Puzzles of the interior

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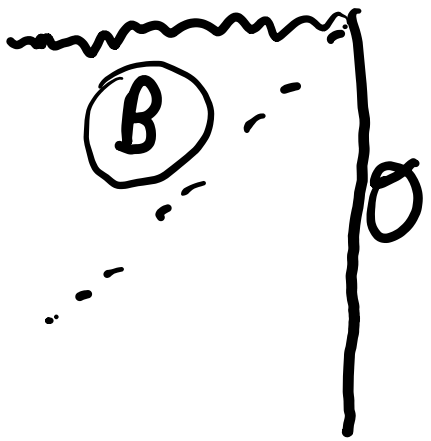
Puzzle of State Dependence

- Review how various proposals for interior operators only work locally in Hilbert space.

- No problem for boundary operators.

- Related to difficulty/impossibility of adding bulk sources.
  (generically, a non-perturbative effect)

Mirror Operators



Papadodimos-Raju, Verlinde Verlinde

single sided black hole

B constructed out of $\mathcal{O}$ and $\hat{\mathcal{O}}$,

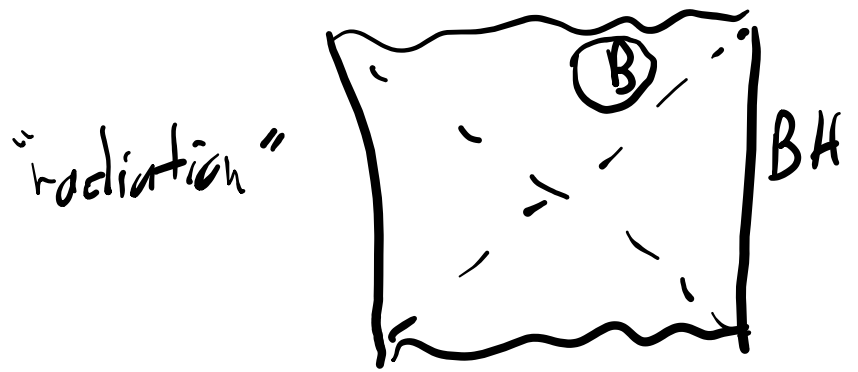
where $\hat{\mathcal{O}} A_{simple} |\Psi\rangle = A_{simple} \underbrace{e^{-\beta H/2} \mathcal{O} e^{\beta H/2}}_{\text{like } \mathcal{O}_L} |\Psi\rangle$

- non-linearly depends on $|\Psi\rangle$.
- unclear whether all interior fluctuations are allowed (frozen vacuum)

$U_{small} |\Psi\rangle$

ER = EPR

- For BH sufficiently entangled with another system (ex. past Hawking radiation), the interior is encoded there.

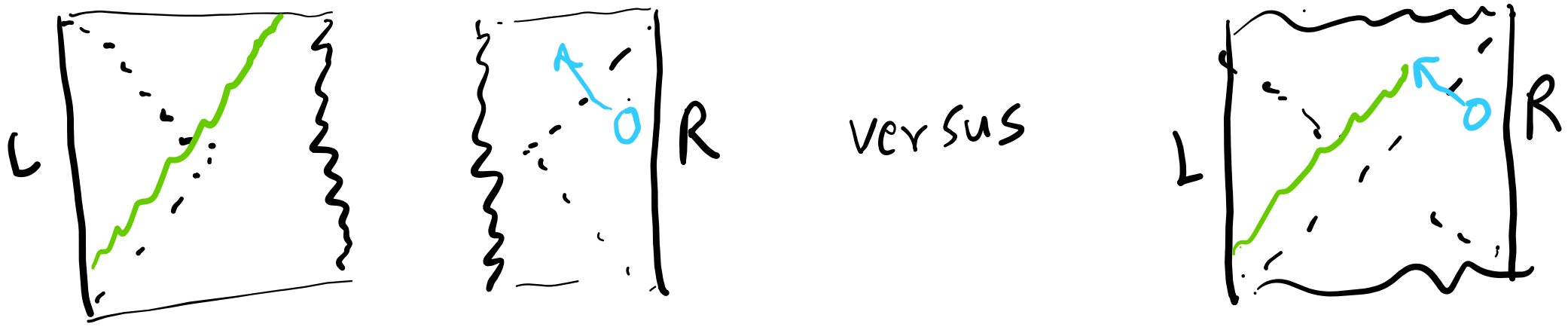


- Provides an answer for which algebra B lives.

