The Black Hole Interior in SYK

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Outline

- SYK Black Hole Microstates. Atypical and Typical States.
- Necessity of State Dependence.
- AdS/CFT as a QEC.
- A Dictionary for the Interior from QEC.
- Comments on the Papadodimas-Raju proposal.

SYK BH Microstates

[Kourkoulou, Maldacena]

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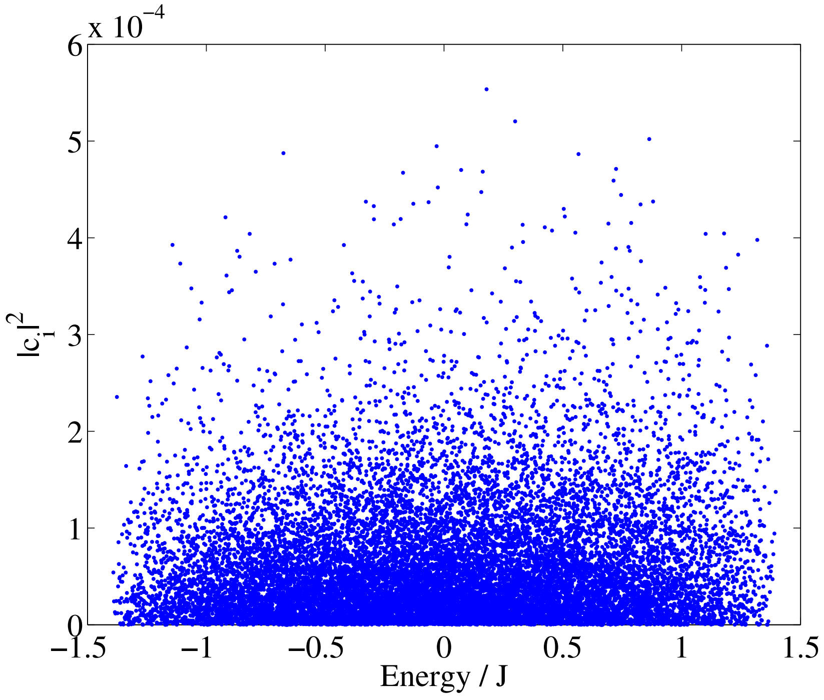

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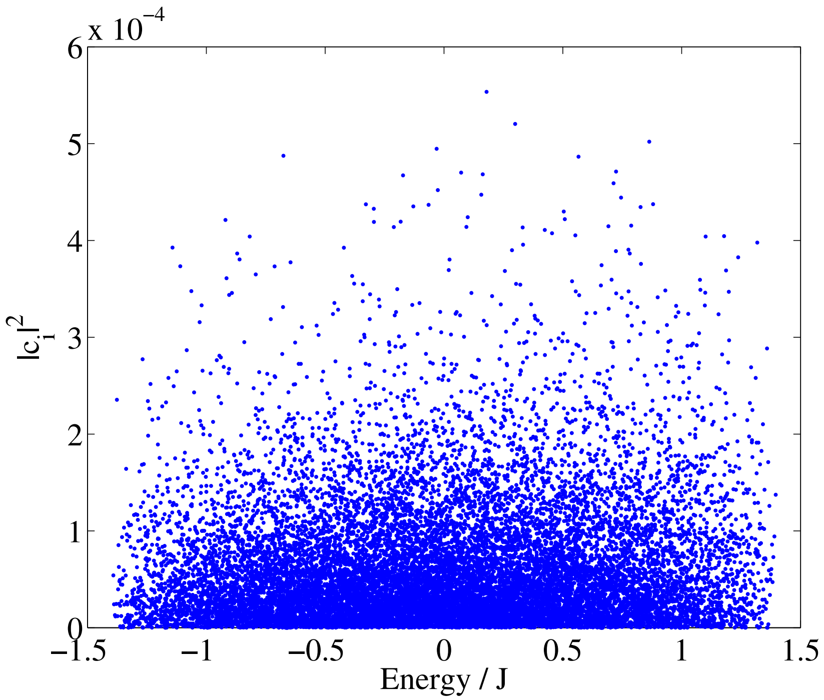
- Lower Energy via Euclidean Ev.

$$|B_s^\beta\rangle = e^{-\frac{\beta}{2}H}|B_s\rangle$$



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- Correlation Functions: ${}_R\langle B_s^\beta|\psi_R^i\psi_R^j|B_s^\beta\rangle_R = {}_{LR}\langle\beta|B_s\rangle_L \left(\psi_R^i\psi_R^j\right) {}_L\langle B_s|\beta\rangle_{LR}$

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- $\mathcal{O}(N)$ Symmetry, $\sim \mathcal{O}(1/N^{q-1})$. "Flip" subgroup: Flip sign of any even fermion. Relates any two states $|B_s\rangle$ and $|B_{s'}^\beta\rangle$

e.g. $\psi^2 \to -\psi^2 \quad \Longrightarrow \quad |\uparrow\uparrow\ldots\uparrow\rangle \to |\downarrow\uparrow\ldots\uparrow\rangle$

$$S_k = 2i\psi^{2k-1}\psi^{2k}$$

Correlation Functions

[Kourkoulou, Maldacena]

- Diagonal Correlator: ${}_R\langle B_s^\beta|\psi_R^1\psi_R^1|B_s^\beta\rangle_R = {}_{LR}\langle\beta|\Big[|B_s\rangle_L\langle B_s| \otimes \psi_R^1\psi_R^1\Big]|\beta\rangle_{LR}$

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Invariant under Flip $\quad \propto \sum_s {}_{LR}\langle\beta|\Big[|B_s\rangle_L\langle B_s|\otimes\psi_R^1\psi_R^1\Big]|\beta\rangle_{LR}$

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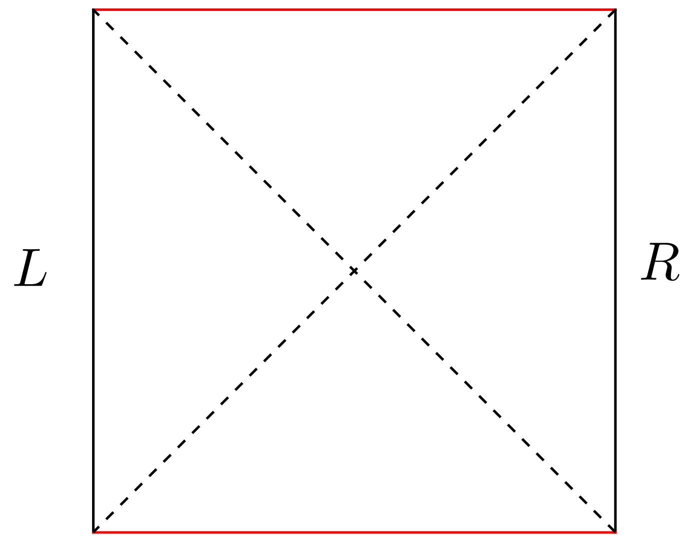
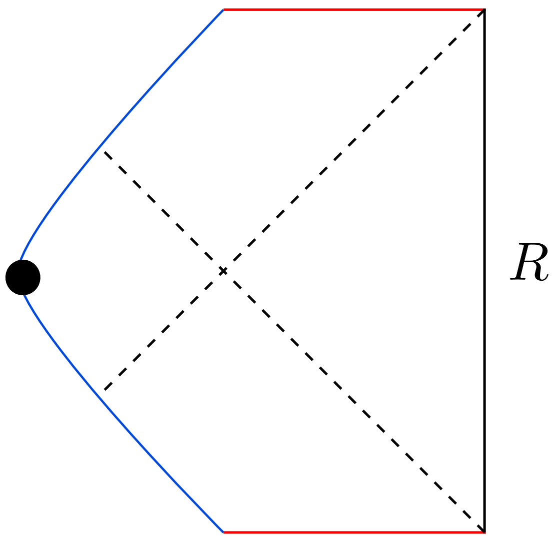
Bulk Picture

[Kourkoulou, Maldacena]



$|\beta\rangle_{LR}$



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- Bulk is deduced from the correlation functions @ $1 \ll \beta J$

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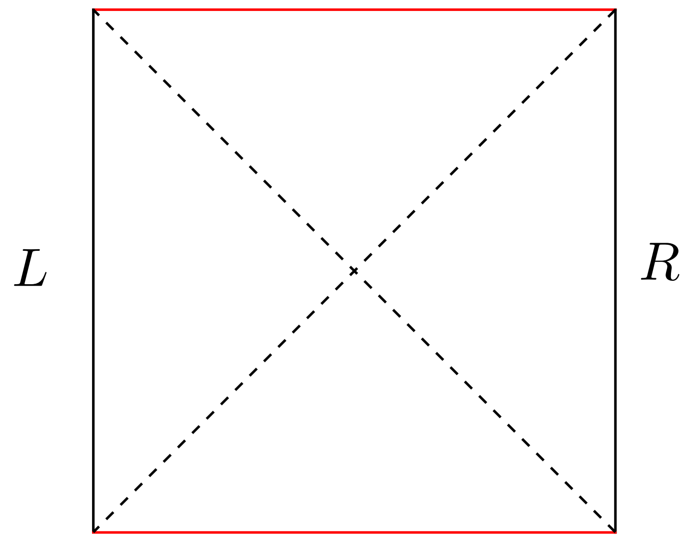

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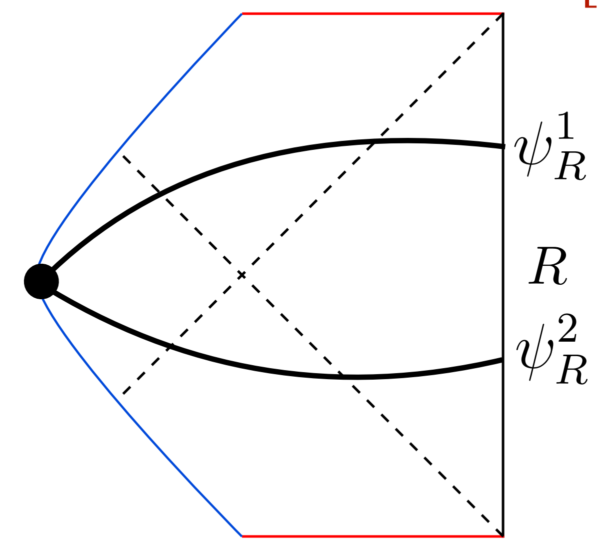

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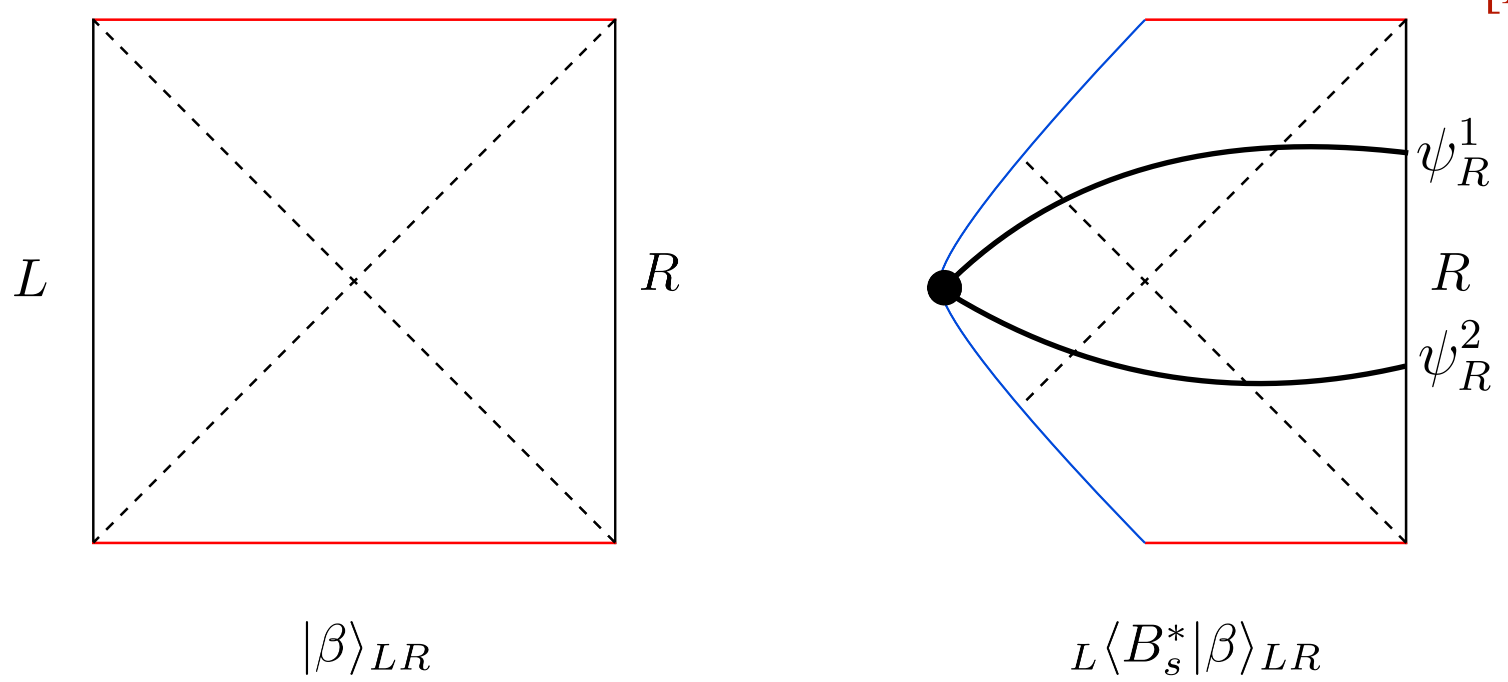

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- These are atypical BH microstates: Simple observables have not thermalized.

