrections to Unruh vaccum needed!

There cannot be an information free horizon!

The need for large corrections

[Mathur; Avery]

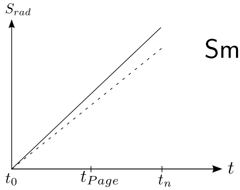


Figure: *Black hole evaporation.*

Small corrections cannot bend the entropy curve!

For *purity* of the final radiation state:

Large corrections to Unruh vaccum needed!

There cannot be an information free horizon!

Mathur's conjecture or the **'fuzzball' proposal**:

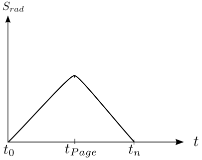
Quantum gravity effects at the scale of the horizon!

Microstates of black hole are **singularity-free** and **horizonless** solutions of quantum gravity.

The firewall argument

[Almheiri, Marolf, Polchinski, Sully]

Argument entirely in the infalling observer's frame → challenges BHC!



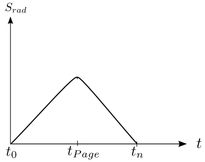
1. To ensure *purity* of the final radiation state: $S_{AB} < S_A$ after Page time. This implies $S_{BC} \neq 0$ no later than t_{Page}.

2. An infalling observer encounters a blue-shifted ($E \gg T_H$) quantum B in her frame and burns at the horizon.

The firewall argument

[Almheiri, Marolf, Polchinski, Sully]

Argument entirely in the infalling observer's frame → challenges BHC!



1. To ensure *purity* of the final radiation state: $S_{AB} < S_A$ after Page time. This implies $S_{BC} \neq 0$ no later than t_{Page}.

2. An infalling observer encounters a blue-shifted ($E \gg T_H$) quantum B in her frame and burns at the horizon.

1 → **Growing concensus** on answer to information question:

Quantum gravity effects at the scale of the horizon!

This supports the fuzzball proposal!

2 → **Controversal opinions** on answer to infall question...

Conditions for unitarity: beyond purity

[Avery, Chowdhury, AP]

Focus so far on *purity* of the final radiation state: $S_{BC} \neq 0$ after t_{Page}.
This is necessary but not sufficient!

For unitarity:

1. Purity: Pure states evolve into pure state.
2. Linearity: The map between initial and final states is linear.
3. Preservation of norm: Evolution of states preserves norm.
4. Invertibility: The map of initial state to the radiation is invertible.

Conditions for unitarity: beyond purity [Avery, Chowdhury, AP]

Focus so far on *purity* of the final radiation state: $S_{BC} \neq 0$ after t_{Page}.
This is necessary but not sufficient!

For unitarity:

1. Purity: Pure states evolve into pure state.
2. Linearity: The map between initial and final states is linear.
3. Preservation of norm: Evolution of states preserves norm.
4. Invertibility: The map of initial state to the radiation is invertible.

Claim: Unitarity requires $S_{BC} \neq 0$ *at every step* of the evaporation process for typical states!

Work under assumptions a) fixed dimension of physical Hilbert space and b) initial black hole state is not special.

The 'moving bit' model I

Simple unitary model of evaporation: moving qubits D from x to y.

Evolution of basis vectors:

$$\begin{aligned}
|\psi_0\rangle &= |D_n^x\rangle \otimes \cdots \otimes |D_1^x\rangle = \bigotimes_{j=n}^{1} |D_j^x\rangle\,, \\
|\psi_i\rangle &= \prod_{j=i}^{1} \mathcal{U}_j |\psi_0\rangle = \bigotimes_{j=n}^{i+1} |D_j^x\rangle \otimes \bigotimes_{k=i}^{1} |D_k^y\rangle \qquad i \geqslant 1\,, \\
|\psi_n\rangle &= \prod_{j=n}^{1} \mathcal{U}_j |\psi_0\rangle = \bigotimes_{j=n}^{1} |D_j^y\rangle\,.
\end{aligned}$$

Where is the *BC pair*?

The 'moving bit' model I

Simple unitary model of evaporation: moving qubits D from x to y.

Evolution of basis vectors:

$$
\begin{aligned}
|\psi_0\rangle &= |D_n^x\rangle \otimes \cdots \otimes |D_1^x\rangle = \bigotimes_{j=n}^{1} |D_j^x\rangle\,, \\
|\psi_i\rangle &= \prod_{j=i}^{1} \mathcal{U}_j |\psi_0\rangle = \bigotimes_{j=n}^{i+1} |D_j^x\rangle \otimes \bigotimes_{k=i}^{1} |D_k^y\rangle \qquad i \geqslant 1\,, \\
|\psi_n\rangle &= \prod_{j=n}^{1} \mathcal{U}_j |\psi_0\rangle = \bigotimes_{j=n}^{1} |D_j^y\rangle\,.
\end{aligned}
$$

Where is the *BC pair*?

