Type I von Neumann algebras from gravitational path integrals: Ryu–Takayanagi as entropy without holography

Based on: arXiv:2310.02189 with **Xi Dong**, **Donald Marolf** and **Zhencheng Wang**

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LOOPs'24 Fort Lauderdale FLORIDA

Quantum Gravity Across Different Approaches

General assumptions ⟶ What follows?

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Which assumptions? ← Results

Which approaches satisfy them? (in a specific approach)

Loop Quantum Gravity

String theory

Causal Sets

Group Field Theory

…

AdS/CFT

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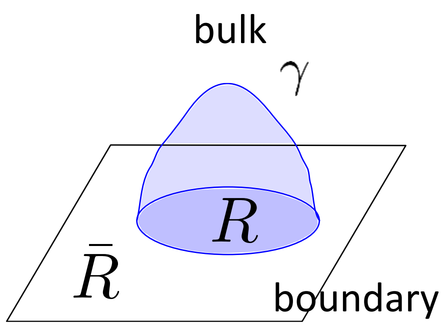
Entropy in quantum gravity:

Ryu–Takayanagi formula

$$S(R) = \frac{A(\gamma)}{4G}$$



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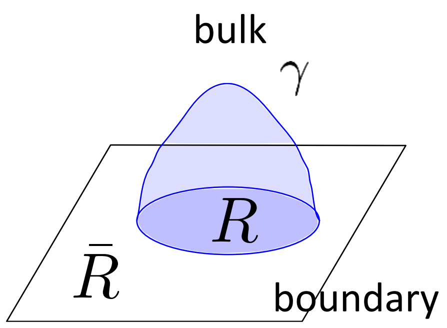

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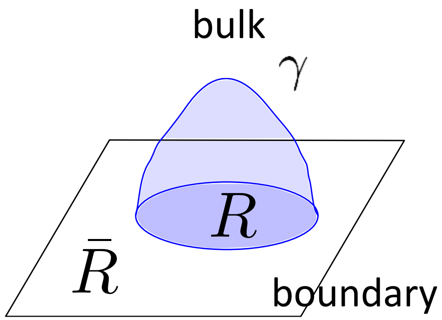


Proposed for holographic entanglement entropy in AdS/CFT

Can we understand it without holography?

YES!

RT from the Gravitational Path Integral

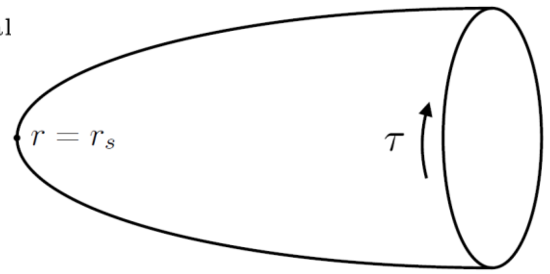
Ryu–Takayanagi was originally proposed to compute holographic entanglement entropy in AdS spacetime, but the present understanding of the formula is much more general!

Gibbons-Hawking (1977)

$$Z(\beta) = \text{Path integral on the Euclidean black hole} \sim e^{I_{\text{classical}}}$$

$$S = (1 - \beta\partial\beta)\log Z(\beta) = \frac{A_{\text{horizon}}}{4G}$$

non-trivial part of variation near $r = r_s$

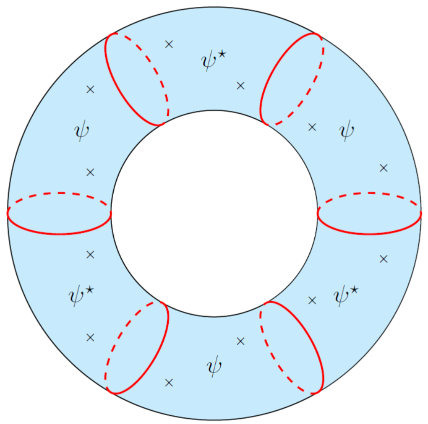


Lewkowycz-Maldacena (2013)

- Path integral prescription for the construction of the state
- Replica trick:
  - consider n copies of the system and compute $\mathrm{Tr}[\rho^n]$
  - analytically continue in n and compute the entropy as

$$S = (1 - n\partial n)\log \mathrm{Tr}[\rho^n]\Big|_{n=1} = \frac{A(\gamma)}{4G}$$

non-trivial part of variation near γ



RT and the information paradox

- RT is the first version of a more general formula for the von Neumann entropy

$$S_{\rm gen} = \frac{A(X)}{4G} + S_{\text{semi-cl}}(\Sigma_X)$$

[Faulkner, Lewkowycz, Maldacena, Engelhardt, Wall…]

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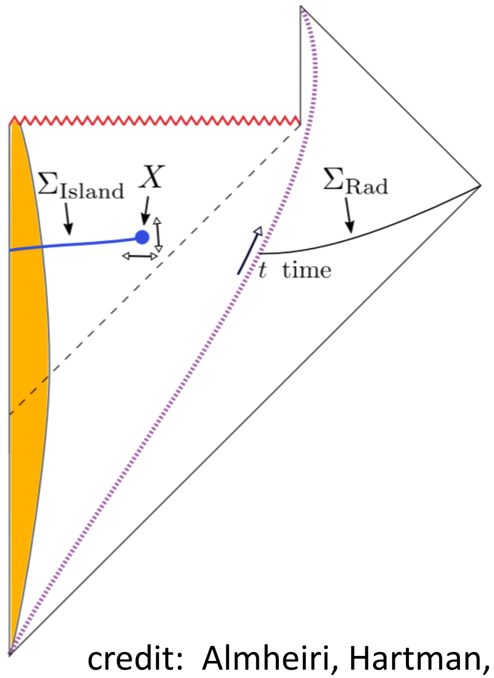
- This formula, applied to the black hole information problem, gives an entropy which follows the Page curve.



[Penington, Almheiri, Engelhardt, Marolf, Maxfield, Maldacena, Hartman…]

credit: Almheiri, Hartman, Maldacena, Shaghoulian, Tajdini 2020

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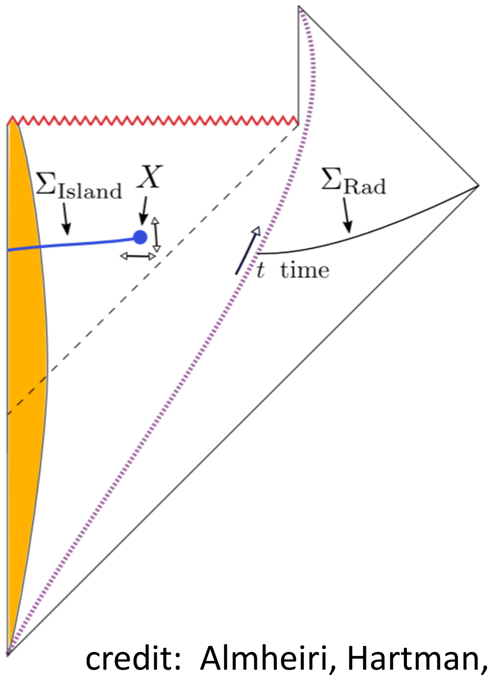
NOT TODAY!



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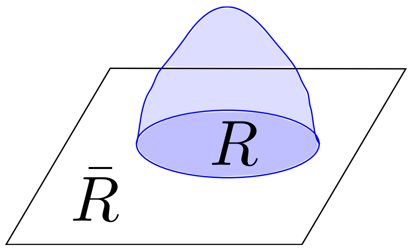
Where to start?

General assumptions ❓ ⟶ **Ryu–Takayanagi formula** without holography?