More Typical Microstates

- Begin with wormhole with OTO shockwaves: $|W\beta\rangle_{LR} \equiv W_L|\beta\rangle_{LR}$

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\begin{aligned}
{}_R\langle B_s^{W_\beta}|\psi_R^1\psi_R^2|B_s^{W_\beta}\rangle_R &\propto 2is_1 \times {}_{LR}\langle W\beta|\Big[\psi_L^1(0)\psi_L^2(0) \otimes \psi_R^1\psi_R^2\Big]|W\beta\rangle_{LR} \\
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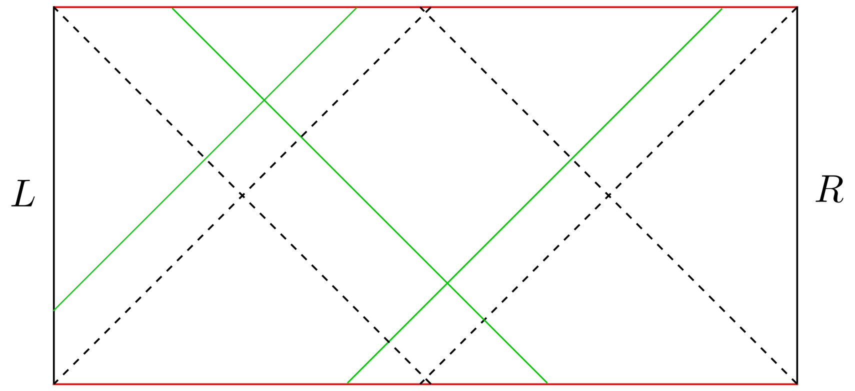
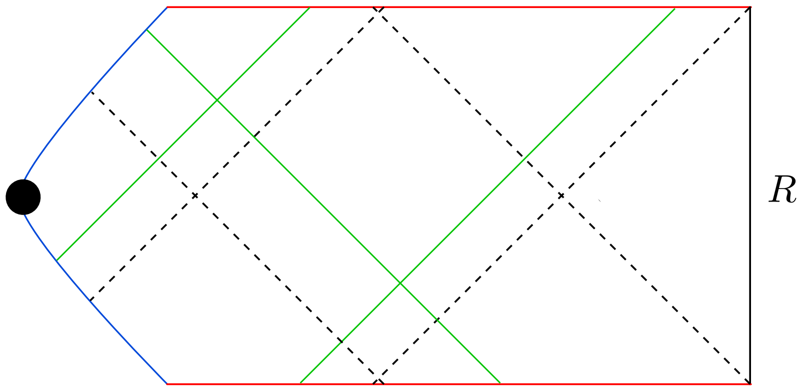


$W_L|\beta\rangle_{LR}$



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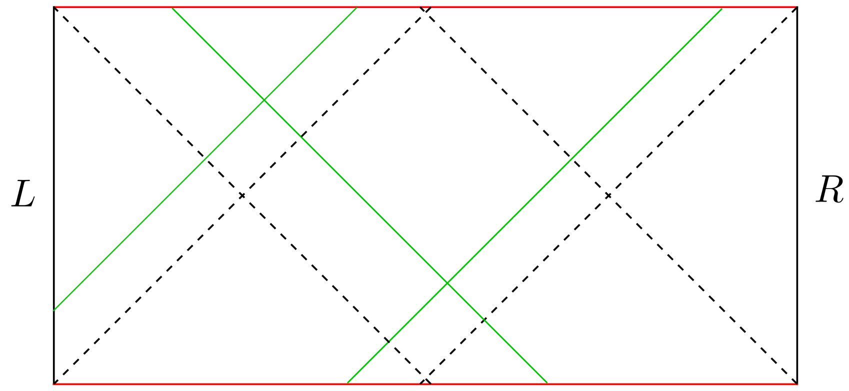

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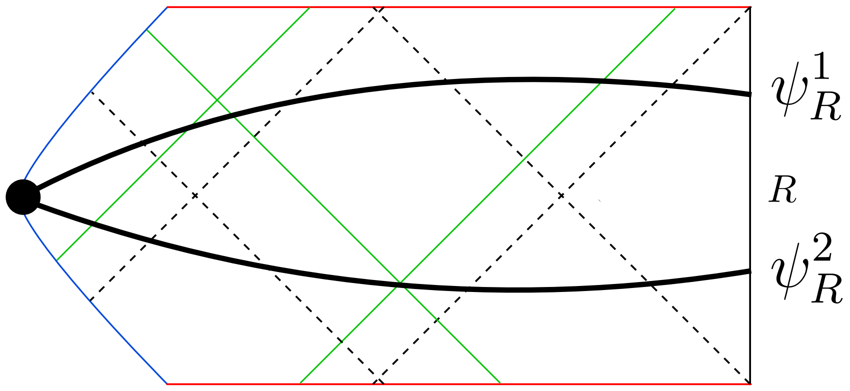

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Also: More Microstates from Modified SYK

[AA, Zhenbin Yang - WIP]

- SYK: $H_{SYK} \sim \sum_{i_1 \dots i_q}^{N} J_{i_1 \dots i_q} \psi^{i_1} \dots \psi^{i_q}$
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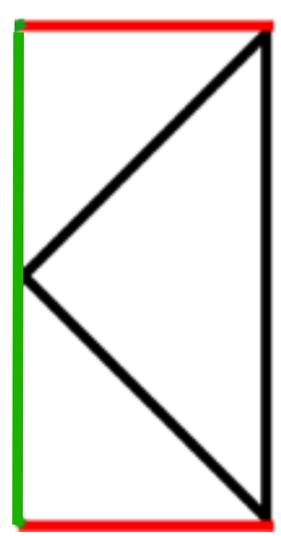
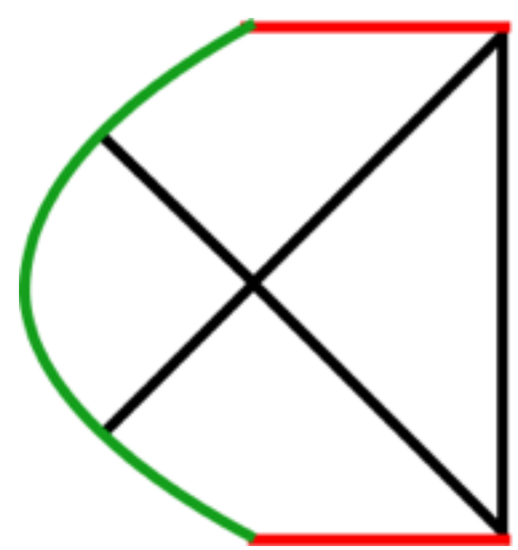


$| \uparrow\uparrow \ldots \uparrow \rangle$ + O(1) spin flips



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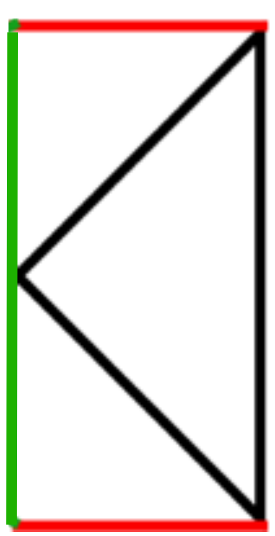

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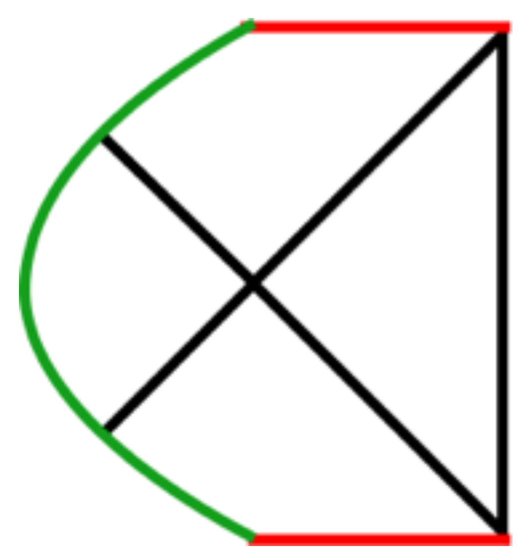

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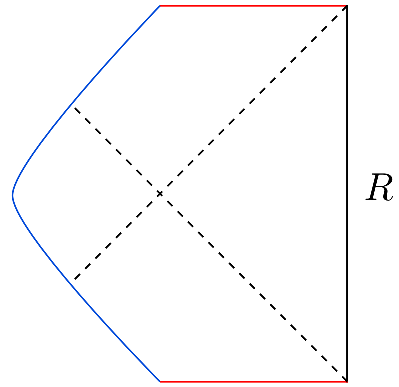
Different Microstates

- Atypical Microstates

$$|B_s^{\beta}\rangle_R = {}_L\langle B_s|\beta\rangle_{LR}$$



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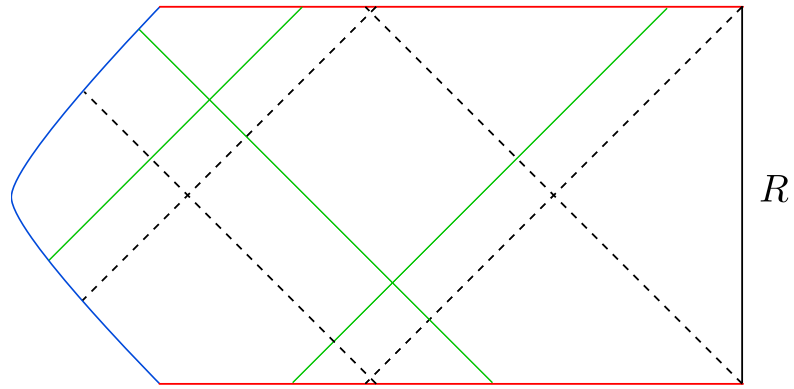

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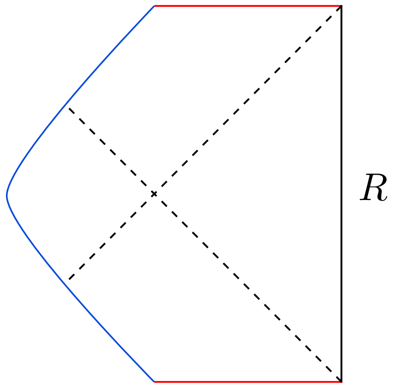

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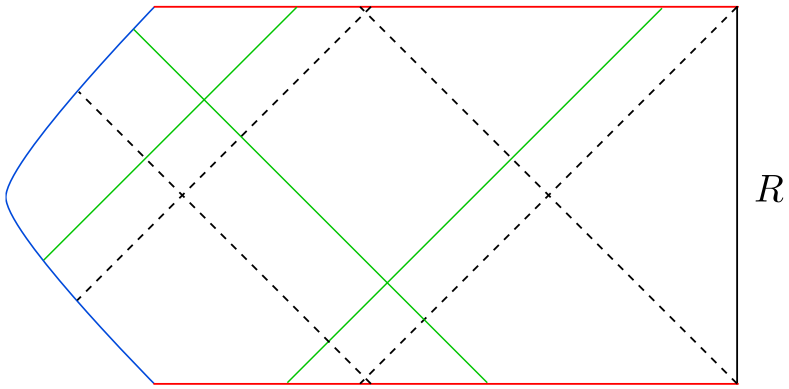

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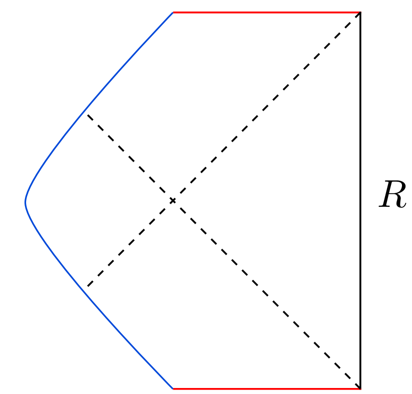

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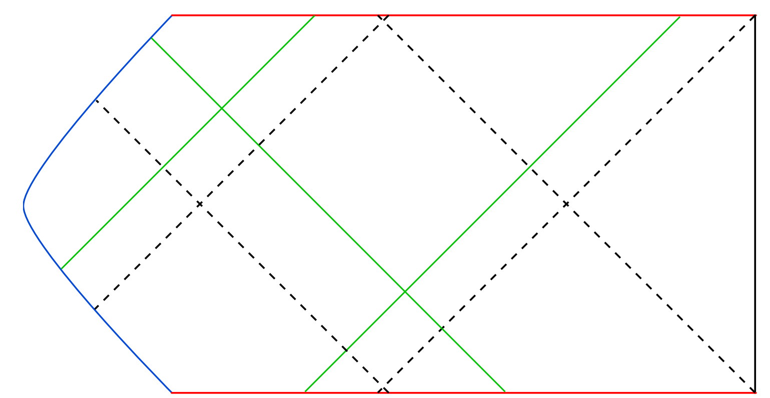

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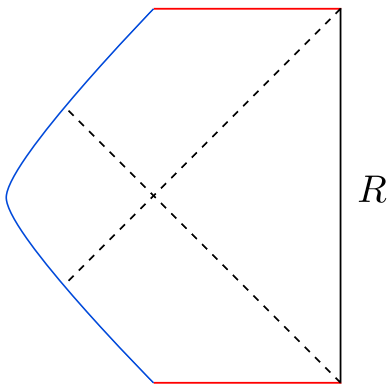
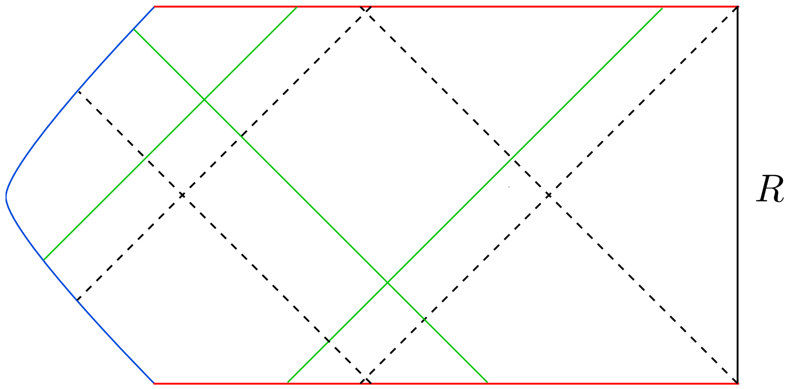
- Does this have consequences for interior reconstruction?

