Young hair

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CEA/Saclay → UCSB

1210.6996

with Steve Avery and Borun Chowdhury

FuzzOrFire KITP, 30 August 2013

In this talk...

I will consider unitarity as the most fundamental principle.

I will be agnostic about the degree of violence for an infalling probe.

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Avery-Chowdhury-AP 1210.6996

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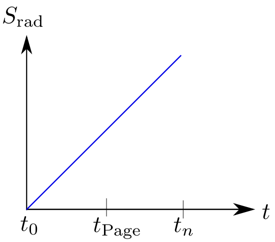
Avery-Chowdhury-AP 1210.6996

See also recently: Bousso 1308.2665 w/ similar techniques,
Marolf-Polchinski 1307.4706 w/ different techniques

and before firewalls: van Raamsdonk *et al* 1206.1323 in context of AdS/CFT

Hawking versus pure evaporation

Von Neumann entropy
$-\mathrm{Tr}\,(\rho_{\mathrm{rad}}\,\log\,\rho_{\mathrm{rad}})$



Final radiation state has $S_{\mathrm{rad}} \neq 0$:
Evaporation via max entangled Hawking pairs ($S_{\mathrm{pair}} = 0$) is non-unitary!

Hawking versus pure evaporation

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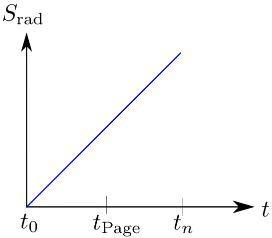
$\downarrow$



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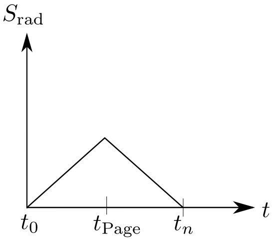
Page curve for typical states:



Any normal evaporating body in a pure intial state has a pure final state: $S_{\mathrm{rad}} = 0$.

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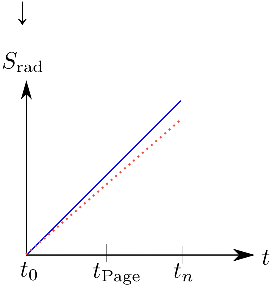

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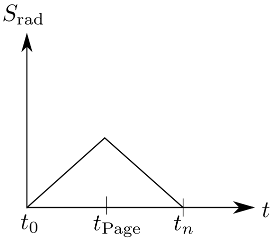

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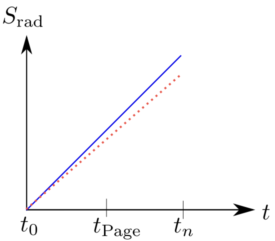

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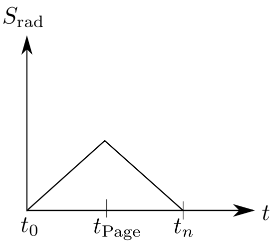

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Any normal evaporating body in a pure intial state has a pure final state: $S_{\mathrm{rad}} = 0$.

Purity of final radiation requires $S_{\mathrm{pair}} \neq 0 \rightarrow$ hair no later than t_{Page}!

Hawking versus pure evaporation

Mathur, Avery, AMPS

I. Outside:

Purity of the final radiation state: pair $\longrightarrow$ hair *no later than* t_{Page}.

II. Infalling:

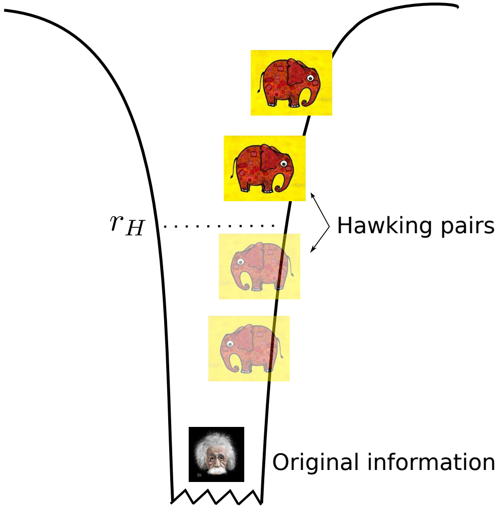
Alice  /  *no later than* t_{Page}.

$\mathcal{Q}$uestions:

Sharper information loss statement from conditions beyond purity?

Do young black holes have hair?

When and how does the original information get out?



Conditions for unitarity

1. Purity: Pure states evolve into pure states.
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.

Do these additional conditions make the statement
of information loss in Hawking's process more precise?