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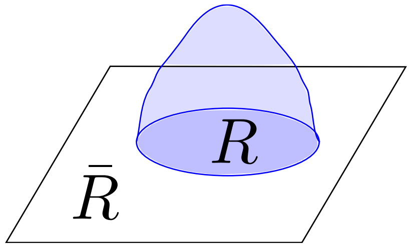
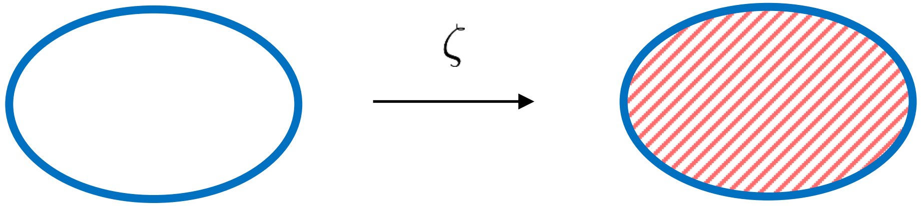


- A UV-complete theory of quantum gravity should contain a map



boundary conditions

M

number

$\zeta(M)$

“transition amplitude”

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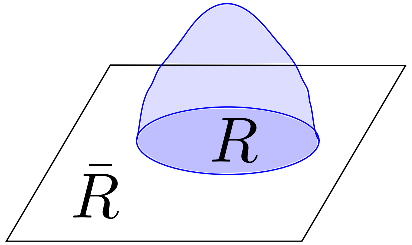

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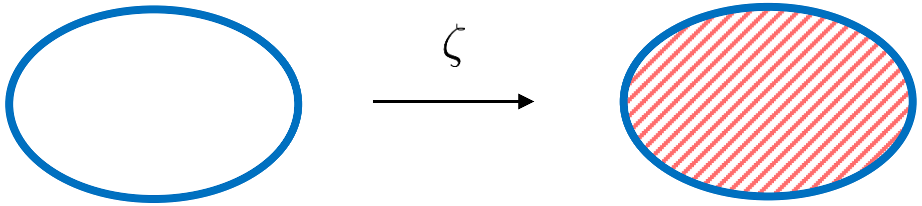


boundary conditions

M

number

$\zeta(M)$

"transition amplitude"

- We might call this map a (Euclidean) gravitational path integral
- It might look like

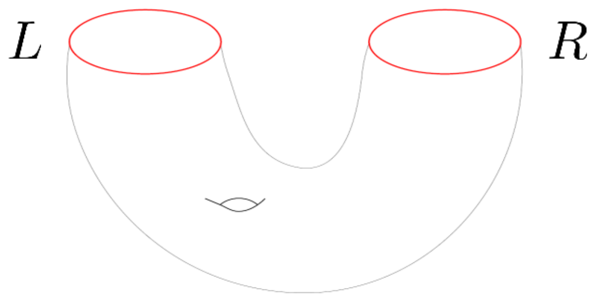
$$\zeta(M) = \int_{\mathrm{bc}:M} \mathcal{D}g e^{-S[g]}$$

not a requirement!

→ assumptions for the gravitational path integral

Setting

- Consider a gravitational system with two asymptotic codimension-2 boundaries



- The Hilbert space $\mathcal{H}_{LR}$ a priori does not factorize!
  - reduced state on L/R?
  - entropy associated to L/R?

- Can we construct a Hilbert space $\mathcal{H}_L$ associated with L such that the corresponding Ryu–Takayanagi formula can be understood in terms of a standard trace on $\mathcal{H}_L$? (True with holography)

$$S_{\mathrm{vN}}(\rho_L) := -\mathrm{Tr}_L(\rho_L \ln \rho_L) = \textbf{RT formula}$$

$$\rho_L = \mathrm{Tr}_R(\rho) \quad \text{reduced state}$$

TODAY:

This type of structure is present in any UV-complete, asymptotically locally AdS theory of quantum gravity in which the Euclidean path integral satisfies a simple set of axioms.

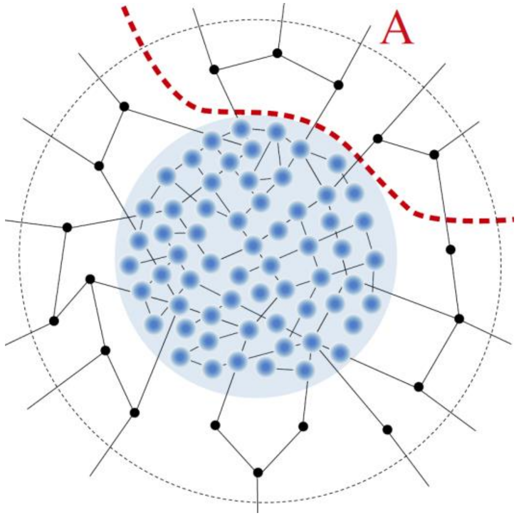
Related work

Axiomatic approach to TQFT and Gravity:

- Axiomatization of topological quantum field theories (TQFT) [Atiyah 1988]
- Attempt to define a gravitational partition function by generalising TQFT axioms [Rovelli, Barrett, Crane, Baez, Dolan, Freidel, Starodubtsev, Oeckl, …]

Ryu-Takayanagi formula for spin network states

- Setting: open spin network graphs
- Entanglement entropy of boundary regions given by a bulk area law, with corrections from entanglement among intertwiners [Chirco, Oriti, Zhang, EC]



Related work

Towards understanding RT in the bulk

- [Lewkowycz, Maldacena (2013)]: gravitational path integral derivation of the RT formula. But the interpretation of RT as a standard entropy still required a holographic dual theory.

- Recent works have shown that, in various contexts, the RT entropy can be derived (up to an infinite constant) as the entropy of a type II von Neumann algebra. [Chandrasekaran, Longo, Penington, Witten, Jensen, Sorce, Speranza, Satishchandran…]

- The entropy of a standard quantum mechanical system is in terms of a Hilbert space trace $\mathrm{Tr}(\cdot) = \sum_i \langle i| \cdot |i\rangle$ which provides a "state-counting interpretation". A Hilbert space trace corresponds to a type I trace.

TODAY:

RT formula with a state-counting interpretation, i.e. as entropy of a type I von Neumann algebra, without holography.

Outline

1. Axioms

2. Hilbert Space

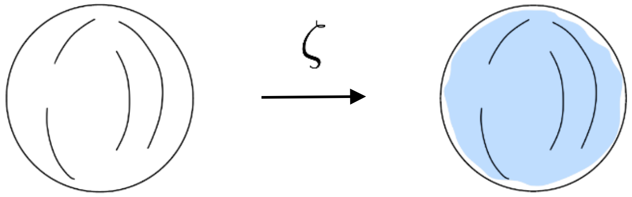
3. Operator Algebras

4. Type I von Neumann Factors

5. Entropy (with state-counting interpretation)

Axioms

(Euclidean) Gravitational Path Integral



$$M \supset g_M, \phi_M$$

boundary conditions
"source-manifold"

$$\zeta(M) = \int_{\mathrm{bc}:M} \mathcal{D}g\mathcal{D}\phi e^{-S[g,\phi]}$$

Axioms

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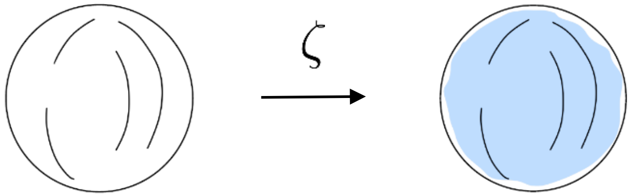