Maldacena-Susskind

- Puzzles are associated to what particular operators in "radiation" are needed to produce particular bulk op's.

Marolf-Wall paradox

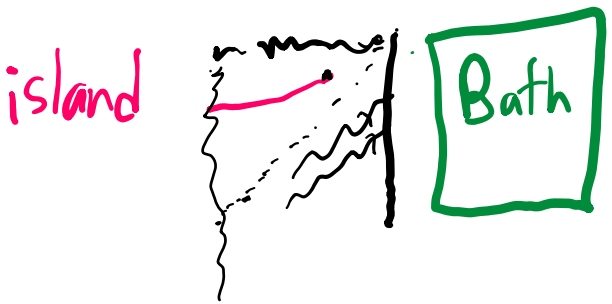


Observer can't see L in any factorized state.

But these span the Hilbert space, including the Htfd7. Impossible for linear operators.

Entanglement Islands

Made precise which part of the interior is encoded in radiation.



After Page time, a non-trivial QES appears, inside of which dof are in the EW of the bath.

Penington, Almheiri Engelhardt Maralf Maxfield

Direct consequence of replica wormholes in euclidean gravity.

Almheiri Hartman Maldacena Shaghoulian Tajdini

Overlaps and Null States

- From the boundary perspective, lack of independence of bulk states due to gravitational instanton corrections to the inner product can explain these features.

- Simple version applies to MW (DLJ)

- In any black hole, the volume of the interior grows in time. Eventually, the canonical entropy $> A/4G_N$

Non-isometric Codes

- As Chris Akers explained, replica wormholes imply the existence of such null states.

$$\mathcal{H}_{bulk} \longrightarrow \mathcal{H}_{boundary} \qquad \sum_{i=1}^{\sim e^S} a_i |i\rangle \to 0.$$

- But then no linear operator can produce the expected bulk answers on all semi-classical states.

Penington Shenker Stanford Yang, Akers Engelhardt Harlow Penington Vardhan

Interior Encoded in Structureless $\mathcal{H}$?

- Island region is encoded in the bath.
- If we can change basis in $\mathcal{H}_{bath}$, acts with a general U. Does this affect the dof in the island?
- Maybe implicit structure to $\mathcal{H}_{bath}$, related to order in which Hawking radiation is absorbed.

Closed Universes

- **Extreme version** - large semi-classical diff. invariant Hilbert space Chatrabhorty Chakravarty Godet Paul Raju
- Holography $\Rightarrow \mathcal{H}$ associated to frozen boundaries $\rightsquigarrow \mathcal{H} \simeq \mathbb{C}$.
- Marolf Maxfield $\Rightarrow$ non-perturbative null states lead to $\mathcal{H} \simeq \mathbb{C}$ if connected AdS configurations are not disordered.
- What are we doing in the physical universe?

Options:

1) Dictionary dependence

This is the usual situation for quantum codes.

- However, then either most of $\mathcal{H}_{bulk}$ is invalid (not in $\mathcal{H}_{code}$), or more data is needed than $|\Psi\rangle$ (ex. which $\mathcal{H}_{code}$), or we need a new dynamical principle to determine it.
- Moreover, "bulk entangling" interior modes with a reference can increase the allowed $\mathcal{H}_{code}$.

2) Ambiguous bulk

Perhaps all bulk are valid interpretations. Seems to give up on making bulk predictions.

3) Stringy / UV fix?

Can the overcounted states be removed by a physical mechanism (ex. stringy exclusion)?

Extreme version - no interior at all (as in some versions of fuzzballs).

4) Wrong paradigm of the dual on the boundary?

In QCD, we live in the IR. By identifying the exact dual quantum system with the boundary, are we confusing something?