[Avery]:

- introduce auxiliary variables at each step
- trace over them to get back physical Hilbert space

The ‘moving bit’ model II

Evaporation via auxiliary qubits:

$$
\begin{aligned}
|\psi_0\rangle &= |D_n^x\rangle \otimes \cdots \otimes |D_1^x\rangle = \bigotimes_{j=n}^{1} |D_j^x\rangle\,,\\
|\psi_1\rangle &= \bigotimes_{j=n}^{2} |D_j^x\rangle \otimes |d_1^x\rangle \otimes |c_1^x\rangle \otimes |B_1^y\rangle\,,\\
|\psi_i\rangle &= \bigotimes_{j=n}^{i+1} |D_j^x\rangle \otimes \bigotimes_{k=i}^{1} \Big(|d_k^x\rangle \otimes |c_k^x\rangle\Big) \otimes \bigotimes_{m=1}^{i} |B_m^y\rangle\,,\\
|\psi_n\rangle &= \bigotimes_{j=n}^{1} \Big(|d_j^x\rangle \otimes |c_j^x\rangle\Big) \otimes \bigotimes_{m=1}^{n} |B_m^y\rangle\,.
\end{aligned}
$$

To match the moving bit model: $B_i^y = D_i^y$.

Unitarity demands the auxiliary states to be in fiducial form:

$$|d_1^x\rangle \otimes |c_1^x\rangle = |\phi\rangle \otimes |\phi\rangle \qquad \forall i\,.$$

The ‘moving bit’ model II

Evaporation via auxiliary qubits:

$$
\begin{aligned}
|\psi_0\rangle &= |D_n^x\rangle \otimes \cdots \otimes |D_1^x\rangle = \bigotimes_{j=n}^{1} |D_j^x\rangle\,, \\
|\psi_1\rangle &= \bigotimes_{j=n}^{2} |D_j^x\rangle \otimes |\phi\rangle \otimes |\phi\rangle \otimes |B_1^y\rangle\,, \\
|\psi_i\rangle &= \bigotimes_{j=n}^{i+1} |D_j^x\rangle \otimes \bigotimes_{k=2i}^{1} |\phi\rangle \otimes \bigotimes_{m=1}^{i} |B_m^y\rangle\,, \\
|\psi_n\rangle &= \bigotimes_{j=2n}^{1} |\phi\rangle \otimes \bigotimes_{m=1}^{n} |B_m^y\rangle\,.
\end{aligned}
$$

To match the moving bit model: $B_i^y = D_i^y$.

Unitarity demands the auxiliary states to be in fiducial form:

$$
|d_1^x\rangle \otimes |c_1^x\rangle = |\phi\rangle \otimes |\phi\rangle \qquad \forall i\,.
$$

This model is a rewriting of the ‘moving bit’ model: manifestely unitary.

The 'moving bit' model: What does it teach us?

Physical lesson:

- Information leaves the system at every step.
- For the above basis vectors: $S_{B_i c_i} = 0$.

  For a **typical state**:
  $$\begin{aligned} S_{B_i c_i} &= S_{B_i} && (c_i \text{ is fiducial}) \\ &= S_{D_i} && (\text{moving bits}) \\ &\neq 0 && \text{at every step!} \end{aligned}$$

  For a non-typical state: even though $S_{B_i c_i} = 0$ possible, the $B_i c_i$ system not in a predetermined state independent of the initial state.

Technical lesson:

- The new quanta B leaving the system must carry information of the old quanta D, **to avoid quantum cloning** the d_i must be bleached.
- **Unitarity** also **requires** the auxiliary quanta c_i to be bleached.

Hawking evaporation via qubit models

[AMPS]: may have $S_{BC} = 0$ until t_{Page}, must have $S_{BC} \neq 0$ after t_{Page}.

Initial black hole state: $|\hat{q}_1 \cdots \hat{q}_n\rangle$.