Framework and rules

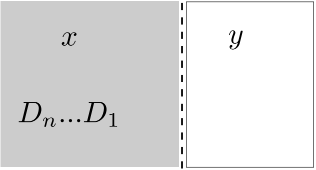
We will model evaporation via qubits and use the following rules:

- The dimension of the physical Hilbert space is constant.
- Fundamental properties of fast scramblers do not depend on the nature of formation.
- The evaporation process can be described within a local framework.
- The general dynamics is state independent.

The ‘moving bit’ model

Unitary model of evaporation:

Move qubits **D** from **x** to **y**.



Typical state: $S_{D_i} \neq 0$.

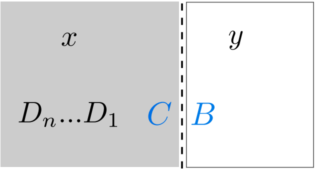
Evolution of basis of states:

$$
\begin{aligned}
|\psi_0\rangle &= \bigotimes_{j=n}^{1} |D_j^x\rangle \\
|\psi_1\rangle &= \bigotimes_{j=n}^{2} |D_j^x\rangle \otimes |D_1^y\rangle \\
&\vdots \\
|\psi_i\rangle &= \bigotimes_{j=n}^{i+1} |D_j^x\rangle \otimes \bigotimes_{k=i}^{1} |D_k^y\rangle \\
&\vdots \\
|\psi_n\rangle &= \bigotimes_{k=n}^{1} |D_k^y\rangle
\end{aligned}
$$

The Hawking model

Non-unitary model of evaporation:

Create qubits **C**, **B** at interface.
Move **C** to **x** and **B** to **y**.



Maximally entangled: $S_{B_i C_i} = 0$.

C annihilate with **D**.

Evolution of basis of states:

$$
\begin{aligned}
|\psi_0\rangle &= \bigotimes_{j=n}^{1} |D_j^x\rangle \\
|\psi_1\rangle &= \bigotimes_{j=n}^{1} |D_j^x\rangle \otimes |{C_1}^x\rangle \otimes |{B_1}^y\rangle \\
&\vdots \\
|\psi_i\rangle &= \bigotimes_{j=n}^{1} |D_j^x\rangle \otimes \bigotimes_{k=i}^{1} \left(|{C_k}^x\rangle \otimes |{B_k}^y\rangle \right) \\
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\end{aligned}
$$

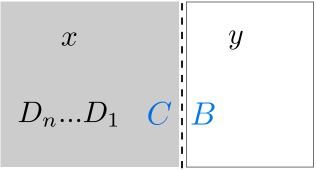
General model framework

Potentially non-unitary model:

Create qubits **C**, **B** at interface.

D, **C**, **B** $\xrightarrow{\mathcal{U}}$ $\tilde{D}$, $\tilde{C}$, $\tilde{B}$.

Move $\tilde{C}$ to **x** and $\tilde{B}$ to **y**.



Identifying two auxiliary qubits.

Tracing out auxiliary qubits.

Evolution of basis of states:

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|\psi_0\rangle &= \bigotimes_{j=n}^{1} |D_j^x\rangle \\
|\psi_1\rangle &= \bigotimes_{j=n}^{1} |\tilde{D}_j^x\rangle \otimes |\tilde{C}_1{}^x\rangle \otimes |\tilde{B}_1{}^y\rangle \\
&\vdots \\
|\psi_i\rangle &= \bigotimes_{j=n}^{1} |\tilde{D}_j^x\rangle \otimes \bigotimes_{k=i}^{1} \left(|\tilde{C}_k{}^x\rangle \otimes |\tilde{B}_k{}^y\rangle \right) \\
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Moving bits via pairs

Evolution of basis of states:

$$|\psi_0\rangle = \bigotimes_{j=n}^{2} |D_j^x\rangle \otimes |D_1^x\rangle$$

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$$\overbrace{|c_1^x\rangle \otimes |B_1^y\rangle}^{\text{pair}}$$

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$B_i = D_i$: rewriting of the moving bit model via pairs $\Rightarrow$ unitary.

‘Moving bit’ model versus Hawking process

Unitary moving bit model:

- $B_i = D_i$ $\rightarrow$ Information leaves the system at every step!

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- For basis states: $S_{B_i c_i} = 0$
- For typical states:

$$\begin{aligned} S_{B_i c_i} &= S_{B_i} \\ &= S_{D_i} \\ &\neq 0 \qquad \text{at every step!} \end{aligned}$$

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- $S_{B_i c_i} = 0 \qquad$ at every step!
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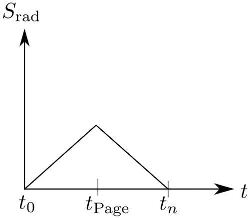
$\Rightarrow$ Unitarity requires $S_{\mathrm{pair}} \neq 0$ at every step for typical states.