Necessity of State-Dependence

- Suppose the existence of a linear operator N_R^F that measures whether there is a shockwave behind the horizon.



$$ {}_R\langle B_s^\beta | N_R^F | B_s^\beta \rangle_R $$



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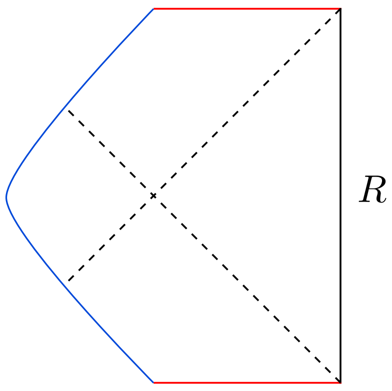

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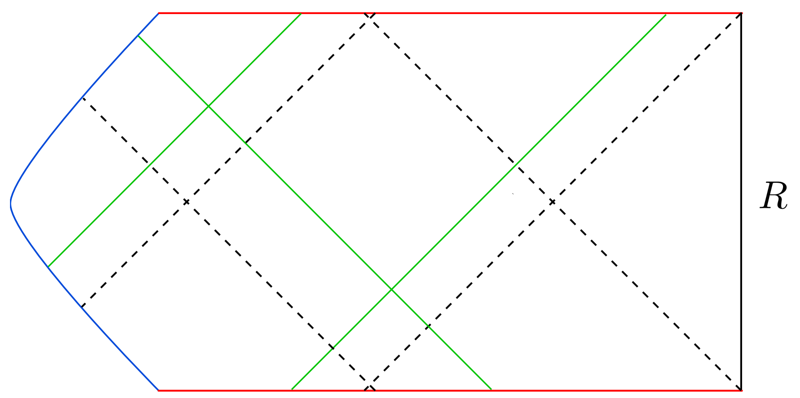

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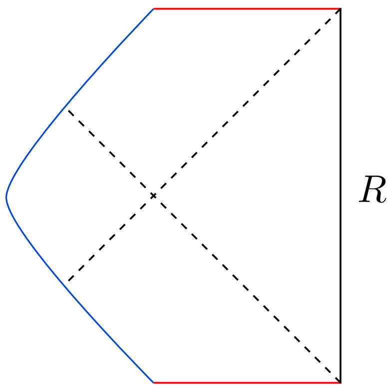

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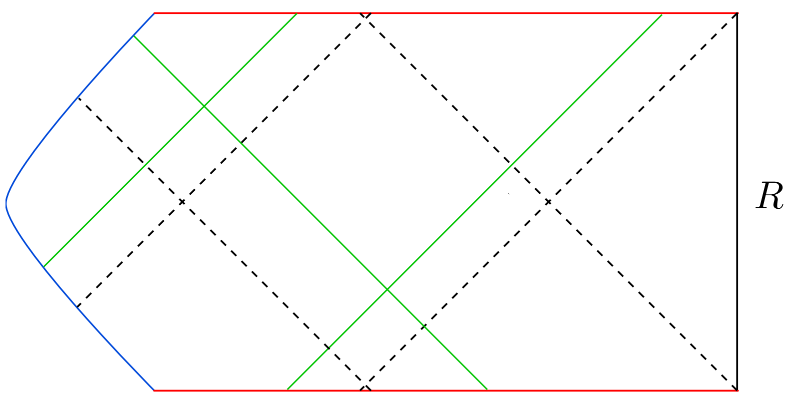

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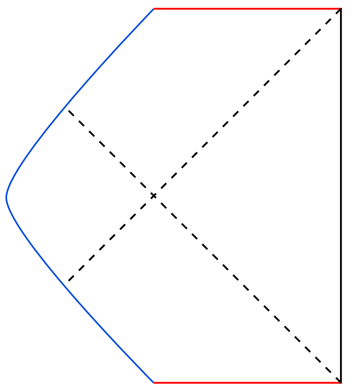

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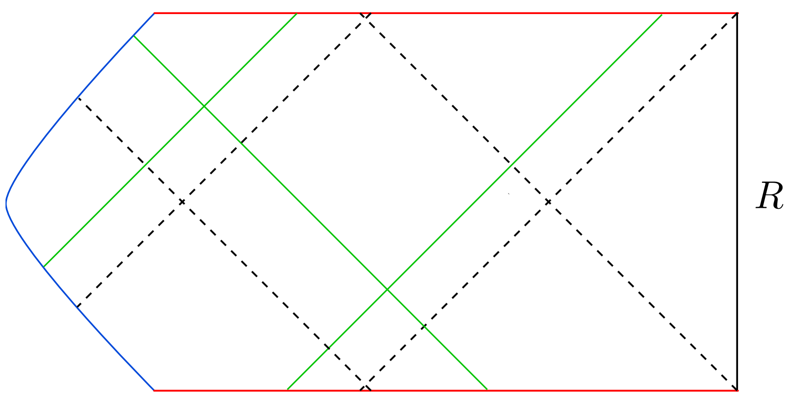

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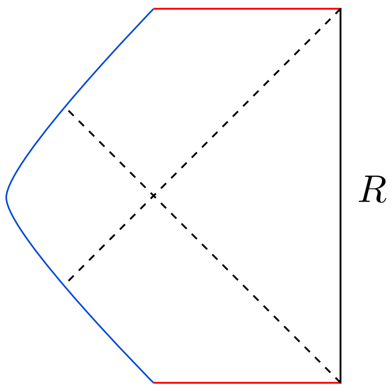

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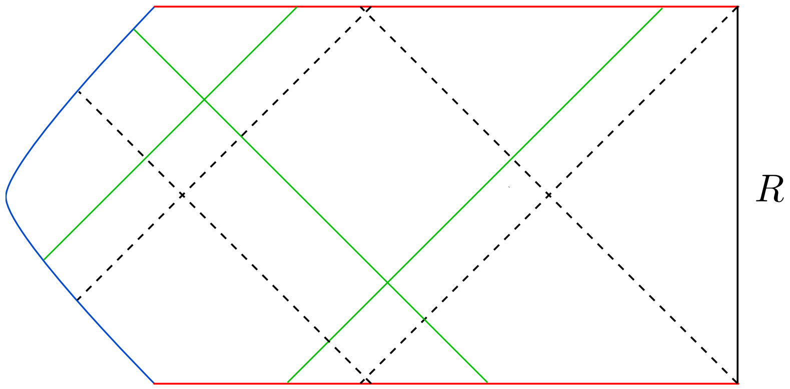

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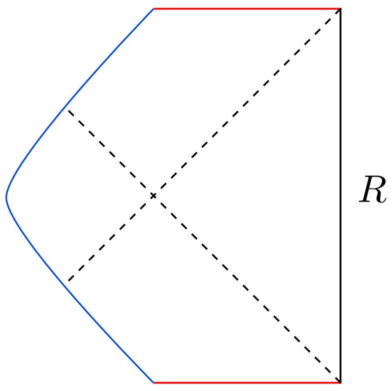

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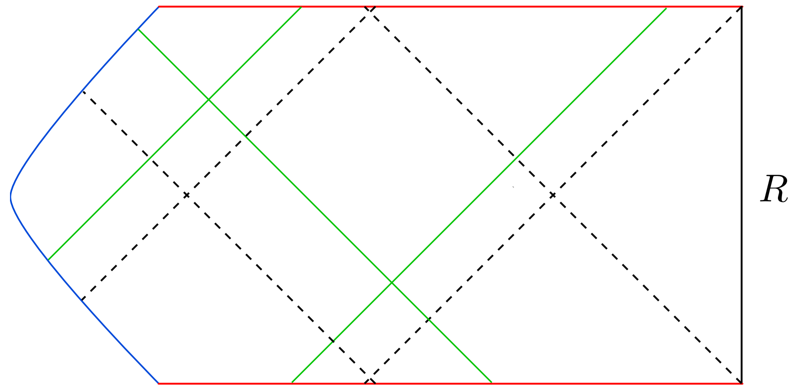

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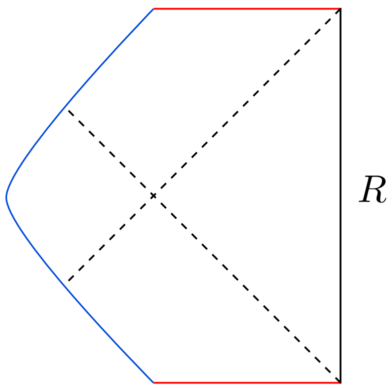

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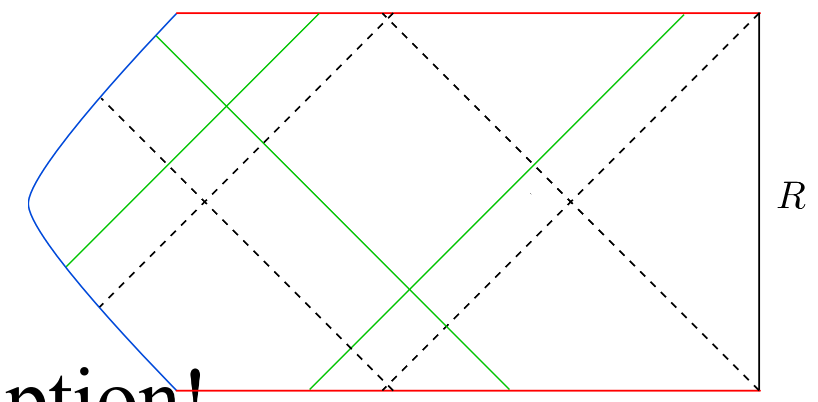

- Contradiction! Can't be the same by assumption!

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- The dictionary for the interior must be state dependent.
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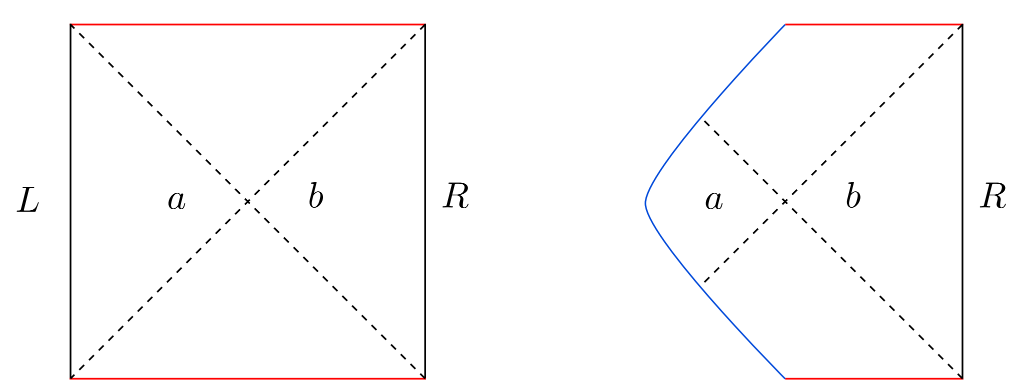
- Can we find such a dictionary?
- Yes! By assuming the AdS/CFT dictionary to be a QEC code, one can generate such a dictionary for the interior!
- Key: the dictionary is fluid, responding to the projection in a way that maps the interior operators to the remaining boundary in a state dependent way.



$|\beta\rangle_{LR}$ $\quad$ ${}_L\langle B_s^*|\beta\rangle_{LR}$

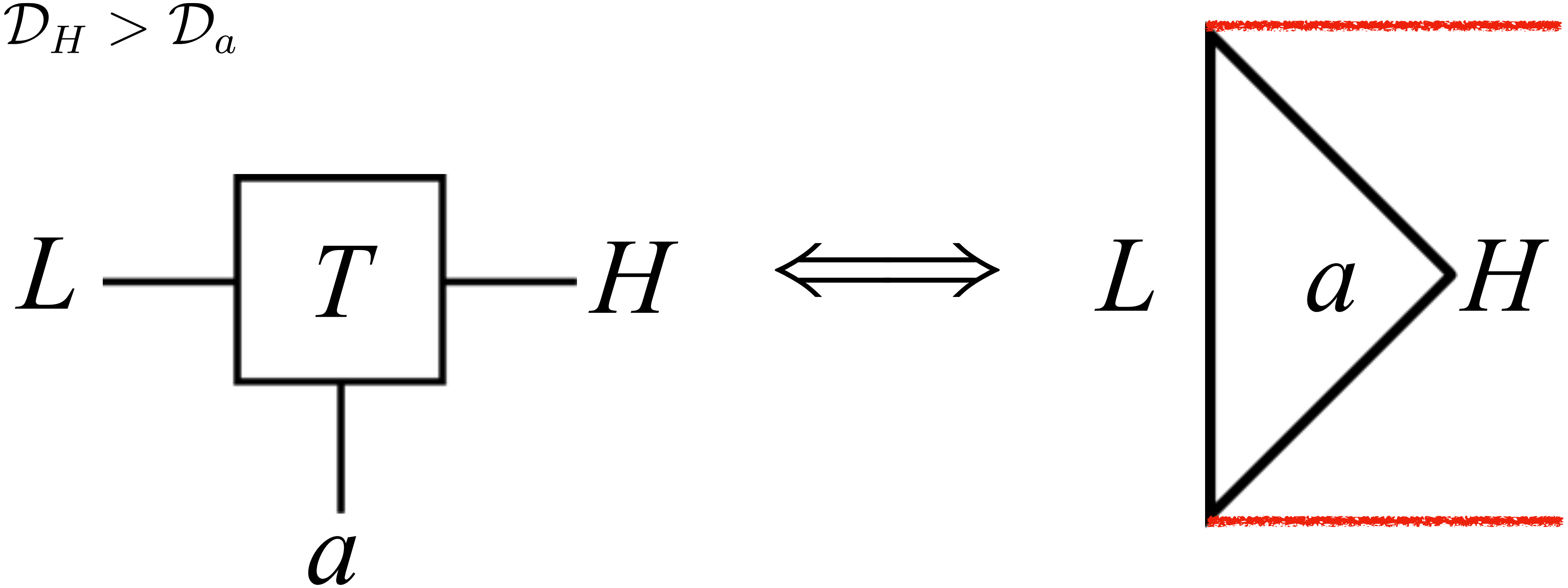
AdS/CFT as QEC

[AA, Dong, Harlow;…]

- I will describe the duality using a circuit diagram.

- Consider Isometry T from systems a & H into L.