Evolution: $$\mathcal{I}_i = \frac{1}{\sqrt{2}}\left(|\hat{0}_{n+i}\rangle|0_i\rangle + |\hat{1}_{n+i}\rangle|1_i\rangle\right) \otimes \hat{I} \quad \text{for} \quad i \leqslant \frac{n}{2} \,.$$

$$\mathcal{I}_i = |\hat{0}0\rangle_{\mathrm{pair}} \otimes |\hat{0}\rangle\langle\hat{0}|_{\frac{n}{2}+i+1} + |\hat{0}1\rangle_{\mathrm{pair}} \otimes |\hat{0}\rangle\langle\hat{1}|_{\frac{n}{2}+i+1} \quad \text{for} \quad i > \frac{n}{2} \,,$$

4-qubit example:

$|\hat{q}_1\hat{q}_2\hat{q}_3\hat{q}_4\rangle$

Hawking evaporation via qubit models

[AMPS]: may have $S_{BC} = 0$ until $t_{\rm Page}$, must have $S_{BC} \neq 0$ after $t_{\rm Page}$.

Initial black hole state: $|\hat{q}_1 \cdots \hat{q}_n\rangle$.

Evolution:
$$\mathcal{I}_i = \frac{1}{\sqrt{2}}\left(|\hat{0}_{n+i}\rangle|0_i\rangle + |\hat{1}_{n+i}\rangle|1_i\rangle\right) \otimes \hat{I} \quad \text{for} \quad i \leqslant \frac{n}{2}.$$

$$\mathcal{I}_i = |\hat{0}0\rangle_{\rm pair} \otimes |\hat{0}\rangle\langle\hat{0}|_{\frac{n}{2}+i+1} + |\hat{0}1\rangle_{\rm pair} \otimes |\hat{0}\rangle\langle\hat{1}|_{\frac{n}{2}+i+1} \quad \text{for} \quad i > \frac{n}{2},$$

4-qubit example:
$$|\hat{q}_1\hat{q}_2\hat{q}_3\hat{q}_4\rangle \quad \xrightarrow{i=1} \quad \frac{1}{\sqrt{2}}|\hat{q}_1\hat{q}_2\hat{q}_3\hat{q}_4\rangle \qquad (|\hat{0}0\rangle + |\hat{1}1\rangle)$$

Hawking evaporation via qubit models

[AMPS]: may have $S_{BC} = 0$ until $t_{\rm Page}$, must have $S_{BC} \neq 0$ after $t_{\rm Page}$.

Initial black hole state: $|\hat{q}_1 \cdots \hat{q}_n\rangle$.

Evolution: $$\mathcal{I}_i = \frac{1}{\sqrt{2}}\left(|\hat{0}_{n+i}\rangle|0_i\rangle + |\hat{1}_{n+i}\rangle|1_i\rangle\right) \otimes \hat{I} \quad \text{for} \quad i \leqslant \frac{n}{2}\,.$$

$$\mathcal{I}_i = |\hat{0}0\rangle_{\rm pair} \otimes |\hat{0}\rangle\langle\hat{0}|_{\frac{n}{2}+i+1} + |\hat{0}1\rangle_{\rm pair} \otimes |\hat{0}\rangle\langle\hat{1}|_{\frac{n}{2}+i+1} \quad \text{for} \quad i > \frac{n}{2}\,,$$

4-qubit example:

$$|\hat{q}_1\hat{q}_2\hat{q}_3\hat{q}_4\rangle \xrightarrow{i=1} \frac{1}{\sqrt{2}}|\hat{q}_1\hat{q}_2\hat{q}_3\hat{q}_4\rangle \qquad (|\hat{0}0\rangle + |\hat{1}1\rangle)$$

$$\xrightarrow{i=2} \frac{1}{2}|\hat{q}_1\hat{q}_2\hat{q}_3\hat{q}_4\rangle \qquad (|\hat{0}\hat{0}00\rangle + |\hat{0}\hat{1}10\rangle + |\hat{1}\hat{0}01\rangle + |\hat{1}\hat{1}11\rangle)$$

Hawking evaporation via qubit models

[AMPS]: may have $S_{BC} = 0$ until $t_{\rm Page}$, must have $S_{BC} \neq 0$ after $t_{\rm Page}$.