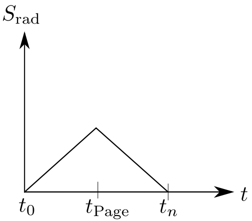
Hawking + 'moving bit' model



$$\mathcal{I}_i^H = |\varphi_i\rangle_{\rm Hawking} \quad \text{for} \quad i \leqslant t_{\rm Page}$$
$$= \frac{1}{\sqrt{2}}\left(|\hat{0}_{n+i}\rangle|0_i\rangle + |\hat{1}_{n+i}\rangle|1_i\rangle\right)_{\rm pair} \otimes \hat{I}\,.$$

$$\mathcal{I}_i^{MB} = |cB\rangle_{\rm pair} \otimes |d\rangle\langle D|_{2n+1-i} \quad \text{for} \quad i > t_{\rm Page}$$
$$= |\hat{0}0\rangle_{\rm pair} \otimes |\hat{0}\rangle\langle\hat{0}|_{2n+1-i} + |\hat{0}1\rangle_{\rm pair} \otimes |\hat{0}\rangle\langle\hat{1}|_{2n+1-i}\,.$$

Hawking + ‘moving bit’ model



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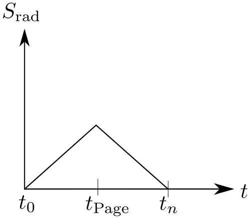
&= |\hat{0}0\rangle_{\mathrm{pair}} \otimes |\hat{0}\rangle\langle\hat{0}|_{2n+1-i} + |\hat{0}1\rangle_{\mathrm{pair}} \otimes |\hat{0}\rangle\langle\hat{1}|_{2n+1-i}\,.
\end{aligned}
$$

$$
\begin{aligned}
|\hat{q}_1\hat{q}_2\hat{q}_3\hat{q}_4\rangle &\xrightarrow{i=1} \frac{1}{\sqrt{2}}|\hat{q}_1\hat{q}_2\hat{q}_3\hat{q}_4\rangle \qquad (|\hat{0}0\rangle + |\hat{1}1\rangle) \\
&\xrightarrow{i=2} \frac{1}{2}|\hat{q}_1\hat{q}_2\hat{q}_3\hat{q}_4\rangle \qquad (|\hat{0}\hat{0}00\rangle + |\hat{1}\hat{0}01\rangle + |\hat{0}\hat{1}10\rangle + |\hat{1}\hat{1}11\rangle) \\
&\xrightarrow{i=3} \frac{1}{2}|\hat{q}_1\hat{q}_2\hat{q}_3\hat{q}_4\hat{0}\rangle \qquad (|\hat{0}\hat{0}000\rangle + |\hat{1}\hat{0}001\rangle + |\hat{0}\hat{0}110\rangle + |\hat{1}\hat{0}111\rangle) \\
&\xrightarrow{i=4} \frac{1}{2}\underbrace{|\hat{q}_1\hat{q}_2\hat{q}_3\hat{q}_4\hat{0}\hat{0}\hat{0}\hat{0}\rangle}_{\text{auxiliary}} \; \underbrace{(|0000\rangle + |1001\rangle + |0110\rangle + |1111\rangle)}_{\text{physical}}\,.
\end{aligned}
$$

Hawking + 'moving bit' model



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$$\begin{aligned} \mathcal{I}_i^{MB} &= |cB\rangle_{\rm pair} \otimes |d\rangle\langle D|_{2n+1-i} \quad \text{for} \quad i > t_{\rm Page} \\ &= |\hat{0}0\rangle_{\rm pair} \otimes |\hat{0}\rangle\langle\hat{0}|_{2n+1-i} + |\hat{0}1\rangle_{\rm pair} \otimes |\hat{0}\rangle\langle\hat{1}|_{2n+1-i}\,. \end{aligned}$$

$$\begin{aligned} |\hat{q}_1\hat{q}_2\hat{q}_3\hat{q}_4\rangle &\xrightarrow{i=1} \frac{1}{\sqrt{2}}|\hat{q}_1\hat{q}_2\hat{q}_3\hat{q}_4\rangle \qquad (|\hat{0}0\rangle + |\hat{1}1\rangle) \\ &\xrightarrow{i=2} \frac{1}{2}|\hat{q}_1\hat{q}_2\hat{q}_3\hat{q}_4\rangle \qquad (|\hat{0}\hat{0}00\rangle + |\hat{1}\hat{0}01\rangle + |\hat{0}\hat{1}10\rangle + |\hat{1}\hat{1}11\rangle) \\ &\xrightarrow{i=3} \frac{1}{2}|\hat{q}_1\hat{q}_2\hat{q}_3\hat{q}_4\hat{0}\rangle \qquad (|\hat{0}\hat{0}000\rangle + |\hat{1}\hat{0}001\rangle + |\hat{0}\hat{0}110\rangle + |\hat{1}\hat{0}111\rangle) \\ &\xrightarrow{i=4} \frac{1}{2}\underbrace{|\hat{q}_1\hat{q}_2\hat{q}_3\hat{q}_4\hat{0}\hat{0}\hat{0}\hat{0}\rangle}_{\rm auxiliary}\underbrace{(|0000\rangle + |1001\rangle + |0110\rangle + |1111\rangle)}_{\rm physical}\,. \end{aligned}$$

Final radiation state pure but independent of initial state!