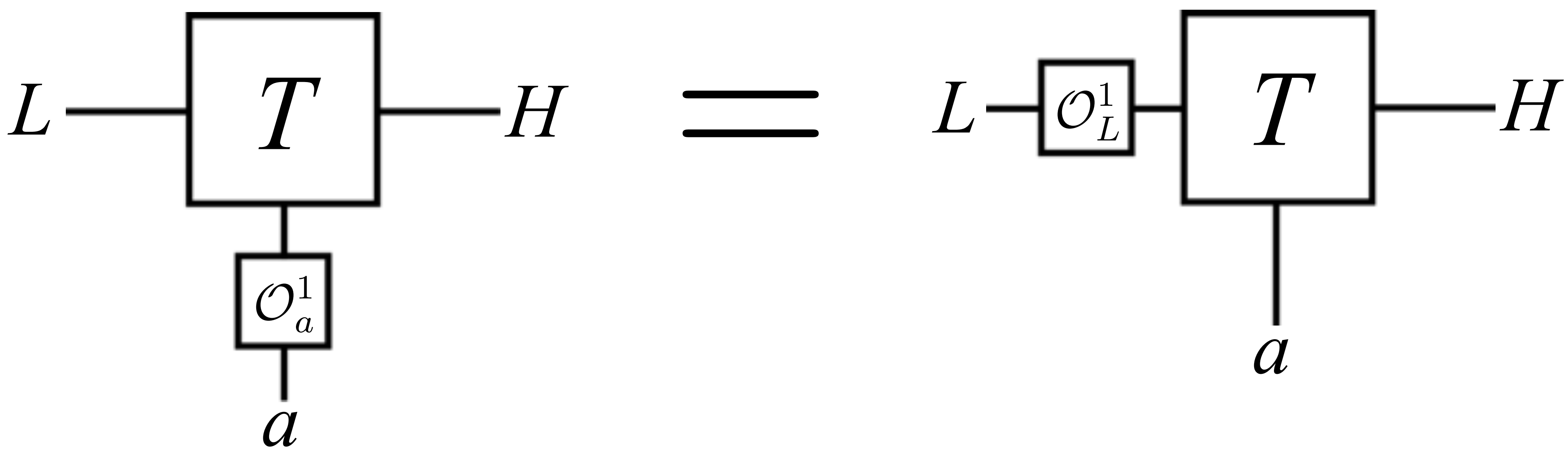
$$\mathcal{D}_L \gg \mathcal{D}_a \times \mathcal{D}_H$$
$$\mathcal{D}_H > \mathcal{D}_a$$



Operator Mapping

[HPPY, Hayden et al]

- Operators can be pushed through the tensors:



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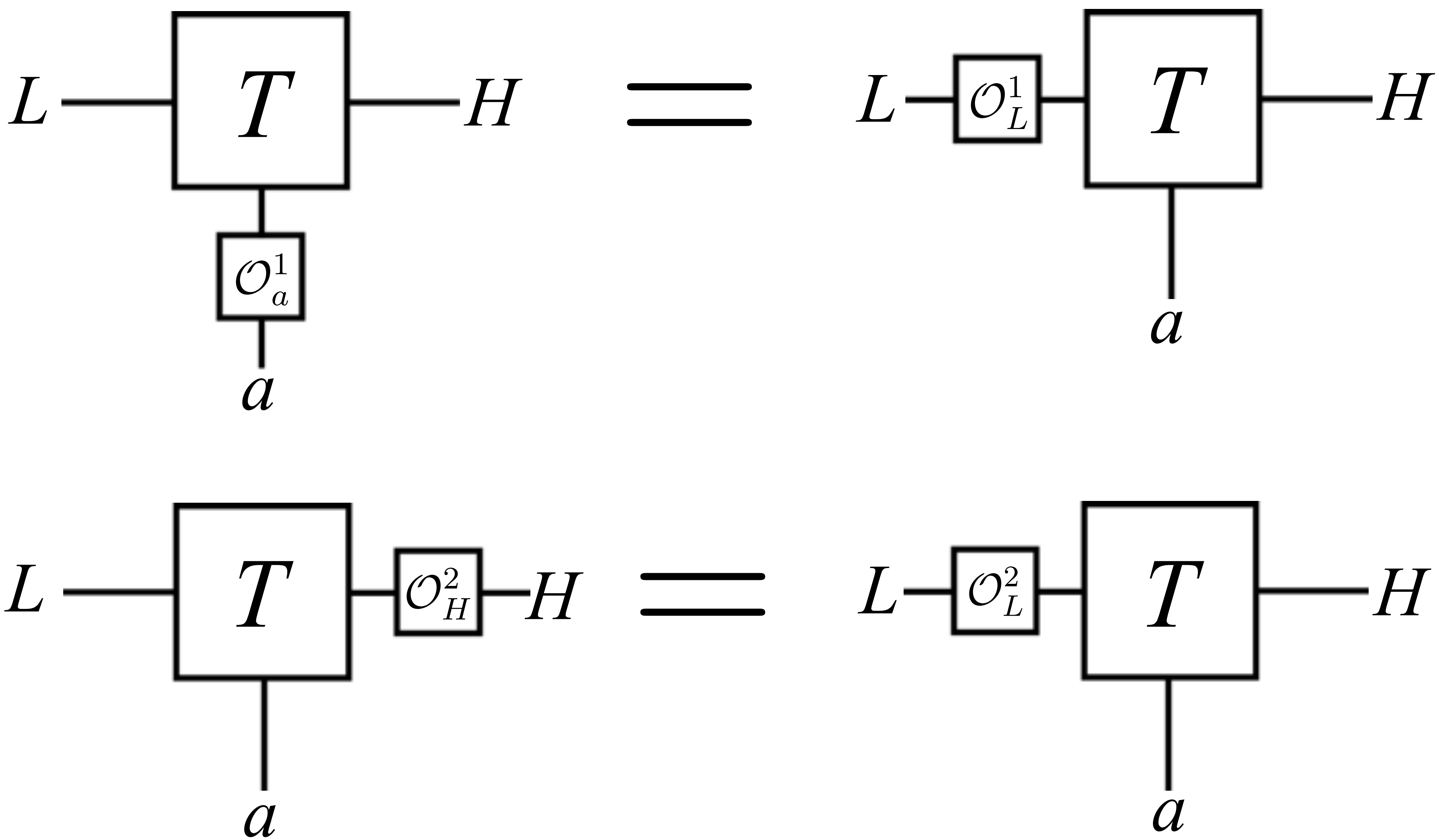
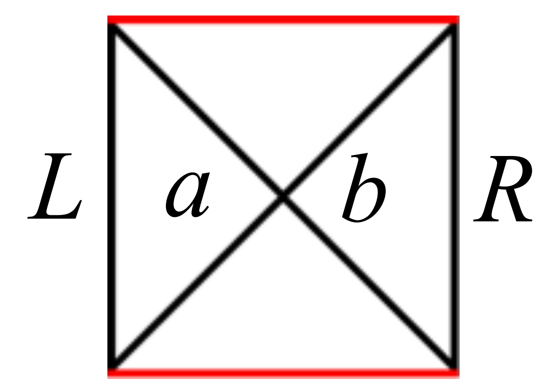
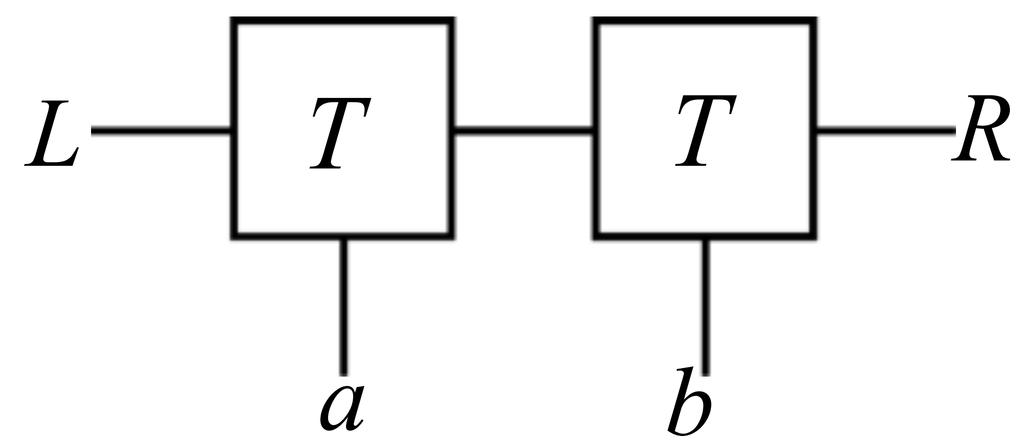


Eternal BH Code

- Eternal BH dictionary is given by:





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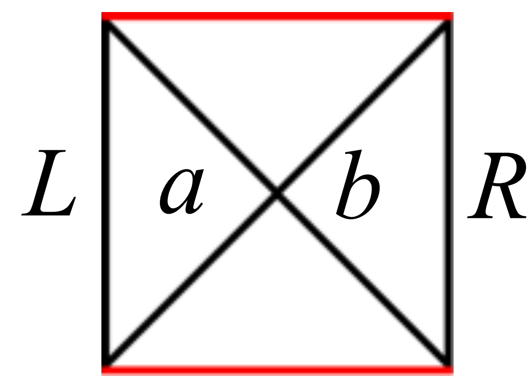

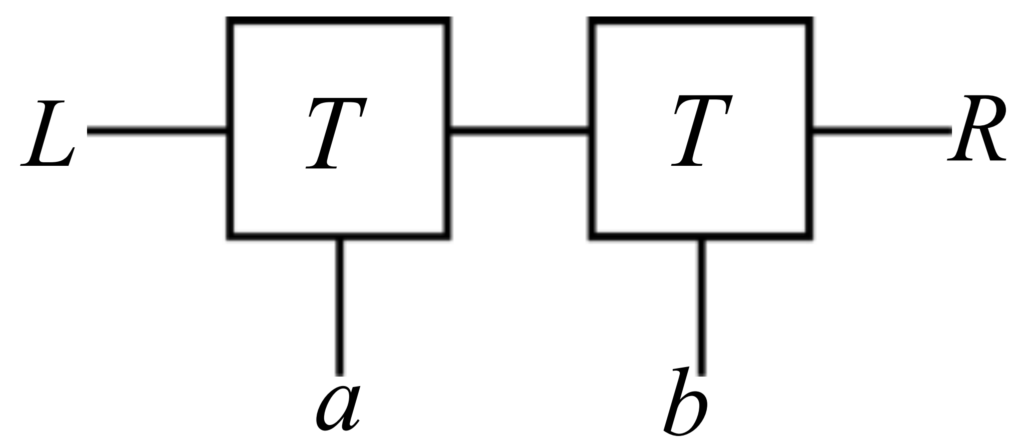

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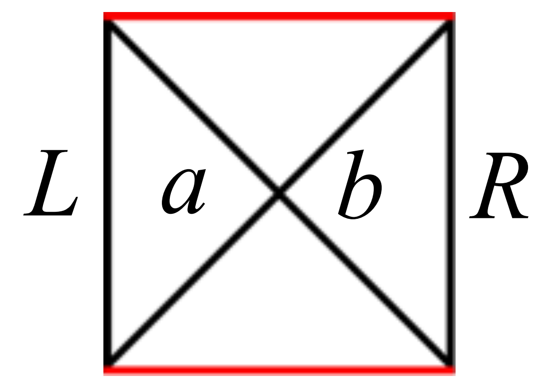
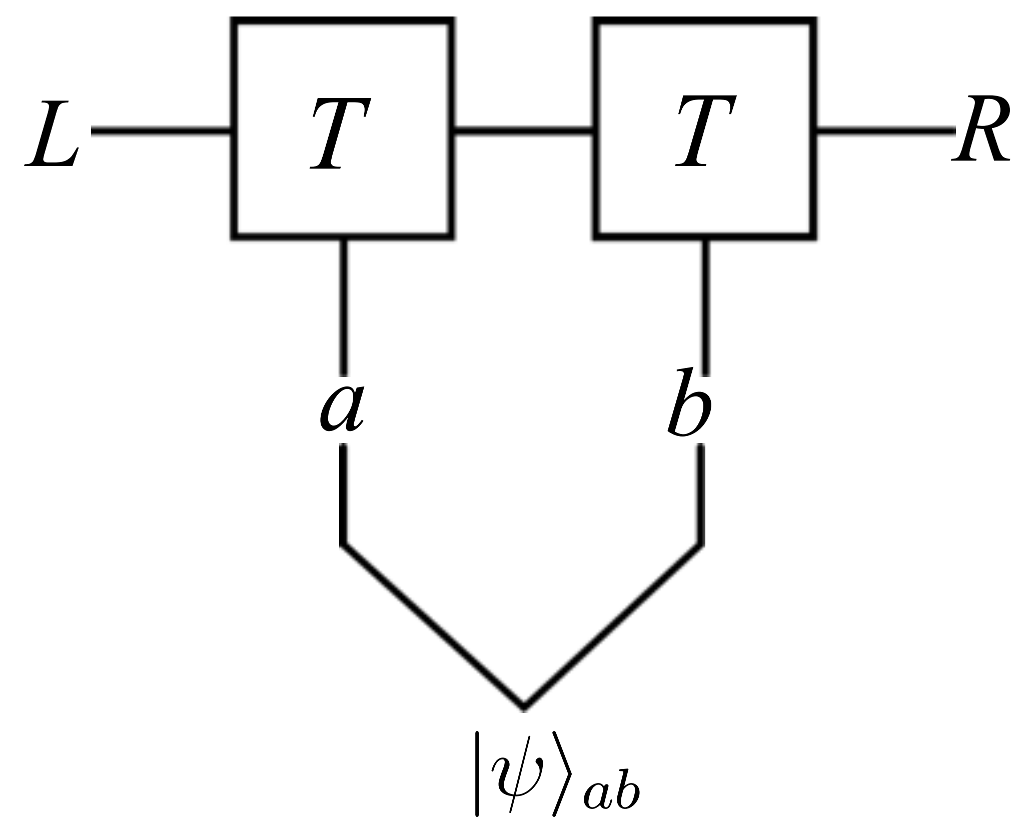
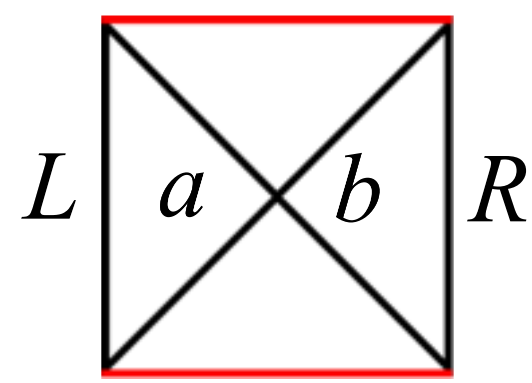
$$|\psi\rangle_{ab} \rightarrow |\widetilde{\psi}\rangle_{LR} \in \mathcal{H}_{code} \subset \mathcal{H}_L \otimes \mathcal{H}_R$$