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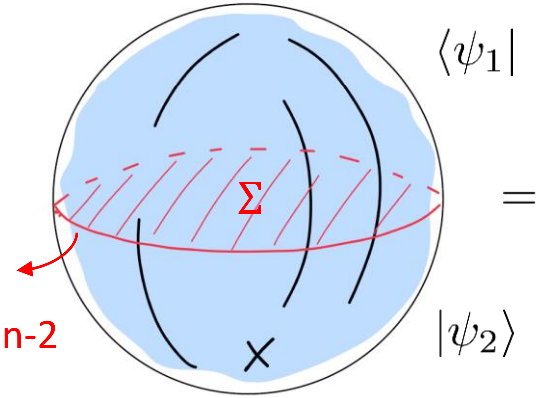
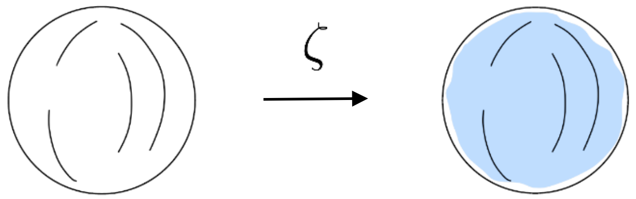


$$= \langle\psi_1|\psi_2\rangle$$

$\partial\Sigma$
codimension-2
surface

Axioms

(Euclidean) Gravitational Path Integral



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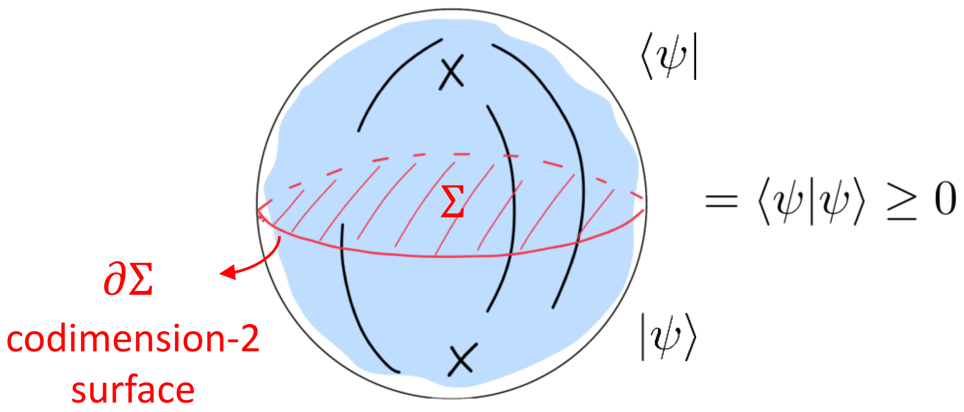


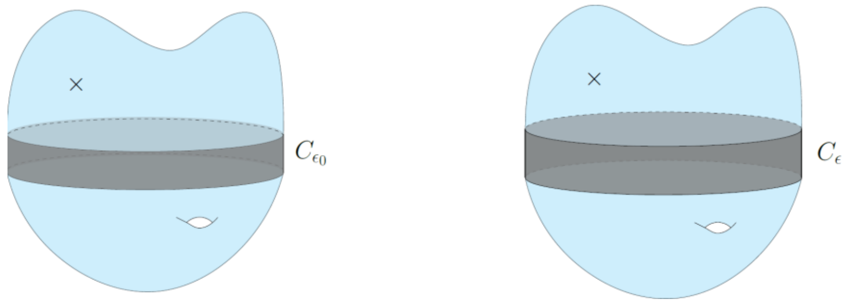
Axioms

1. **Finiteness:** The path integral gives a well-defined map ζ from boundary conditions defined by smooth manifolds to the complex numbers $\mathbb{C}$

2. **Reality:** ζ is a real function of (possibly complex) boundary conditions, i.e. $[\zeta(M)]^* = \zeta(M^*)$

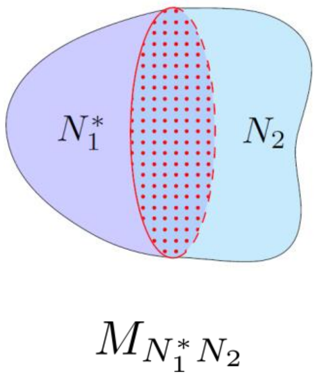
3. **Reflection Positivity**: ζ is reflection-positive

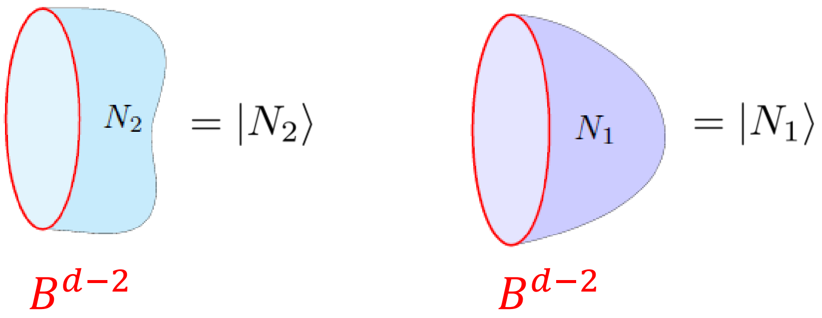
4. **Continuity:** if the boundary manifold contains a cylinder of size ε, ζ is continuous under changes of ε



5. **Factorization:** $\zeta(M_1 \sqcup M_2) = \zeta(M_1)\zeta(M_2)$

Hilbert Space





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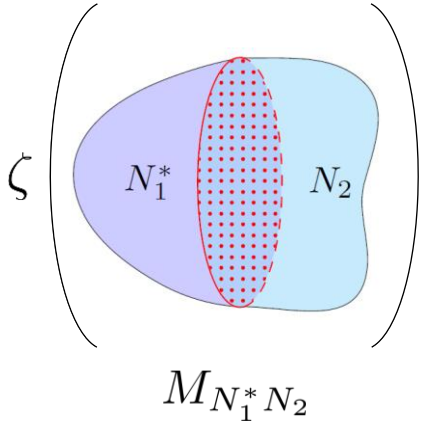
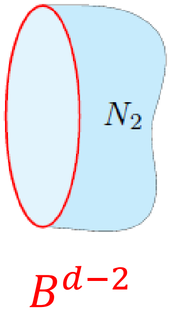
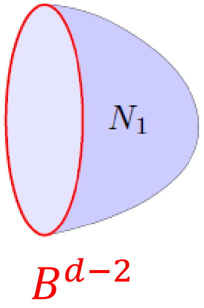