Initial black hole state: $|\hat{q}_1 \cdots \hat{q}_n\rangle\,.$

Evolution: $$\mathcal{I}_i = \frac{1}{\sqrt{2}}\big(|\hat{0}_{n+i}\rangle|0_i\rangle + |\hat{1}_{n+i}\rangle|1_i\rangle\big)\otimes\hat{I} \quad \text{for} \quad i \leqslant \frac{n}{2}\,.$$

$$\mathcal{I}_i = |\hat{0}0\rangle_{\rm pair}\otimes|\hat{0}\rangle\langle\hat{0}|_{\frac{n}{2}+i+1} + |\hat{0}1\rangle_{\rm pair}\otimes|\hat{0}\rangle\langle\hat{1}|_{\frac{n}{2}+i+1} \quad \text{for} \quad i > \frac{n}{2}\,,$$

4-qubit example:

$$|\hat{q}_1\hat{q}_2\hat{q}_3\hat{q}_4\rangle \xrightarrow{i=1} \frac{1}{\sqrt{2}}|\hat{q}_1\hat{q}_2\hat{q}_3\hat{q}_4\rangle \qquad (|\hat{0}0\rangle + |\hat{1}1\rangle)$$

$$\xrightarrow{i=2} \frac{1}{2}|\hat{q}_1\hat{q}_2\hat{q}_3\hat{q}_4\rangle \qquad (|\hat{0}\hat{0}00\rangle + |\hat{0}\hat{1}10\rangle + |\hat{1}\hat{0}01\rangle + |\hat{1}\hat{1}11\rangle)$$

$$\xrightarrow{i=3} \frac{1}{2}|\hat{q}_1\hat{q}_2\hat{q}_3\hat{q}_4\hat{0}\rangle \qquad (|\hat{0}\hat{0}000\rangle + |\hat{1}\hat{0}010\rangle + |\hat{0}\hat{0}101\rangle + |\hat{1}\hat{0}111\rangle)$$

Hawking evaporation via qubit models

[AMPS]: may have $S_{BC} = 0$ until t_{Page}, must have $S_{BC} \neq 0$ after t_{Page}.

Initial black hole state: $|\hat{q}_1 \cdots \hat{q}_n\rangle$.

Evolution: $$\mathcal{I}_i = \frac{1}{\sqrt{2}}\left(|\hat{0}_{n+i}\rangle|0_i\rangle + |\hat{1}_{n+i}\rangle|1_i\rangle\right) \otimes \hat{I} \quad \text{for} \quad i \leqslant \frac{n}{2}.$$

$$\mathcal{I}_i = |\hat{0}0\rangle_{\text{pair}} \otimes |\hat{0}\rangle\langle\hat{0}|_{\frac{n}{2}+i+1} + |\hat{0}1\rangle_{\text{pair}} \otimes |\hat{0}\rangle\langle\hat{1}|_{\frac{n}{2}+i+1} \quad \text{for} \quad i > \frac{n}{2},$$

4-qubit example:

$$|\hat{q}_1\hat{q}_2\hat{q}_3\hat{q}_4\rangle \xrightarrow{i=1} \frac{1}{\sqrt{2}}|\hat{q}_1\hat{q}_2\hat{q}_3\hat{q}_4\rangle \quad (|\hat{0}0\rangle + |\hat{1}1\rangle)$$

$$\xrightarrow{i=2} \frac{1}{2}|\hat{q}_1\hat{q}_2\hat{q}_3\hat{q}_4\rangle \quad (|\hat{0}\hat{0}00\rangle + |\hat{0}\hat{1}10\rangle + |\hat{1}\hat{0}01\rangle + |\hat{1}\hat{1}11\rangle)$$

$$\xrightarrow{i=3} \frac{1}{2}|\hat{q}_1\hat{q}_2\hat{q}_3\hat{q}_4\hat{0}\rangle \quad (|\hat{0}\hat{0}000\rangle + |\hat{1}\hat{0}010\rangle + |\hat{0}\hat{0}101\rangle + |\hat{1}\hat{0}111\rangle)$$

$$\xrightarrow{i=4} \frac{1}{2}|\hat{q}_1\hat{q}_2\hat{q}_3\hat{q}_4\hat{0}\hat{0}\hat{0}\hat{0}\rangle \quad (|0000\rangle + |1010\rangle + |0101\rangle + |1111\rangle).$$

Hawking evaporation via qubit models

[AMPS]: may have $S_{BC} = 0$ until t_{Page}, must have $S_{BC} \neq 0$ after t_{Page}.

Initial black hole state: $|\hat{q}_1 \cdots \hat{q}_n\rangle$.