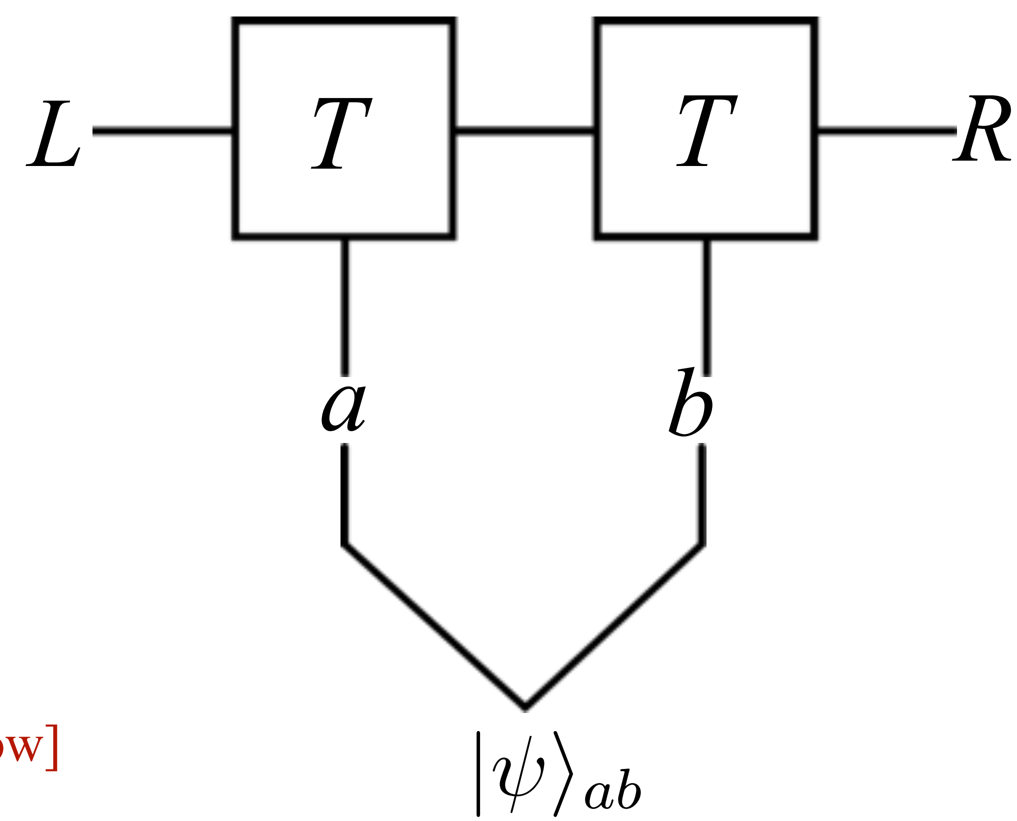


Eternal BH Code

- Eternal BH dictionary is given by:
- a and b represent bulk quantum fields.



$$|\psi\rangle_{ab} \to |\widetilde{\psi}\rangle_{LR} \in \mathcal{H}_{code} \subset \mathcal{H}_L \otimes \mathcal{H}_R$$

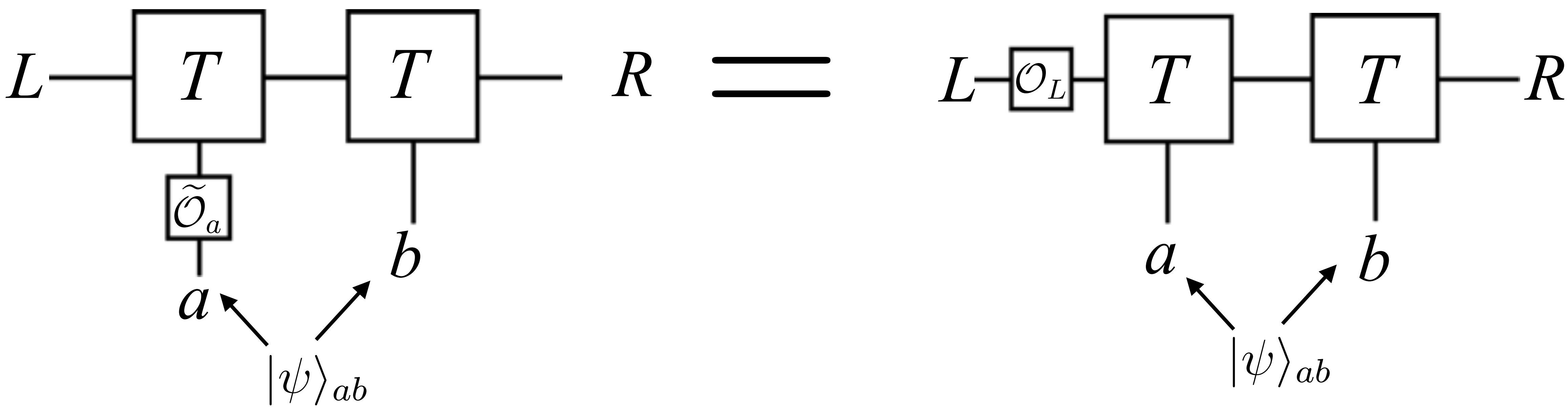


- Reproduces quantum corrected RT formula.

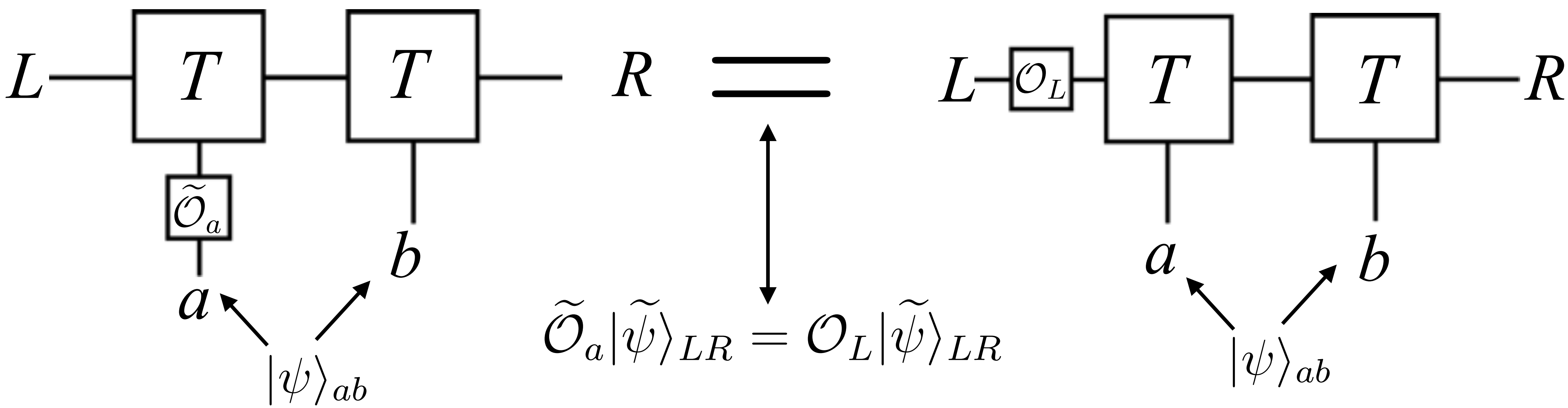
$$S(\rho_R^{\widetilde{\psi}}) = \ln \mathcal{D}_H + S(\rho_b^{\psi})$$

[Harlow]

Subregion-Subregion Duality



Subregion-Subregion Duality



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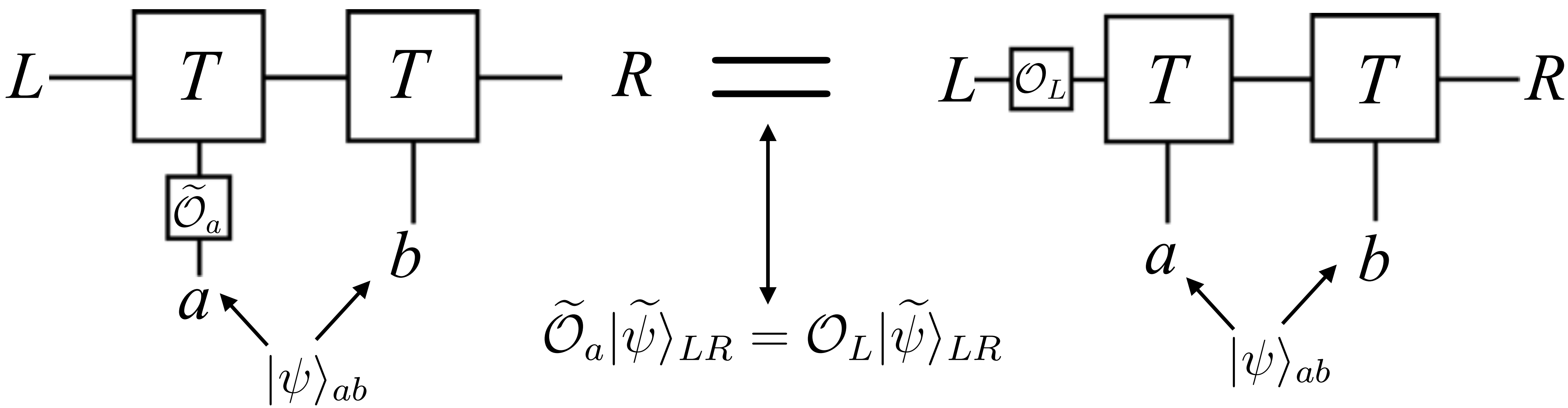
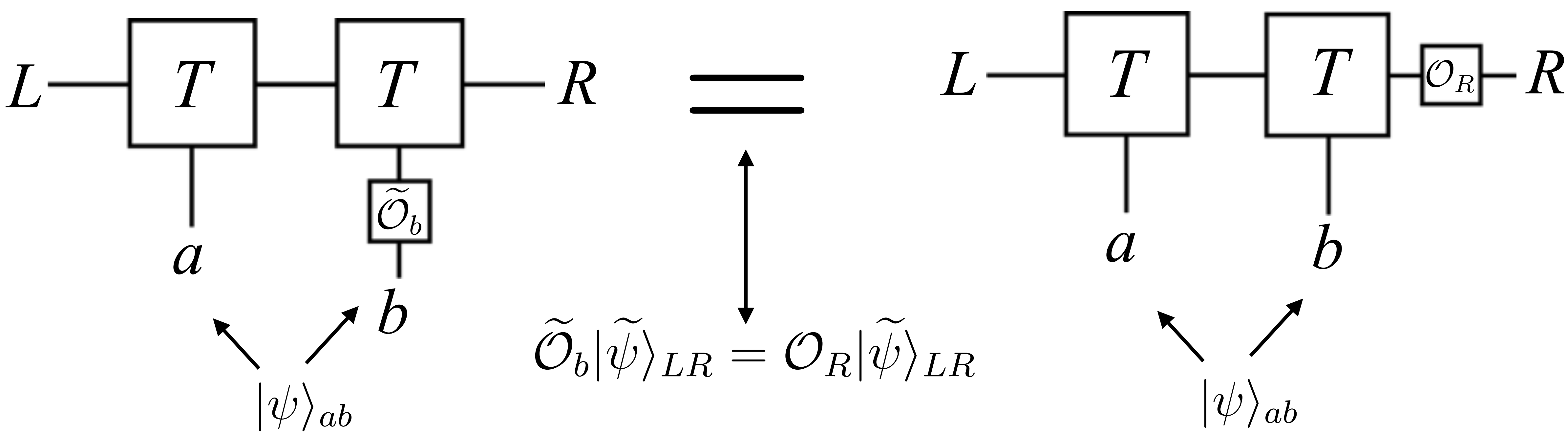
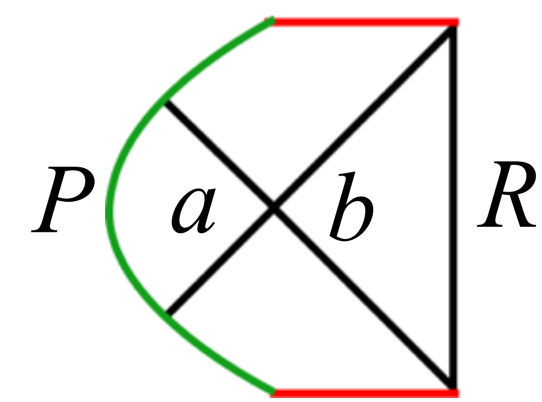
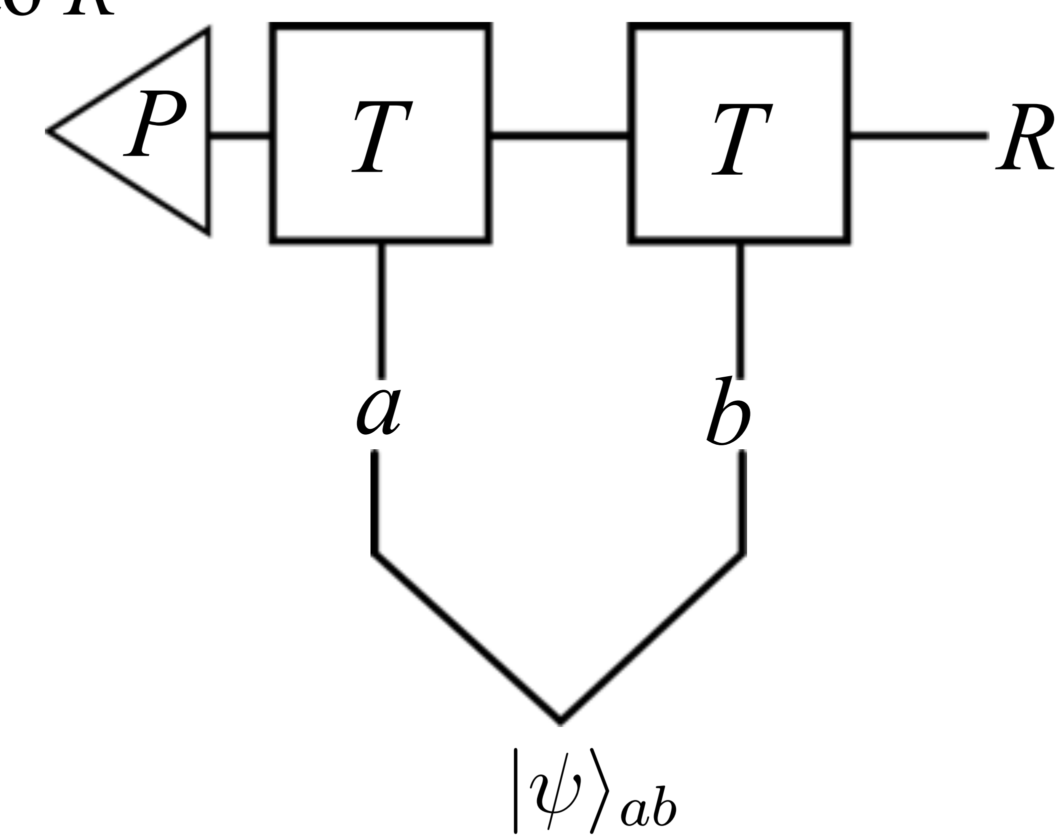