$= \langle N_1 | N_2 \rangle$

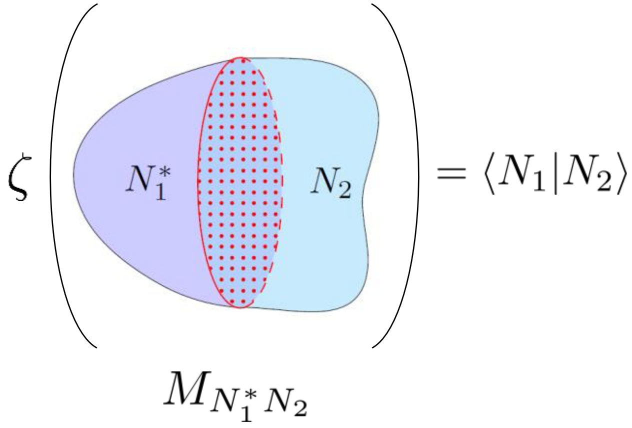


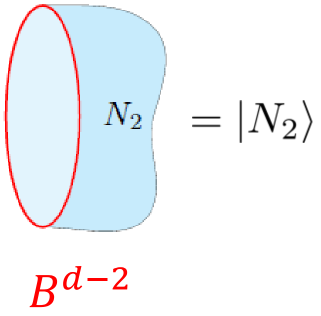
$= |N_2\rangle$

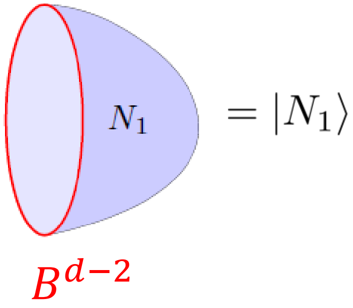


$= |N_1\rangle$

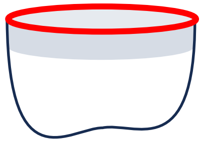
Hilbert Space



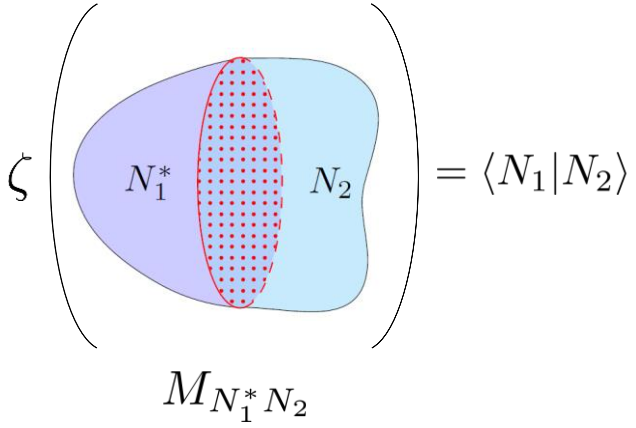


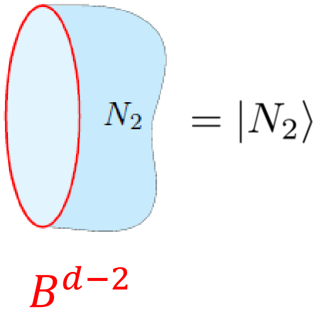


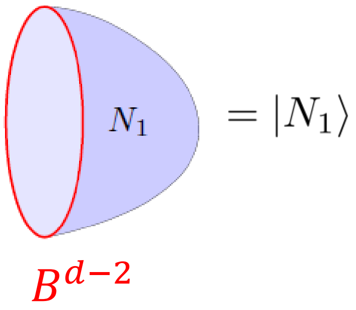
- The source-manifold $M_{N_1^* N_2}$ might not be smooth, and so $\zeta(M_{N_1^* N_2})$ might not be well defined
- We introduce rims:



Hilbert Space







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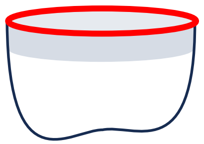
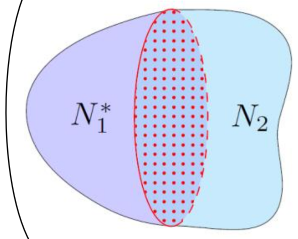


- $Y_B^{d-1} =$ set of rimmed source-manifolds with boundary B
- $\underline{Y}_B^{d-1} =$ linear combinations of rimmed source-manifolds with boundary B

Hilbert Space

- Define the pre-Hilbert space $H_B = \{|N\rangle : N \in \underline{Y}_B^{d-1}\}$

$$\langle N_1 | N_2 \rangle := \zeta \left(\quad \right)$$



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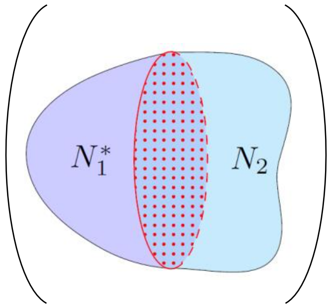

- Consider the quotient of H_B by its null space and complete the result: Hilbert space $\mathcal{H}_B$

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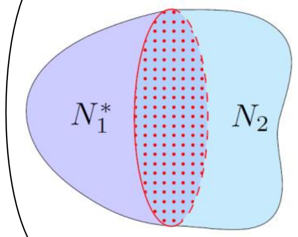

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- $\mathcal{H}_B$ is the B-sector of the full quantum gravity Hilbert space:

$$\mathcal{H}_{QG} = \bigoplus_B \mathcal{H}_B$$

Outline

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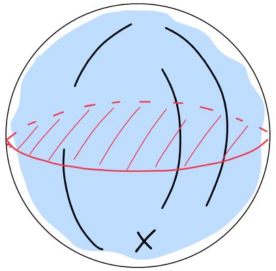
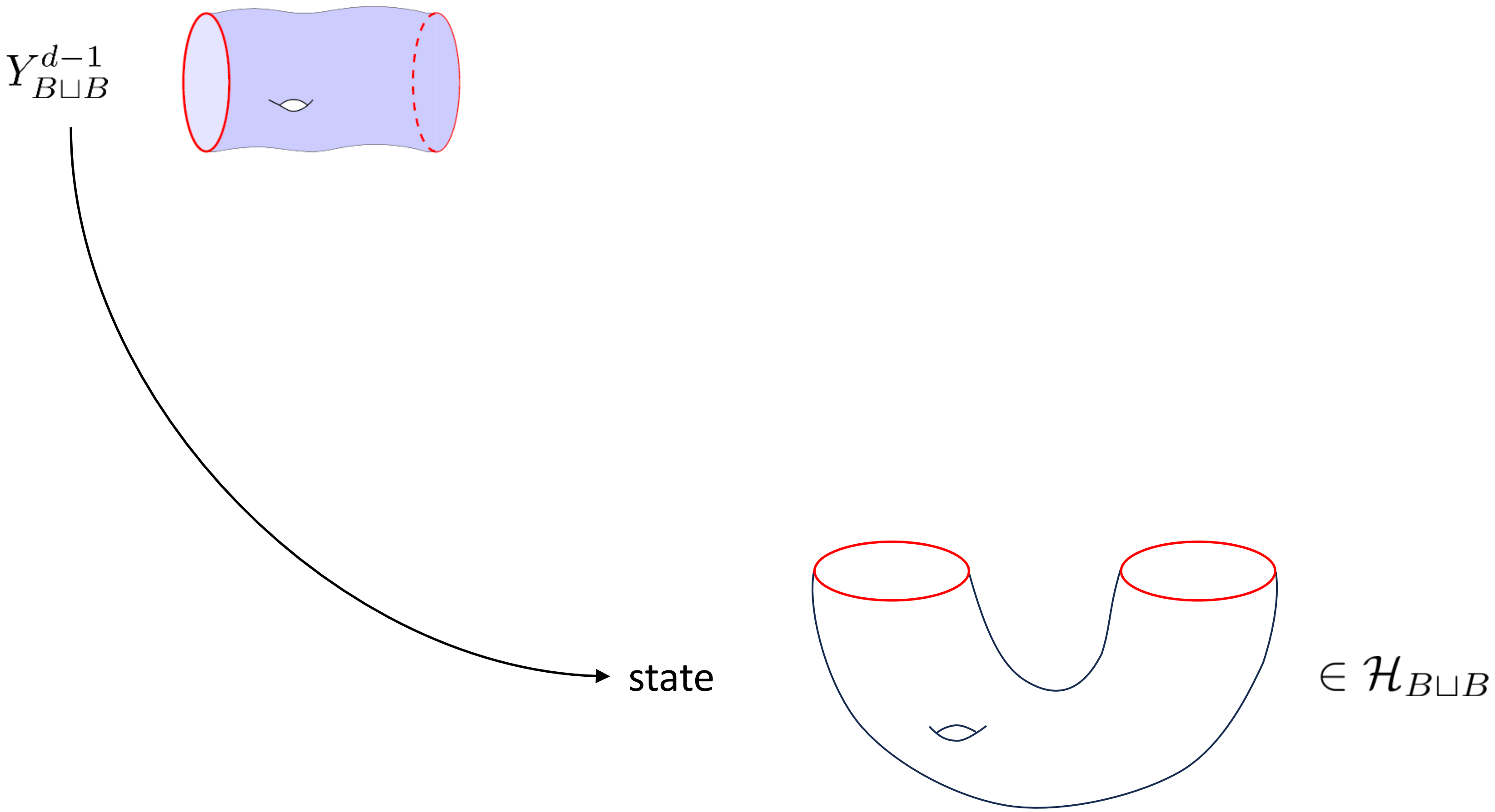
2. Hilbert Space ✓