Information of the original state never came out!

Where is the information?

Tracking state:

$$|T\rangle = \frac{1}{2^{\frac{n}{2}}} \sum_{i=1}^{2^n} |\widehat{bh}_i\rangle |\tilde{r}_i\rangle \,,$$

$\{|\hat{w}_i\rangle\}, \{|\tilde{r}_i\rangle\}$ are orthonormal bases for the n-qubit initial state and reference system.

- The decrease of the entanglement entropy of the black hole quantifies how much information has left the black hole.
- The entanglement entropy of the external radiation quantifies how much information is now in the radiation.
- Mutual information vanishes in qubit framework.
  (Moreover conjectured to be zero for black hole evaporation [Giddings,Shi]).
  $\rightarrow$ Information loss occurs in wrong identification of auxiliary qubits.

Losing a qubit

How much information is lost if we trace out the wrong qubit?

Initial tracking state:

$$|T_0\rangle = \frac{1}{2}\Big(|\hat{0}\hat{0}\rangle|\tilde{0}\tilde{0}\rangle + |\hat{0}\hat{1}\rangle|\tilde{0}\tilde{1}\rangle + |\hat{1}\hat{0}\rangle|\tilde{1}\tilde{0}\rangle + |\hat{1}\hat{1}\rangle|\tilde{1}\tilde{1}\rangle\Big)\,,$$

Evolution operator:

$$\mathcal{I}_i = \Big(|\hat{0}\hat{0}\rangle|0\rangle\langle\hat{0}|_{(3-i)} + |\hat{0}\hat{0}\rangle|1\rangle\langle\hat{1}|_{(3-i)}\Big)_{D_{i-1}} \otimes I_{A_{i-1}} \otimes I_{R_{i-1}} \quad \text{for} \quad i = 1, 2\,.$$

$$i = 1: \quad |T_1\rangle = \mathcal{I}_1|T_0\rangle = |\hat{0}\hat{0}\rangle \otimes \frac{1}{2}\Big(|\hat{0}0\rangle|\tilde{0}\tilde{0}\rangle + |\hat{0}1\rangle|\tilde{0}\tilde{1}\rangle + |\hat{1}0\rangle|\tilde{1}\tilde{0}\rangle + |\hat{1}1\rangle|\tilde{1}\tilde{1}\rangle\Big)\,.$$

Info loss from wrong identification of auxiliary space with bleaching space:

$$S(\mathcal{A}_1) = -\mathrm{Tr}(\rho_1^{aux}\log\rho_1^{aux}) \underset{\uparrow}{=} \log 2\,.$$

$$\rho_1^{aux} = |\hat{0}\rangle\langle\hat{0}| \otimes \tfrac{1}{2}\Big(|\hat{0}\rangle\langle\hat{0}| + |\hat{1}\rangle\langle\hat{1}|\Big)$$

Simple example: maximum amount of information loss on a qubit.

General: $0 < S(\mathcal{A}_i) \leqslant \log 2$ for each erroneously traced out physical qubit.

Summary

Black hole evaporation via Hawking pair production is non-unitary.

Need deviation from vacuum at horizon no later than t_{Page}. ($\Leftarrow$ Purity)

Hawking, Mathur, Avery, AMPS

Summary

Black hole evaporation via Hawking pair production is non-unitary.

Need deviation from vacuum at horizon no later than t_{Page}. ($\Leftarrow$ Purity)

Hawking, Mathur, Avery, AMPS

- Purity does not guarantee that any information can be recovered.

- Information of original state out in every step. ($\Leftarrow$ Invertibility)

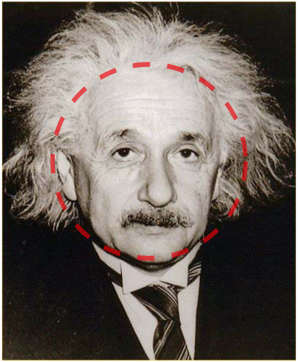
$\Rightarrow$ Need horizon-scale structure/hair before t_{Page}!

- No difference in rate of information release before and after $t_{\rm Page}$.

$\Rightarrow$ If Alice / *after* $t_{\rm Page}$ she will also / *before* $t_{\rm Page}$!

Avery-Chowdhury-AP

Also young black holes have hair!



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Unexpected but interesting: learn something deep about QG.