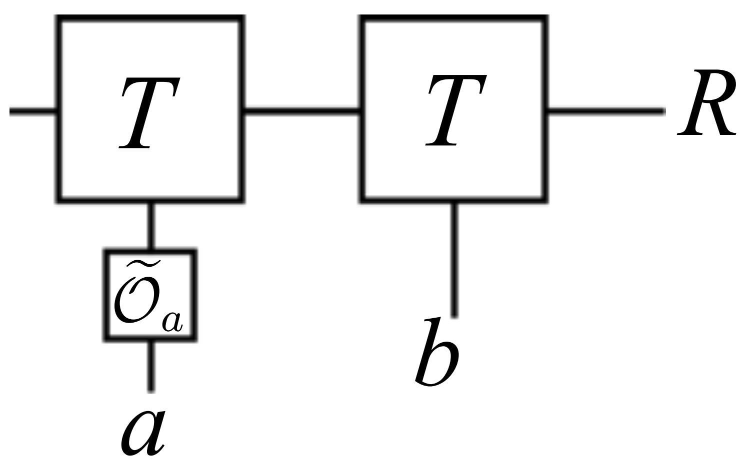
Projected BH Code

- Projected BH has 'same' geometry.
- Project on original tensor network.
- We want to understand the conditions on P such that operators acting on a map to R





Condition on the Projector



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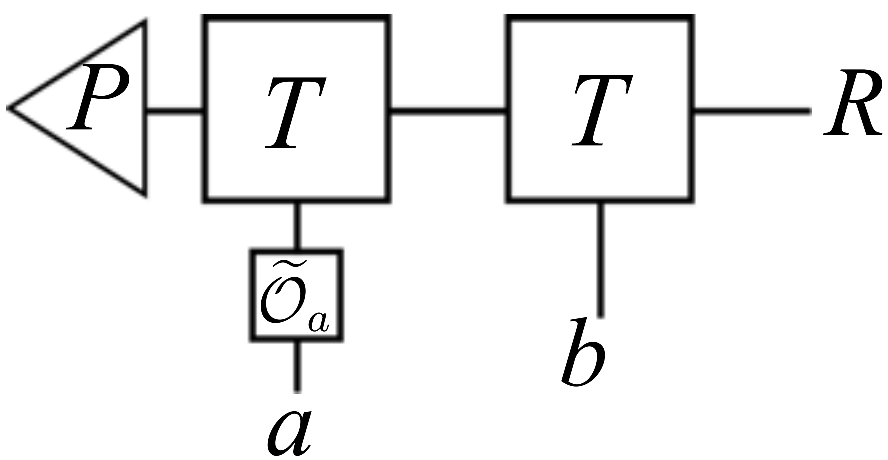
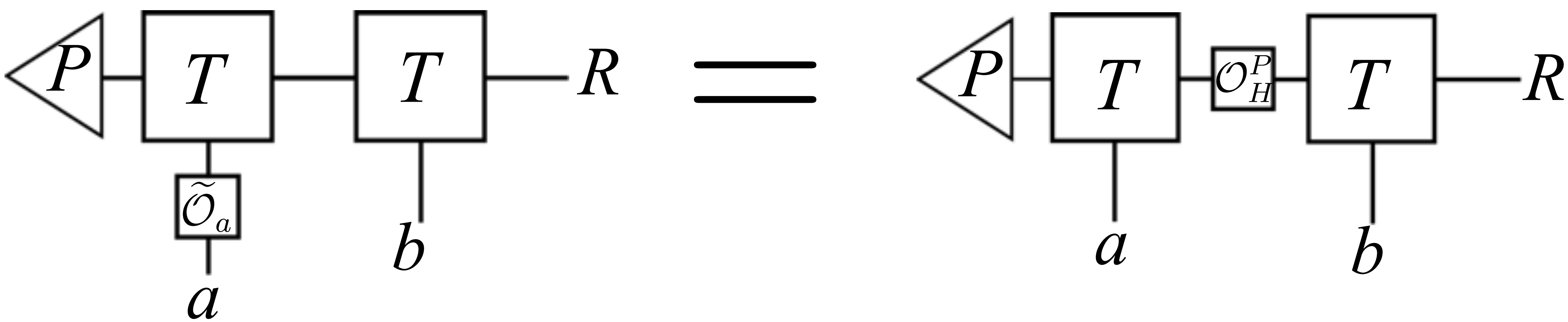


Condition on the Projector



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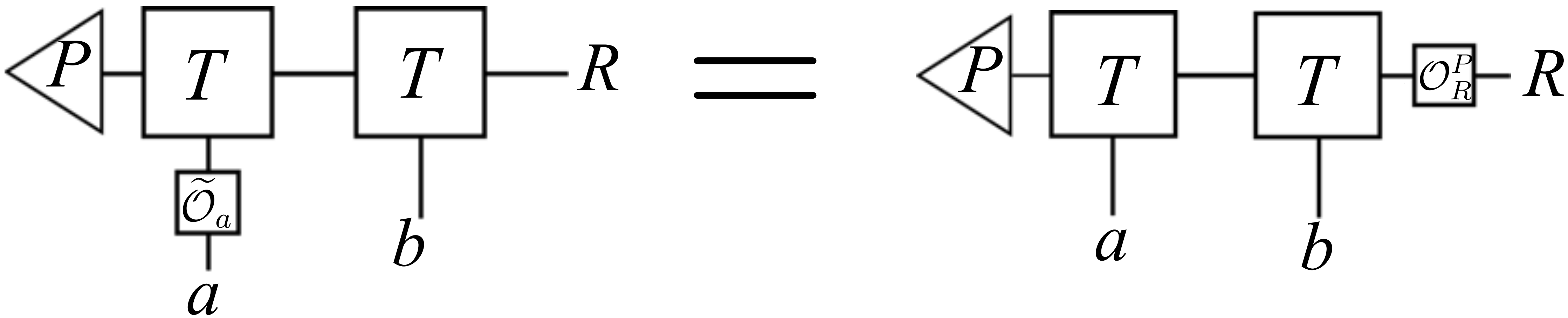

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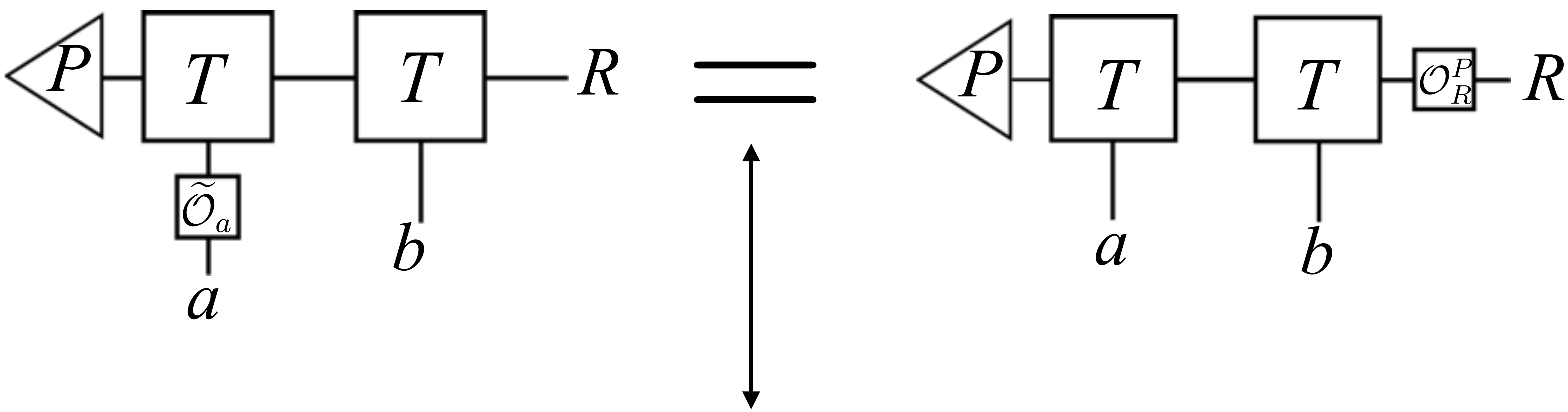
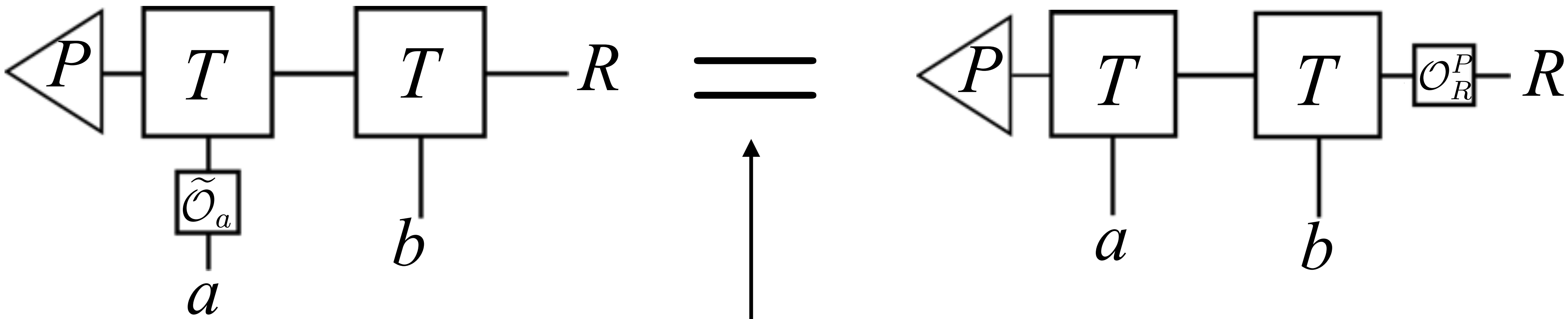
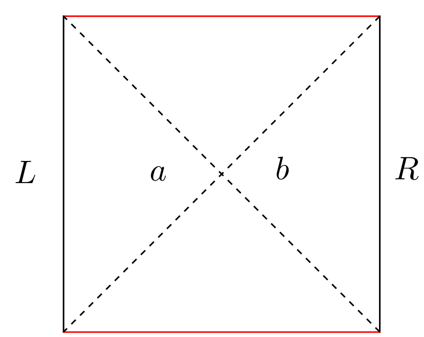


$$ {}_L\langle P|\widetilde{\mathcal{O}}_a|\widetilde{\psi}\rangle_{LR} = \mathcal{O}_R^P \; {}_L\langle P|\widetilde{\psi}\rangle_{LR} $$

Condition on the Projector





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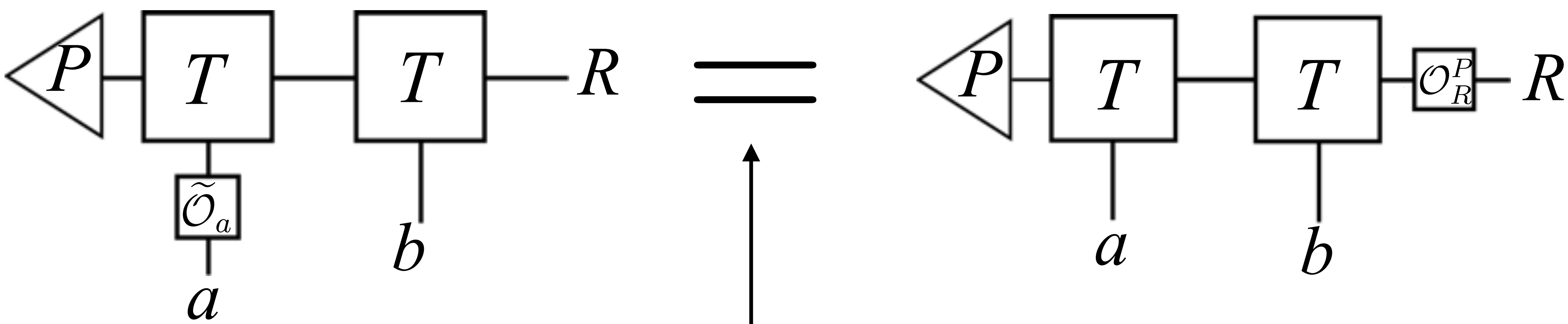
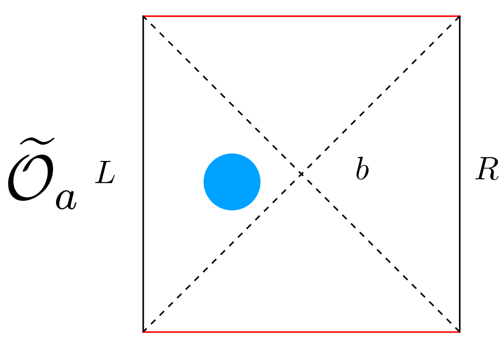
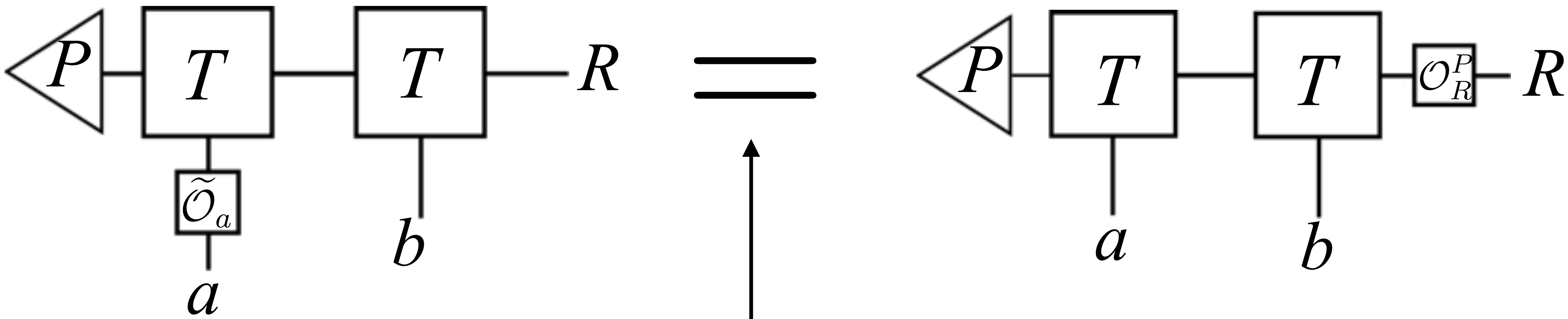




$${}_L\langle P|\widetilde{\mathcal{O}}_a|\widetilde{\psi}\rangle_{LR} = \mathcal{O}^P_R \; {}_L\langle P|\widetilde{\psi}\rangle_{LR}$$