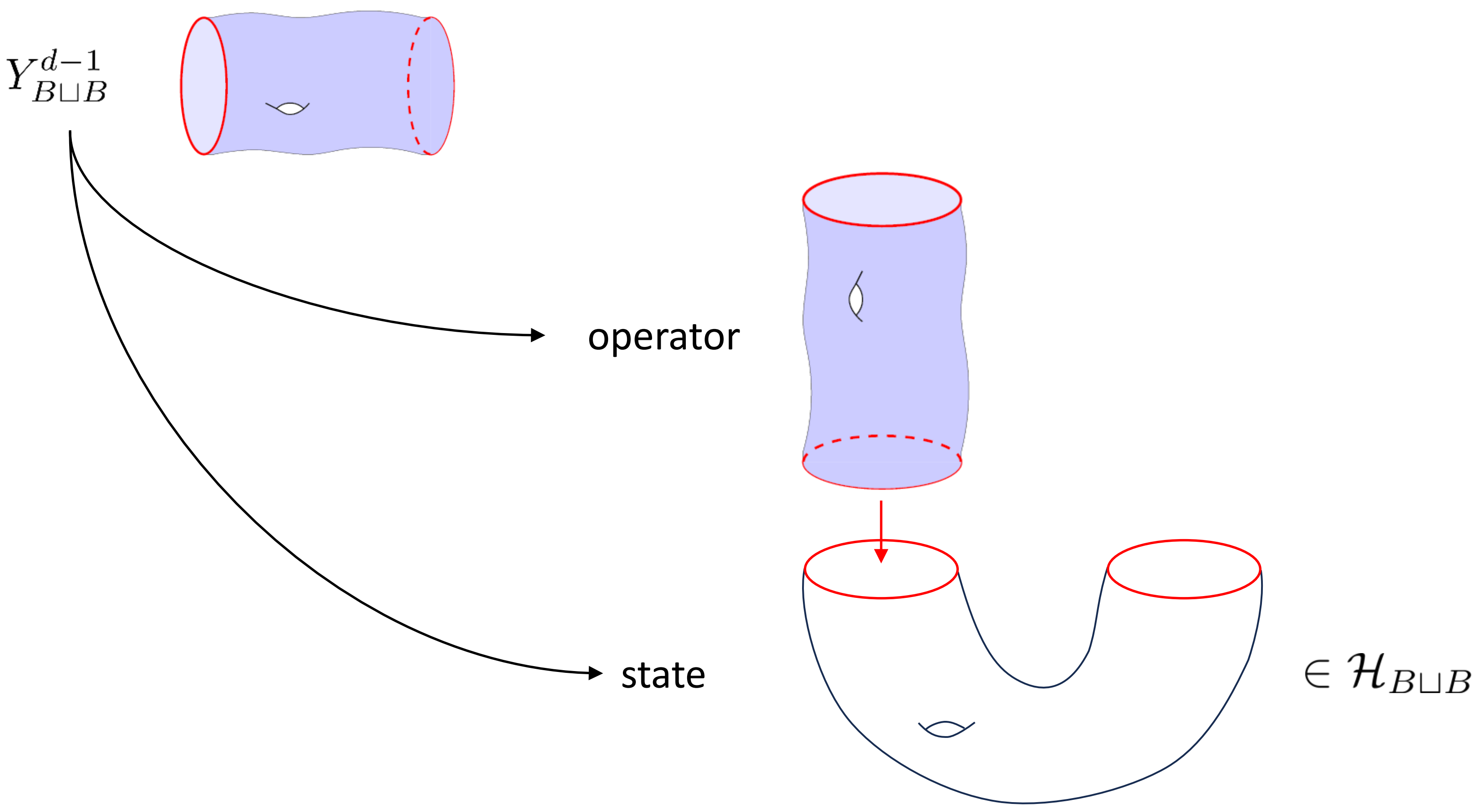
$\mathcal{H}_B$

3. Operator Algebras ⬅
4. Type I von Neumann Factors
5. Entropy (with state-counting interpretation)

Algebra



Algebra



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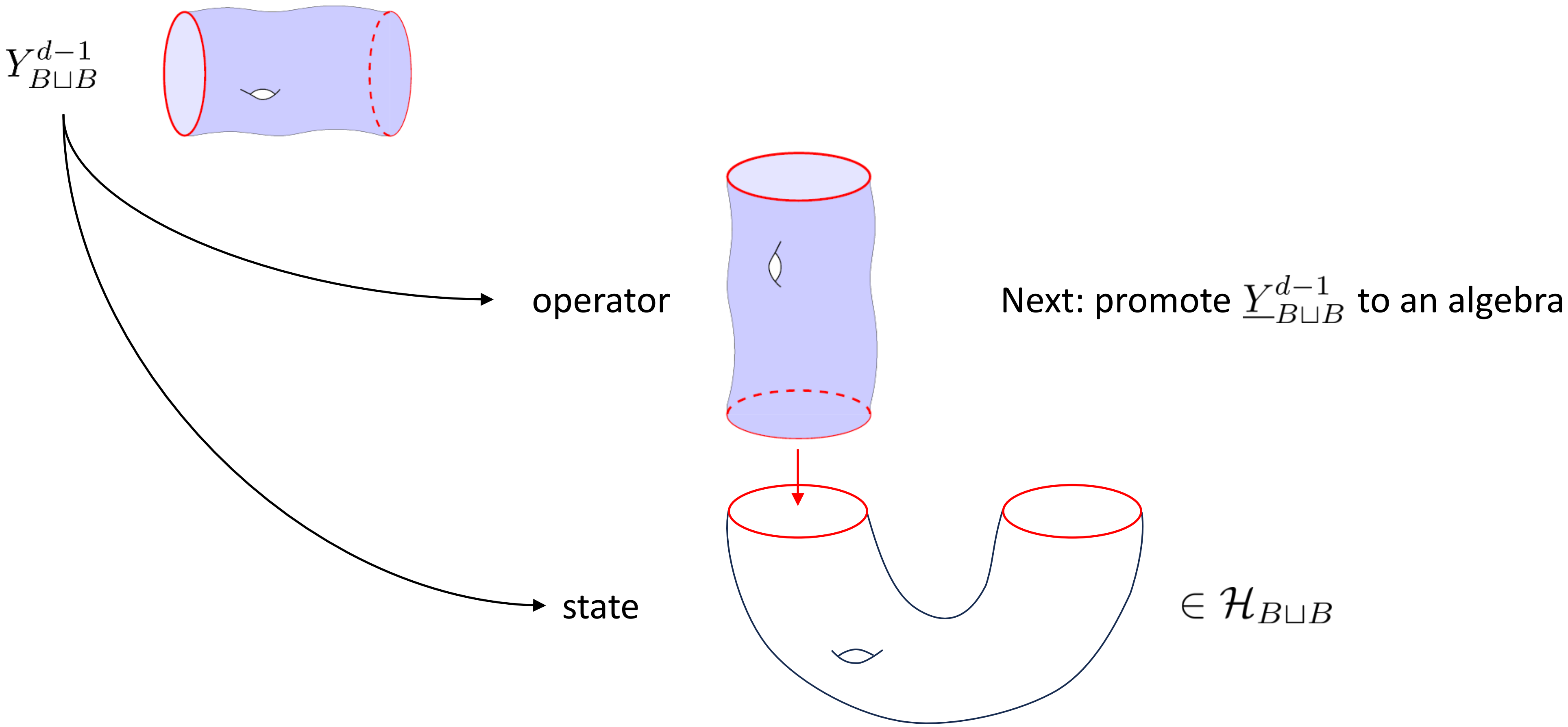
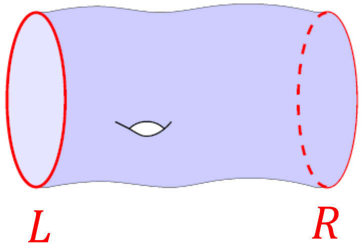