Evolution: $\mathcal{I}_i = \frac{1}{\sqrt{2}}\left(|\hat{0}_{n+i}\rangle|0_i\rangle + |\hat{1}_{n+i}\rangle|1_i\rangle\right) \otimes \hat{I} \quad \text{for} \quad i \leqslant \frac{n}{2}$.

$$\mathcal{I}_i = |\hat{0}0\rangle_{\text{pair}} \otimes |\hat{0}\rangle\langle\hat{0}|_{\frac{n}{2}+i+1} + |\hat{0}1\rangle_{\text{pair}} \otimes |\hat{0}\rangle\langle\hat{1}|_{\frac{n}{2}+i+1} \quad \text{for} \quad i > \frac{n}{2},$$

4-qubit example:

$$|\hat{q}_1\hat{q}_2\hat{q}_3\hat{q}_4\rangle \xrightarrow{i=1} \frac{1}{\sqrt{2}}|\hat{q}_1\hat{q}_2\hat{q}_3\hat{q}_4\rangle \quad (|\hat{0}0\rangle + |\hat{1}1\rangle)$$

$$\xrightarrow{i=2} \frac{1}{2}|\hat{q}_1\hat{q}_2\hat{q}_3\hat{q}_4\rangle \quad (|\hat{0}\hat{0}00\rangle + |\hat{0}\hat{1}10\rangle + |\hat{1}\hat{0}01\rangle + |\hat{1}\hat{1}11\rangle)$$

$$\xrightarrow{i=3} \frac{1}{2}|\hat{q}_1\hat{q}_2\hat{q}_3\hat{q}_4\hat{0}\rangle \quad (|\hat{0}\hat{0}000\rangle + |\hat{1}\hat{0}010\rangle + |\hat{0}\hat{0}101\rangle + |\hat{1}\hat{0}111\rangle)$$

$$\xrightarrow{i=4} \frac{1}{2}|\hat{q}_1\hat{q}_2\hat{q}_3\hat{q}_4\hat{0}\hat{0}\hat{0}\hat{0}\rangle \quad (|0000\rangle + |1010\rangle + |0101\rangle + |1111\rangle).$$

Final radiation state **pure** but information of the *original state* never came out! This evaporation process is thus **non-unitary**!

Fuzzballs: resolution to the information ‘paradox’

Black hole evaporation via Hawking radiation is **non-unitary**!

To preserve unitarity:

- Information of the original state to come out in every step.
- Large corrections to Unruh vacuum at horizon needed!

Fuzzballs: resolution to the information 'paradox'

Black hole evaporation via Hawking radiation is **non-unitary**!

To preserve unitarity:

- Information of the original state to come out in every step.
- Large corrections to Unruh vacuum at horizon needed!

$\hookrightarrow$ exist in string theory:

string/brane configuration which have an effective size $\sim$ horizon radius

Fuzzballs provide a mechanism for structure at the horizon scale unlike black hole complementarity which gives no mechanism for the membrane!

> Black hole is a coarse-grained description of the true microstates which are *singularity-free* and *horizon-less* solutions of quantum gravity.

Fuzzball evaporation via emission from its surface is **unitary**!

Fuzzballs: an explicit construction

[Bena, AP, Vercnocke]

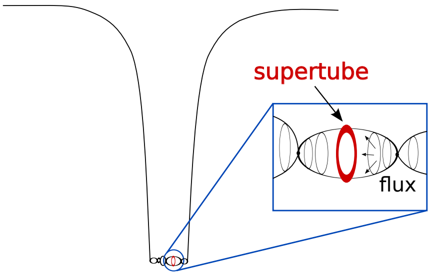


Figure: *Near-extremal black hole microstates from supertubes in deep throat region of backgrounds with charge dissolved in flux.*

Configurations of different size:

- structure l_{Planck} away from the horizon → realization of firewalls in string theory?
- structure much further away from the horizon.

Regardless, all of these near-extremal microstates differ from the classical black hole solution at the scale of the horizon.

Our construction puts flesh and branes on the fuzzball proposal!

Falling into typical fuzzballs: an approximation

Use AdS/CFT but expect lesson to hold more generally.