Condition on the Projector



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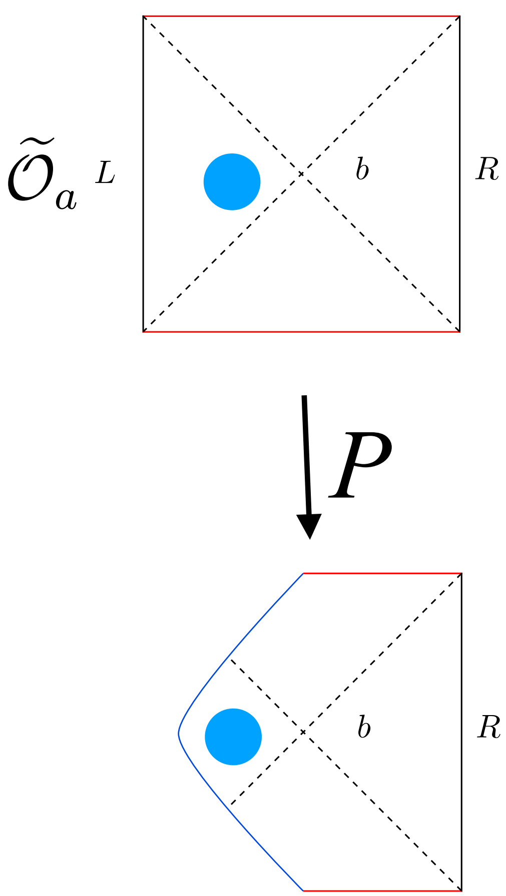

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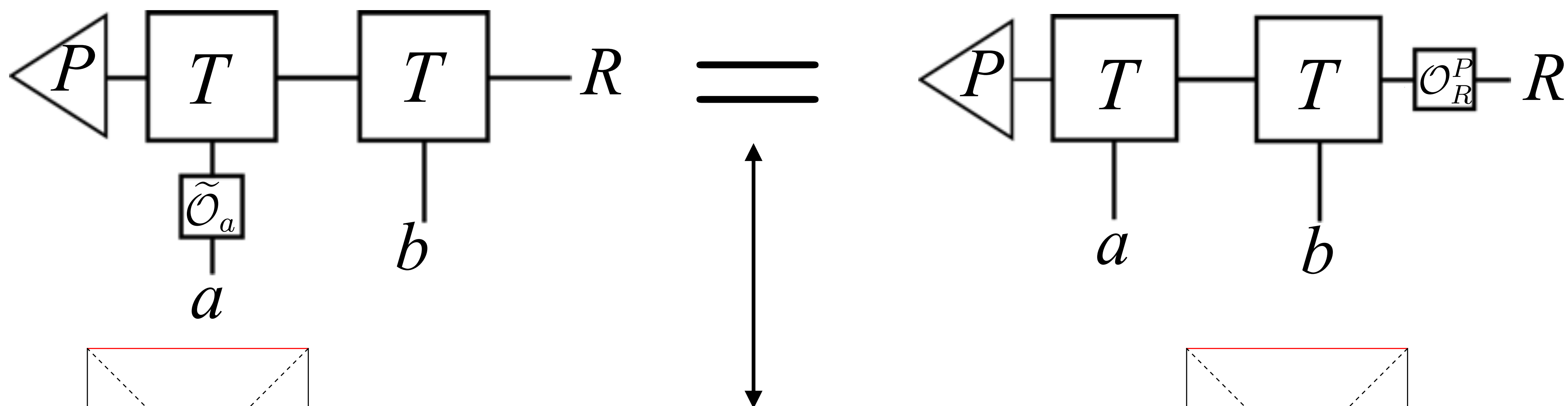

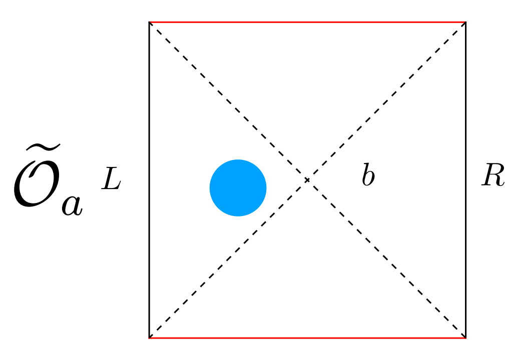

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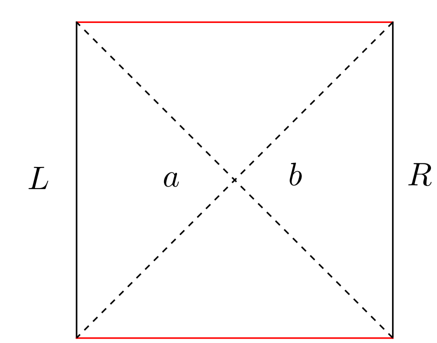
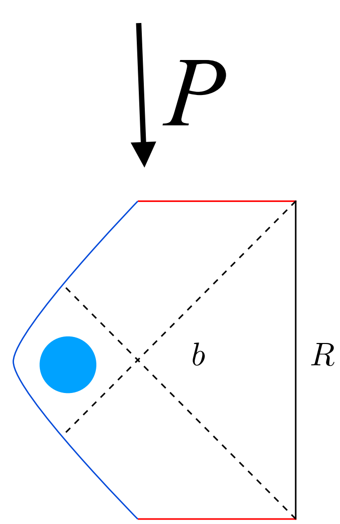
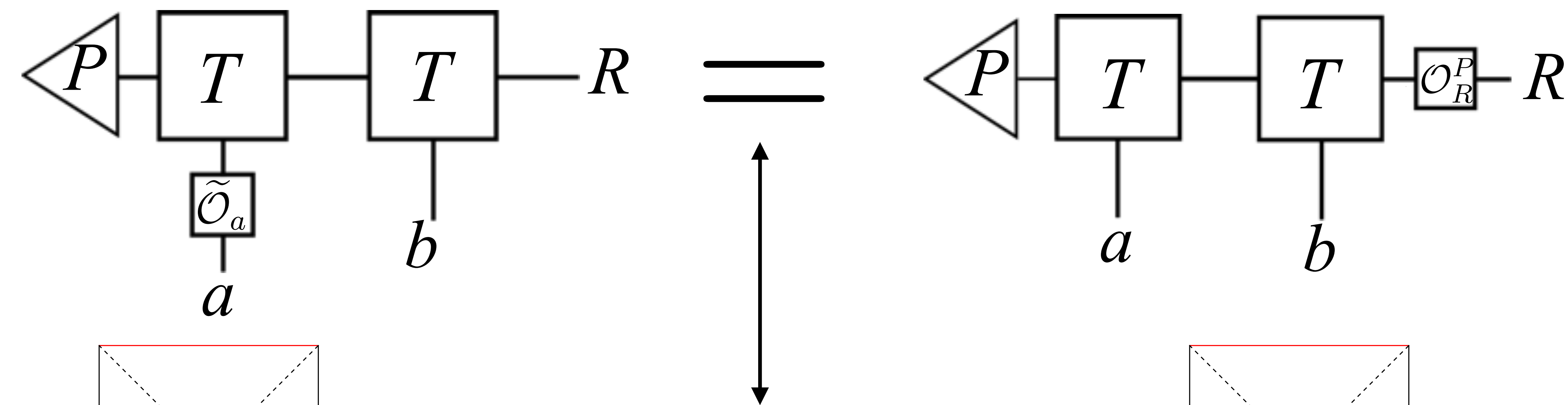




Condition on the Projector



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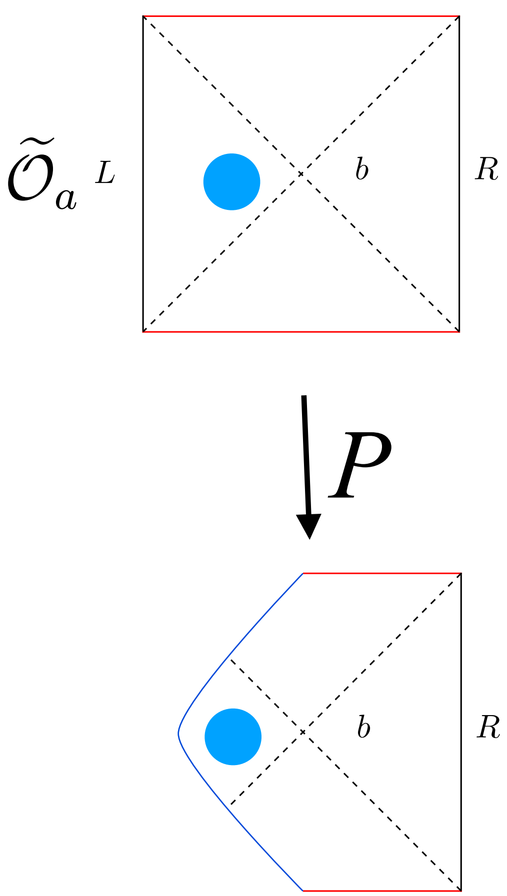

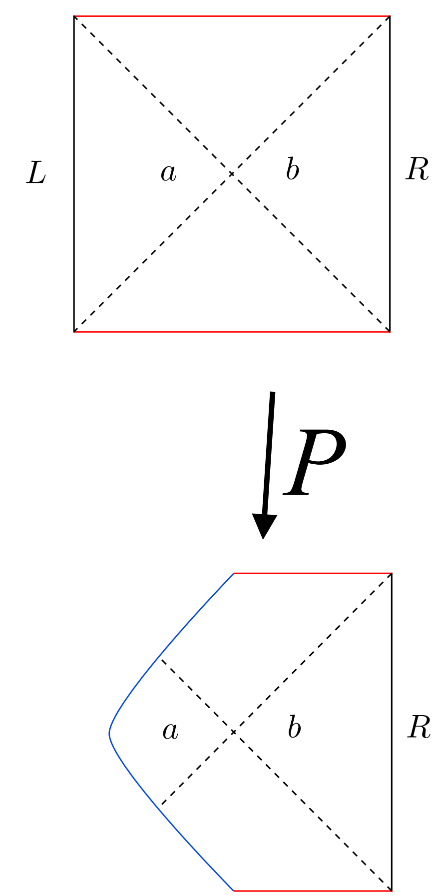

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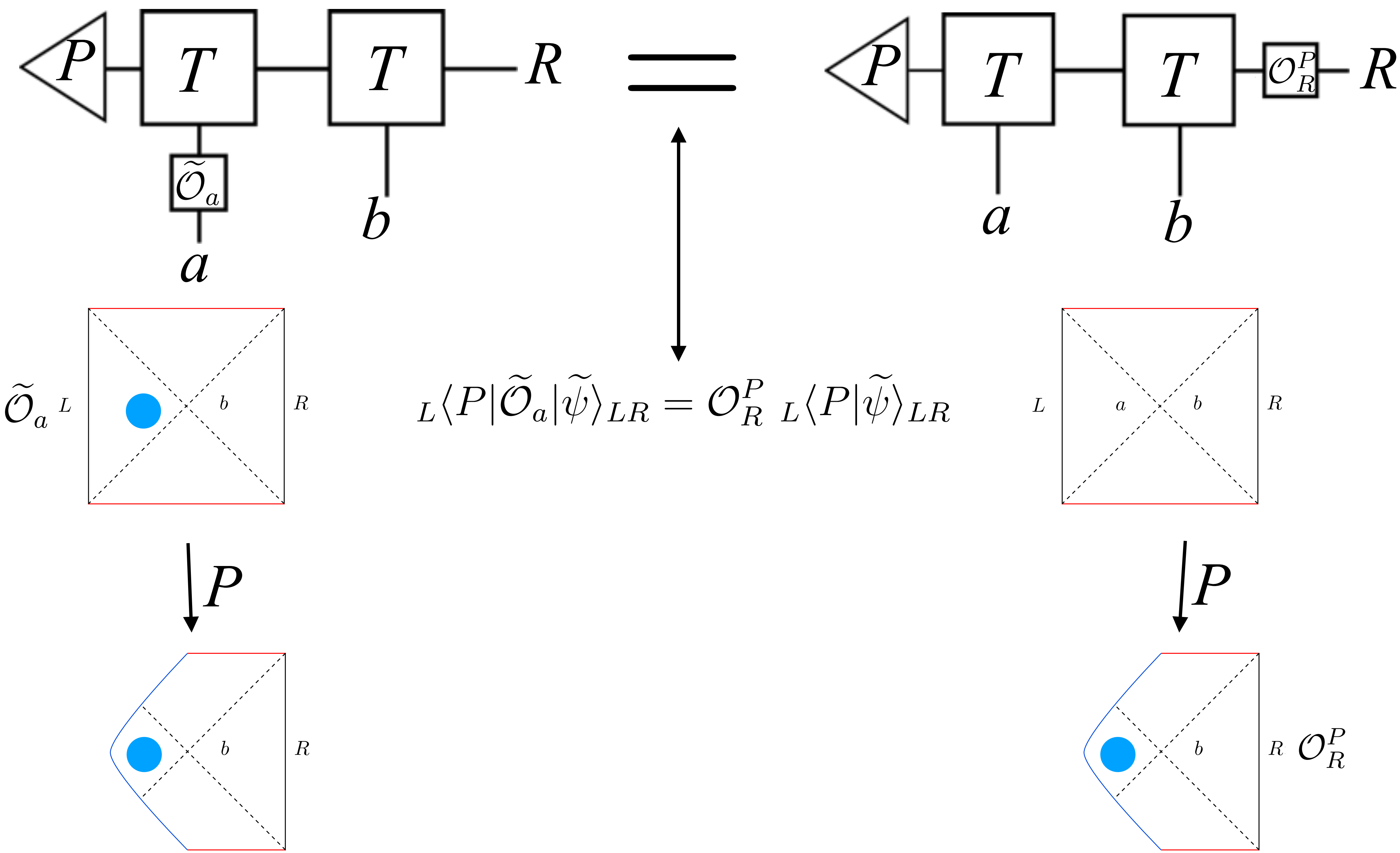