$Y^{d-1}_{B\sqcup B}$
operator
state
$\in \mathcal{H}_{B\sqcup B}$
Next: promote $\underline{Y}^{d-1}_{B\sqcup B}$ to an algebra

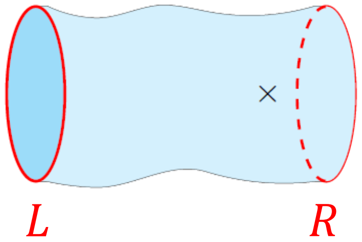
Algebra

- On the set $\underline{Y}^{d-1}_{B\sqcup B}$ we define a *left product* and a *right product*:

$a =$



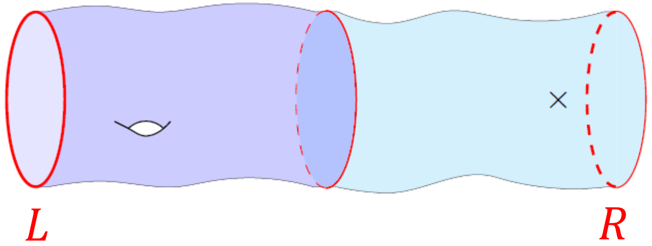
$b =$



<u>left product:</u>

$(\cdot_L)$

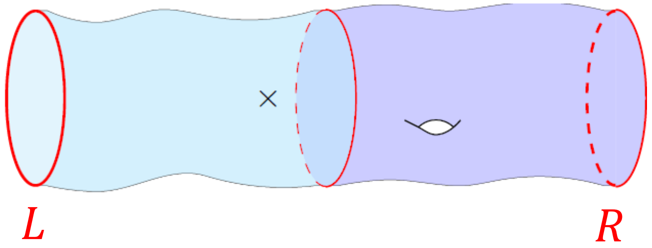
$a \cdot_L b =$



<u>right product:</u>

$(\cdot_R)$

$a \cdot_R b =$



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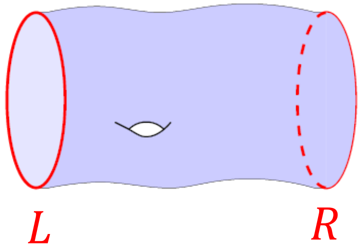

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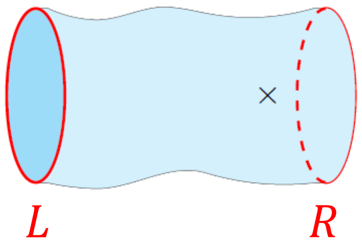
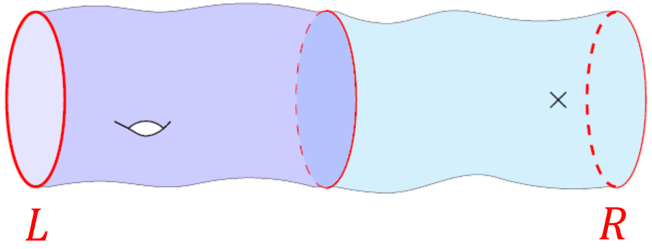
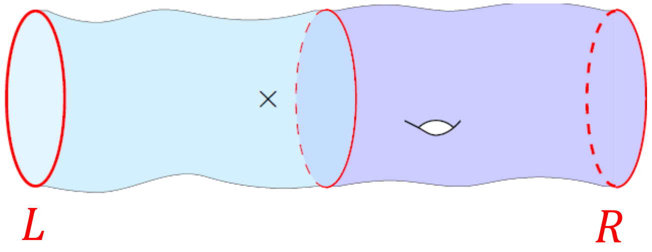


<u>left product:</u> $(\cdot_L)$ $a \cdot_L b =$



<u>right product:</u> $(\cdot_R)$ $a \cdot_R b =$



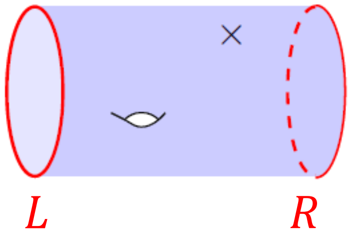
- For convenience $ab := a \cdot_L b = b \cdot_R a$

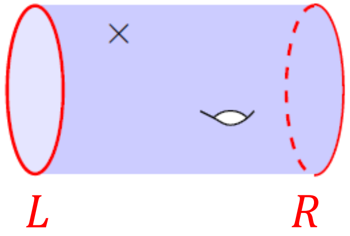
- The set $\underline{Y}^{d-1}_{B\sqcup B}$ equipped with the left (right) product defines a left (right) surface algebra A_L (A_R)

Algebra

- The algebras A_L and A_{R} are related by an antilinear isomorphism $\star$

$$a^\star := (a^*)^t$$

$a =$ 

$a^\star =$ 

Algebra

- The algebras A_L and A_{R} are related by an antilinear isomorphism $\star$

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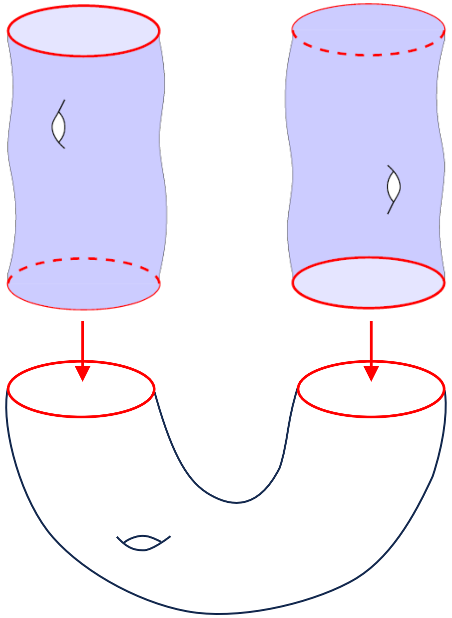
- We will see that the left (right) algebra as a natural action on the left (right) B of $\mathcal{H}_{B\sqcup B}$

$\underline{Y}^{d-1}_{B\sqcup B}, (\cdot_L)$

Left surface algebra

A_L



$\underline{Y}^{d-1}_{B\sqcup B}, (\cdot_R)$

Right surface algebra

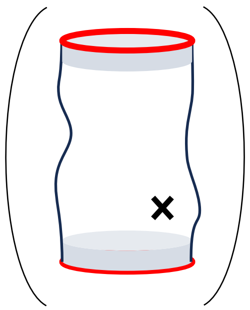
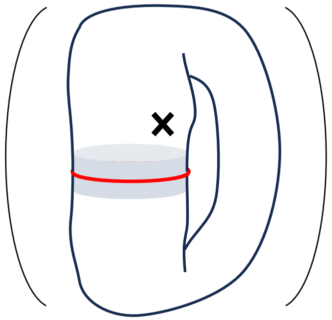
A_R