5) Axiomatic framework beyond linear operators on $\mathcal{H}$

The most direct, albeit radical, implication.

what is the framework?

Puzzle of Theory Dependence

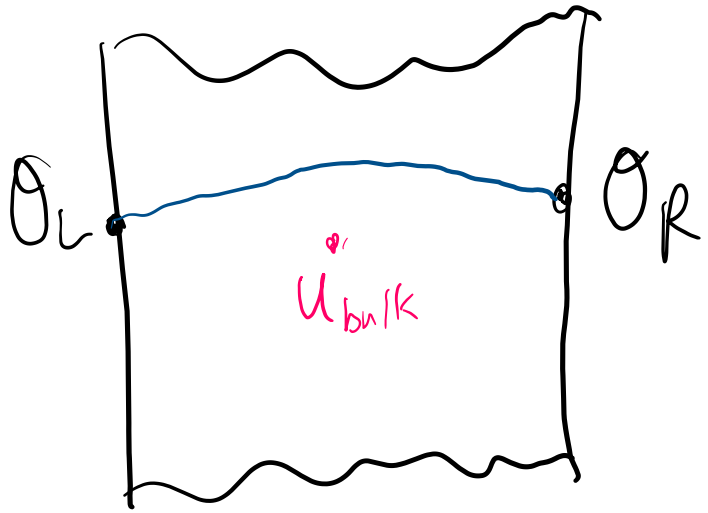
- Most bulk reconstruction involves solving the bulk and boundary.

- Especially true in the interior, where one basically defines operators $\hat{\mathcal{O}}\,i|\psi\rangle \simeq i\,\mathcal{O}_{bulk}|\psi\rangle$ for $i: \mathcal{H}_{bulk} \to \mathcal{H}_{boundary}$

- One might hope for a deeper principle, where the bulk configuration was an output, not an input.

Operational Constructions

$\langle O_L O_R \rangle \sim e^{-mL}$



Doesn't really probe interior in general states.

$[U_{bulk}, O_L O_R] = 0$.

- Acting with this can open the interior (traversable wormhole)
- $\sum_i O_L^i O_R^i$ can act as a near horizon symmetry Lin Maldacena Zhao
- Modifications in other states became state dependent

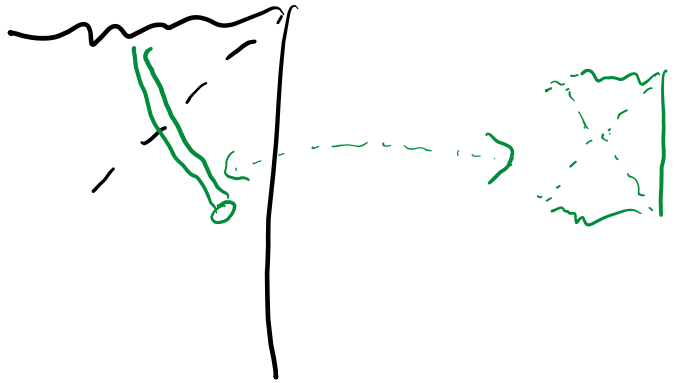
de Boer van Breukelen Lokhande Papadodimas Verlinde

- Modular flow

$\{A_{simple}\}U(K = -\log \rho)\}$ generates the EW algebra. Faulkner Lewkowycz

However, K is not a state-independent bulk operator.

- Probe black hole



K_{probe} acts locally as proper time

DLJ Lamprou

Frozen vacuum might be solvable by keeping track of complexity of the constructed operators de Boer DLJ Lamprou

Role of the Observer

- More generally, perhaps the interior is only unambiguous when an observer is included.

- Measurement $\longleftrightarrow$ entanglement with reference. Bulk entangling can apply when interior qubit ends up encoded in the reference!

- Possibly related to observer algebras of Chandrasekaran Longo Penington Witten.

Questions

- What is the axiomatic framework for interior observables in general states?
- Are $|\Psi\rangle$ and H the only data needed?
- Does this impact bulk dynamics?
- What is the role of the BH singularity?