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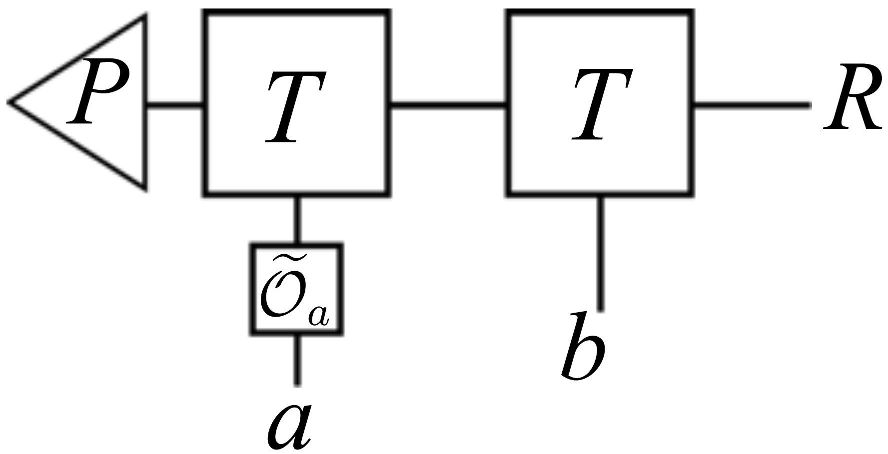

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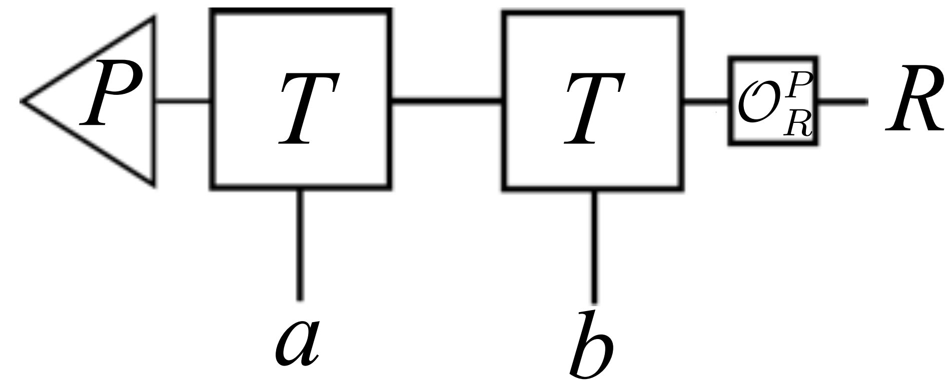
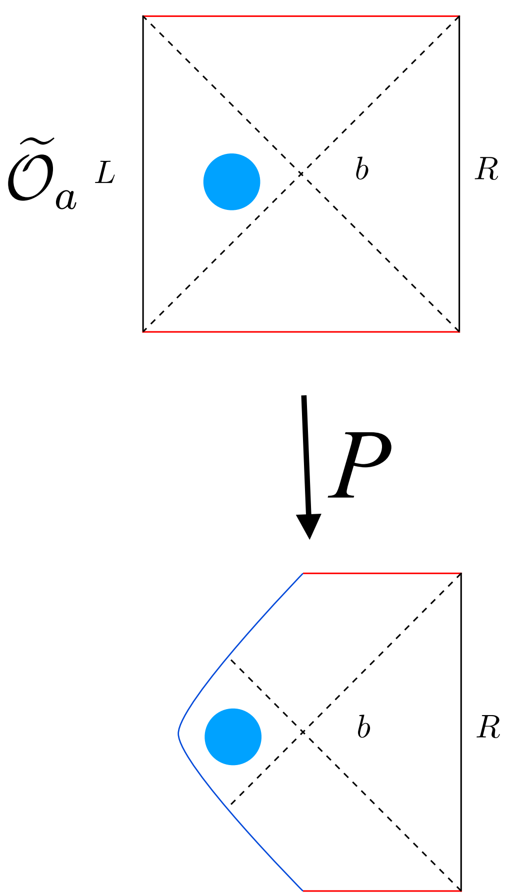


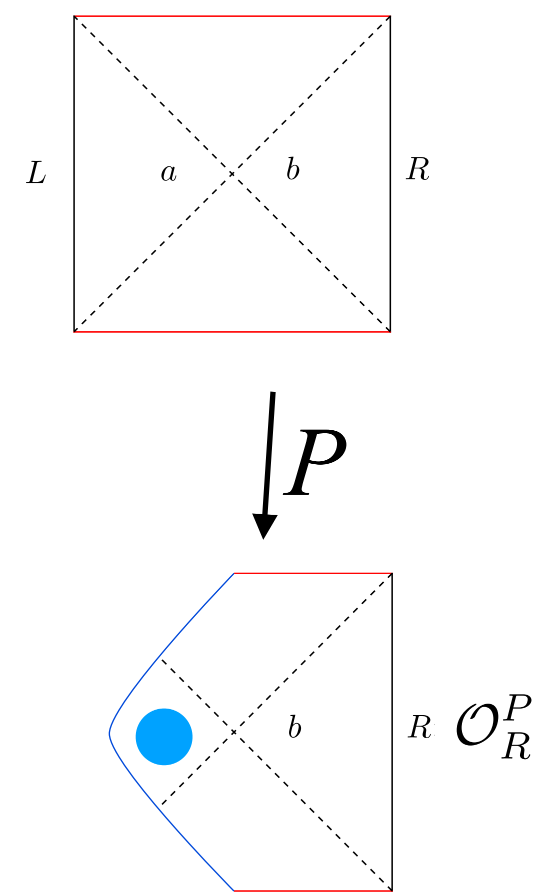


$$_L\langle P|\widetilde{\mathcal{O}}_a|\widetilde{\psi}\rangle_{LR} = \mathcal{O}_R^P \ {}_L\langle P|\widetilde{\psi}\rangle_{LR}$$

$$\Updownarrow$$

$$\mathcal{P}_{code}\left[P_L, \widetilde{\mathcal{O}}_a\right]\mathcal{P}_{code} = 0$$

$$P_L \equiv |P\rangle_L\langle P|$$



Properties of the Dictionary

$$ {}_L\langle P|\widetilde{\mathcal{O}}_a|\widetilde{\psi}\rangle_{LR} = \mathcal{O}_R^P \; {}_L\langle P|\widetilde{\psi}\rangle_{LR} $$

- Operators $\mathcal{O}_R^P$ are a dictionary for the interior.
- These are state dependent!

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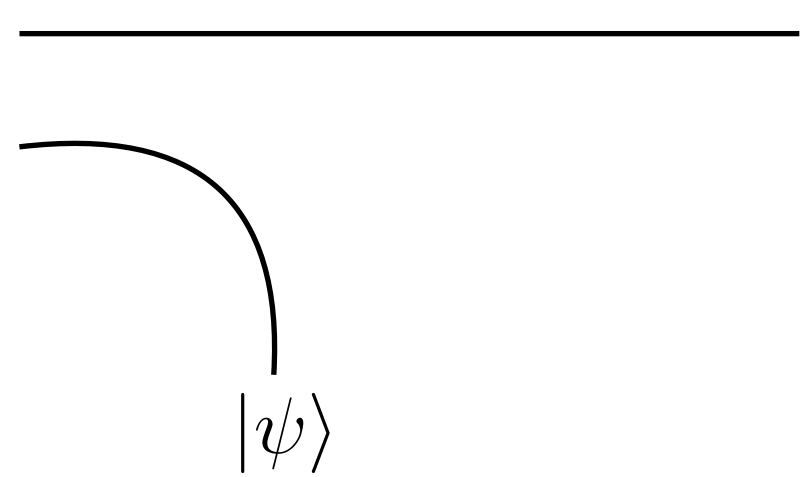
- This state dependence is like that of Quantum Teleportation:



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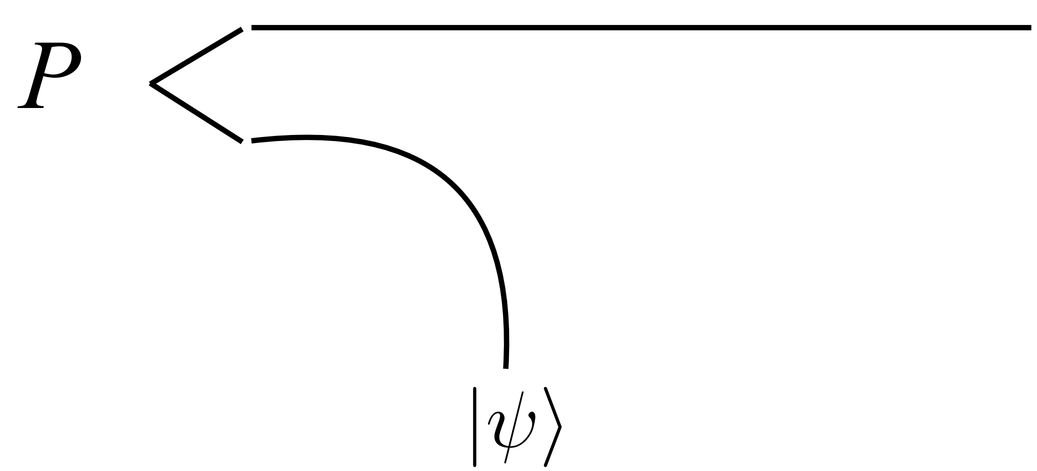

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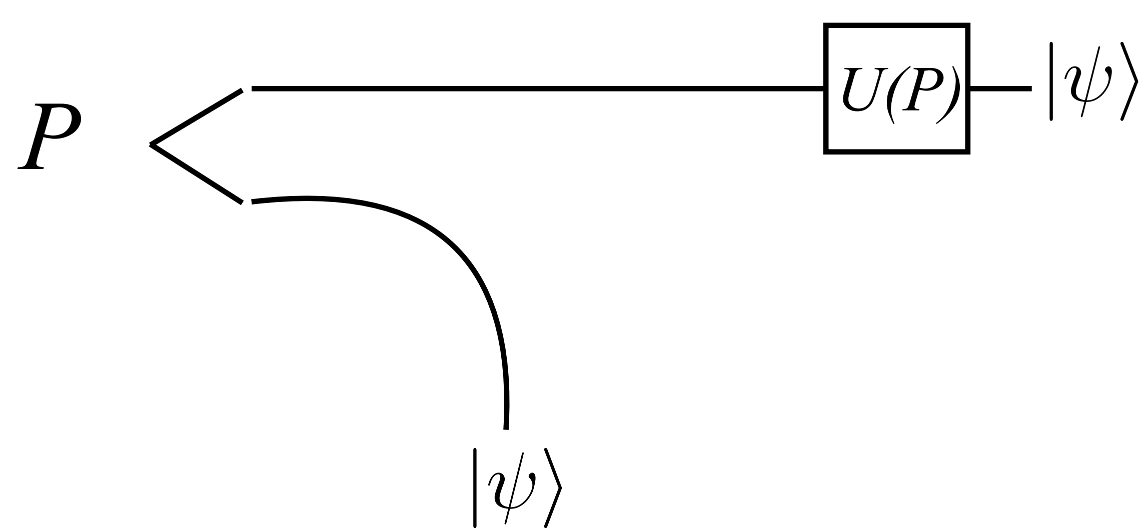
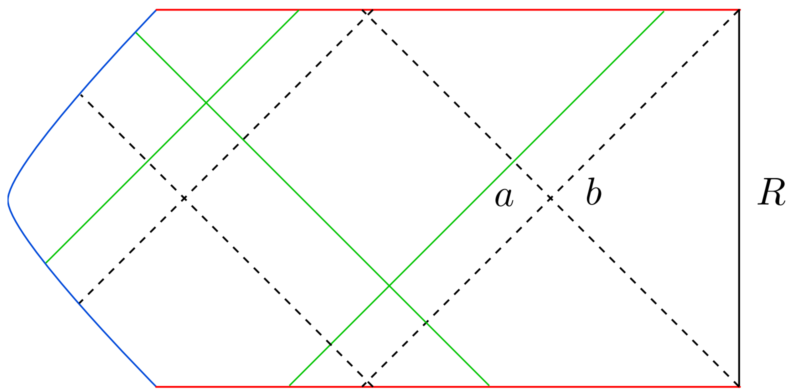


Relation to PR

- Problem with PR: Consider Typical Microstates
- All simple operators have thermalized
- Mirror construction would predict ‘nothing’ behind the horizon.



${}_L\langle B_s^* | W_L | \beta \rangle_{LR}$

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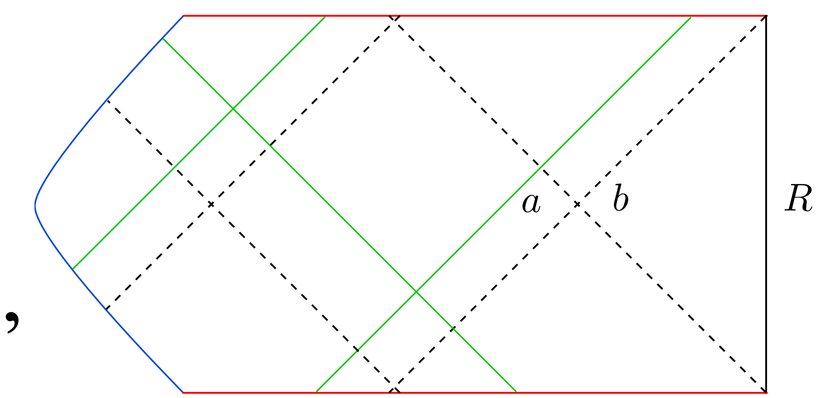

$_L\langle B_s^*|W_L|\beta\rangle_{LR}$

- The QEC construction is not a statement about typical states, but states constructed in a special way.

- It IS sensitive to what happens behind the horizon.

Thank You!

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