$\in \mathcal{H}_{B\sqcup B}$

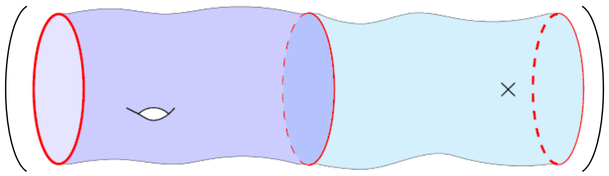
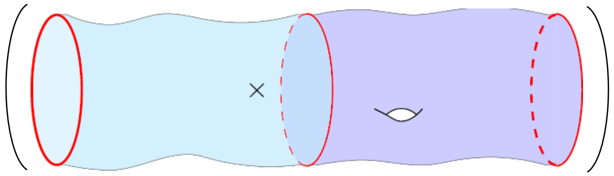
Trace

- The path integral defines a trace operation:

$$\mathrm{tr} : A_{L/R} \to \mathbb{C}$$

tr  $= \zeta$ 

- It satisfies the cyclic property:

tr  $= \mathrm{tr}$ 

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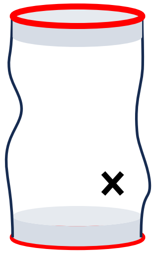
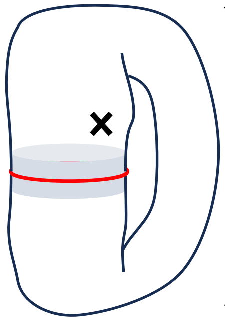
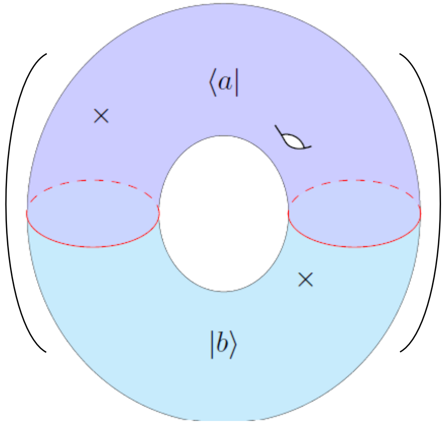
$\mathrm{tr}\Bigg($  $\Bigg) = \zeta\Bigg($  $\Bigg)$

- The trace on A_L and A_R corresponds to the inner product on $\mathcal{H}_{B\sqcup B}$:

$\langle a|b\rangle = \mathrm{tr}(a^\star b) = \zeta\Bigg($ 

$\Bigg)$

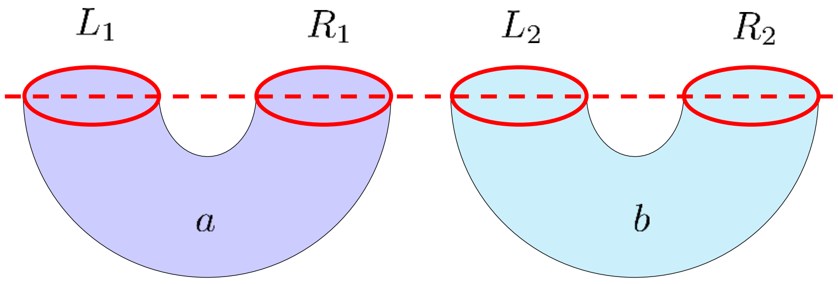
- It is positive-definite: $\mathrm{tr}(a^\star a) = \zeta\left(M(a^\star a)\right) = \langle a|a\rangle \geq 0$

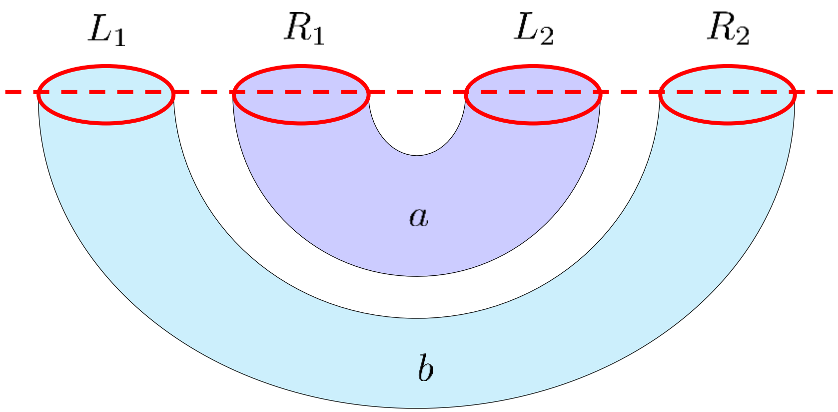
↑ Axiom 3

Trace Inequality

- We can prove the trace inequality $\mathrm{tr}(aa^\star bb^\star) \leq \mathrm{tr}(a^\star a)\mathrm{tr}(b^\star b)$

  Use $a, b \in Y^{d-1}_{B \sqcup B}$ to define elements of $Y^{d-1}_{(B \sqcup B)\sqcup(B \sqcup B)}$





$|\cup\cup\rangle := |a_{L_1R_1}, b_{L_2R_2}\rangle$

$|\Cup\rangle := |a_{L_2R_1}, b_{L_1R_2}\rangle$

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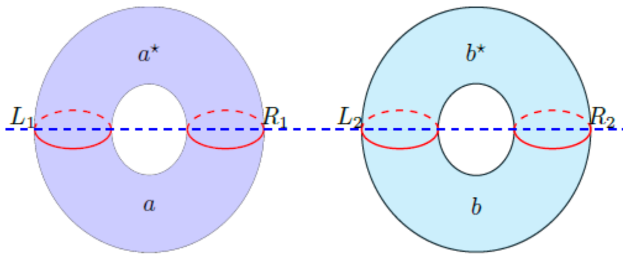
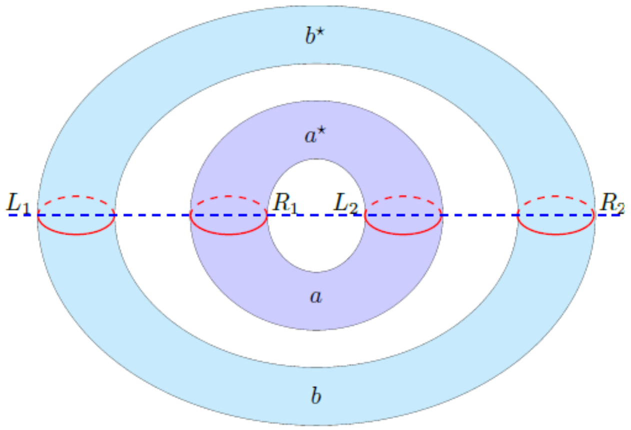
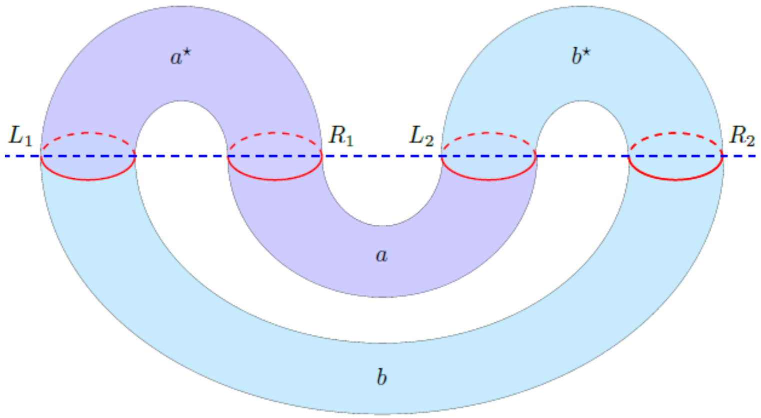




$$\langle \cup \cup \mid \cup \cup \rangle = \langle \Cup | \Cup \rangle = \langle a|a\rangle \, \langle b|b\rangle = \mathrm{tr}(a^\star a)\mathrm{tr}(b^\star b)$$