Approximate a typical state by a thermal state:

$$\langle\psi|\hat{O}|\psi\rangle \approx Tr(\rho\hat{O}) = \frac{1}{\sum_i e^{-\frac{E_i}{T_H}}} \sum_k e^{-\frac{E_k}{T_H}} \langle E_k|\hat{O}|E_k\rangle \,.$$

Purify the density matrix:

$$|\Psi\rangle = \frac{1}{\sqrt{\sum_i e^{-\frac{E_i}{T_H}}}} \sum_k e^{-\frac{E_k}{2T_H}} |E_k\rangle_L \otimes |E_k\rangle_R \,,$$

Such entangled CFT states are dual to eternal AdS black hole: [Maldacena]

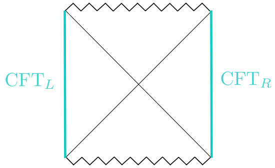


Figure: *Penrose diagram of the extended AdS Schwarzschild black hole.*

Black holes from fuzzballs

AdS/CFT: CFT state dual to (asymptotically) gravitational solution

Entanglement of CFT states → entanglement of gravitational solutions:
[Van Raamsdonk]

CFT
$$|\Psi\rangle = \frac{1}{\sqrt{\sum_i e^{-\frac{E_i}{T_H}}}} \sum_k e^{-\frac{E_k}{2T_H}} |E_k\rangle_L \otimes |E_k\rangle_R \,,$$

Bulk
$$|G\rangle_{eternal} = \frac{1}{\sqrt{\sum_i e^{-\frac{E_i}{T_H}}}} \sum_k e^{-\frac{E_k}{2T_H}} |g_k\rangle_L \otimes |g_k\rangle_R \,.$$

What are the $|g\rangle$'s?

$$\sum_k e^{-\frac{E_k}{2kT}}$$

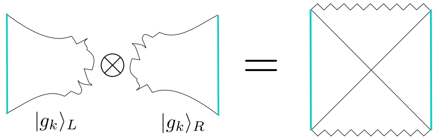


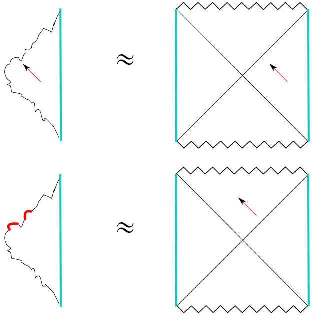
Figure: *The extended AdS Schwarzschild black hole can be understood as the sum over entangled fuzzball solutions $|g_k\rangle_L$ and $|g_k\rangle_R$.*

Alice fuzzes but may not even know it!

Infalling high-energy quanta will be absorbed by the fuzzball and excite its collective modes.

This process can be approximated by infall into the eternal AdS black hole.

Note: Spacetime behind the horizon and singularity are a short-lived $t \sim M$ approximate description!



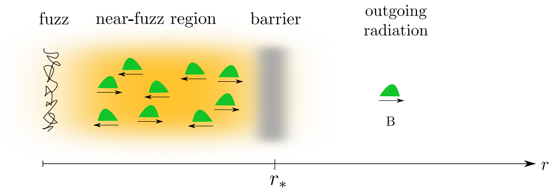


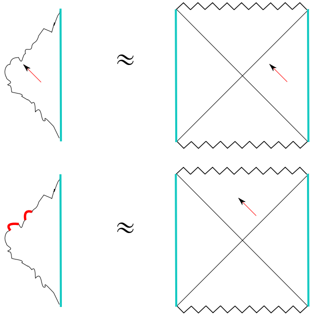
Figure: *Inside of potential barrier of fuzzball ≈ black hole in Hartle-Hawking state.*

Alice fuzzes but may not even know it!

Infalling high-energy quanta will be absorbed by the fuzzball and excite its collective modes.

This process can be approximated by infall into the eternal AdS black hole.

Note: Spacetime behind the horizon and singularity are a short-lived $t \sim M$ approximate description!



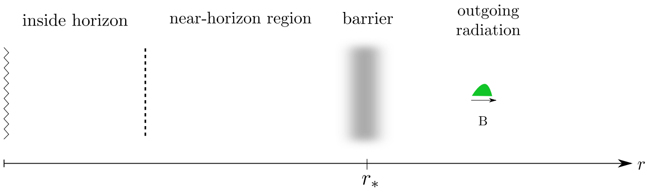


Figure: *Inside of potential barrier of fuzzball ≈ black hole in Hartle-Hawking state.*

Conclusions

Information 'paradox': *When and how does the information come out?*

- Unitary evaporation requires information of the original state to come out in every step of the evolution → traditional black hole horizon inconsistent with unitarity at every step.
- No information 'paradox' for fuzzballs! Can explicitly construct near-extremal microstates with structure at the horizon scale.

Infall 'problem': *Is Alice burning of fuzzing?*

- Fuzzball complementarity: fine-grained operators experience the details of the fuzzball microstate and coarse-grained operators experience the black hole.
- Energy-scale dependence: Infalling high-energy $E \gg kT_H$ observers experience free fall while low-energy $E \sim kT_H$ observers do not.