From the Cauchy-Schwarz inequality (consequence of positivity of the inner product on $\mathcal{H}_{B\sqcup B\sqcup B\sqcup B}$):

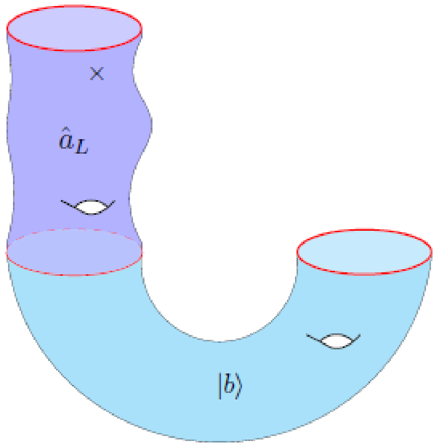
$$\left| \langle \Cup | \cup \cup \rangle \right| \leq \left| |\cup\cup\rangle \right| \left| |\Cup\rangle \right|$$



Operator algebras

- We define a representation of the left surface algebra on the Hilbert space: given $a \in A_L$ there is an associated operator $\hat{a}_L \in \hat{A}_L$ such that

$$\hat{a}_L |b\rangle = |a \cdot_L b\rangle = |ab\rangle$$



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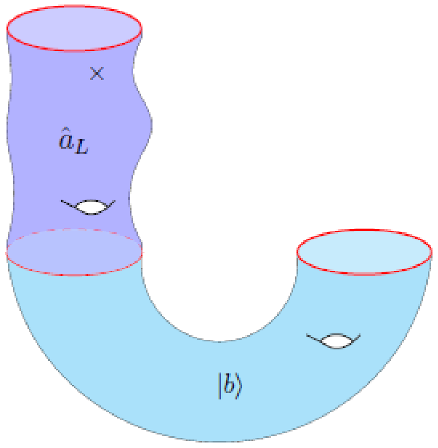
- These operators are **bounded**:

$$|\hat{a}_L|b\rangle|^2 = \langle ab|ab\rangle = \mathrm{tr}(a^\star abb^\star) \leq \mathrm{tr}(a^\star a)\mathrm{tr}(bb^\star) = \mathrm{tr}(a^\star a)\langle b|b\rangle$$

trace inequality



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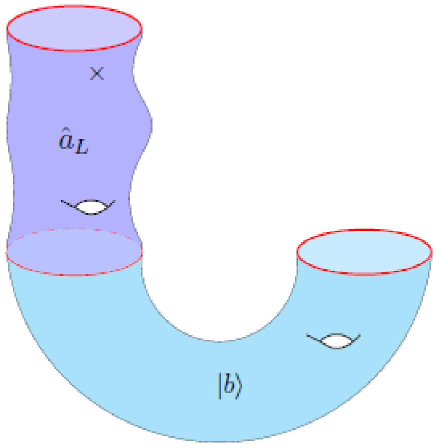

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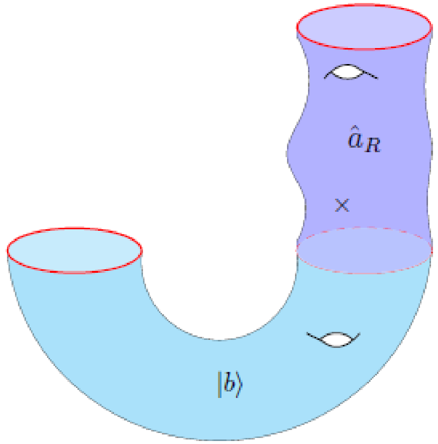
trace inequality

- We can similarly define a representation $\hat{A}_R$ of A_R :



$$\hat{a}_R \left|b\right\rangle = \left|a \cdot_R b\right\rangle = \left|b \cdot_L a\right\rangle = \left|ba\right\rangle$$

Operator algebras

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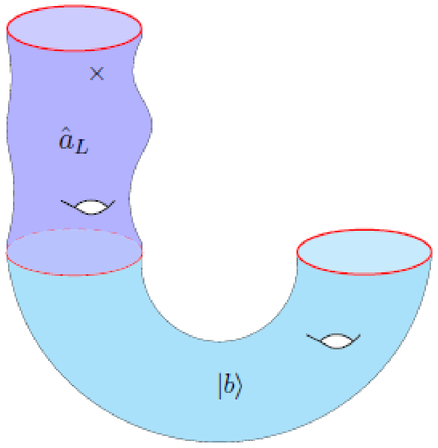

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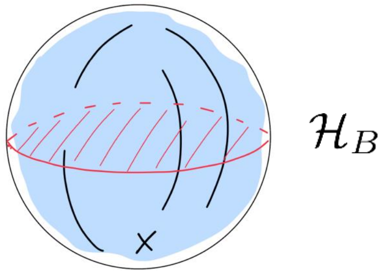
trace inequality

- The operator algebras $\hat{A}_{L/R}$ get a trace from the trace on $A_{L/R}$:

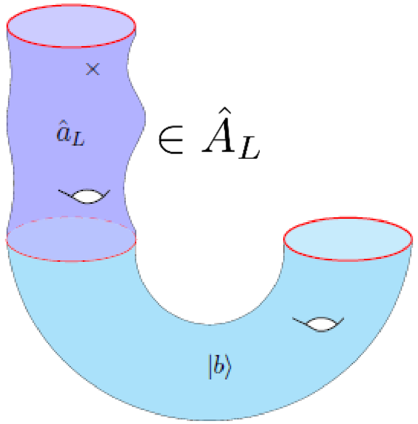
$$\mathrm{tr}(\hat{a}) := \mathrm{tr}(a)$$

Outline

1. Axioms ✓
2. Hilbert Space ✓



3. Operator Algebras ✓



4. Type I von Neumann Factors ⬅

5. Entropy (with state-counting interpretation)

Type I von Neumann algebras

- We constructed $\hat{A}_L, \hat{A}_R =$ commuting algebras of bounded operators on $\mathcal{H}_{B\sqcup B}$

- We can complete $\hat{A}_L, \hat{A}_R$ to von Neumann algebras $\mathcal{A}_L, \mathcal{A}_R$ by taking the closure in the weak (or strong) operator topology (or taking the double commutant of $\hat{A}_{L/R}$)

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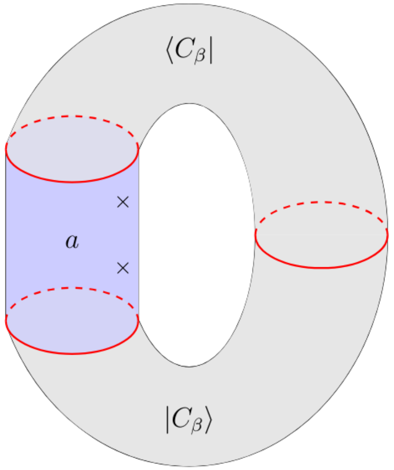
- We can complete $\hat{A}_L, \hat{A}_R$ to von Neumann algebras $\mathcal{A}_L, \mathcal{A}_R$ by taking the closure in the weak (or strong) operator topology (or taking the double commutant of $\hat{A}_{L/R}$)
- We show that the trace defined on $\hat{A}_{L/R}$ can be extended to (all positive elements of) the von Neumann algebra:

$$\mathrm{tr}(a) = \lim_{\beta\downarrow 0}\langle C_\beta|a|C_\beta\rangle$$



- We can study the structure of the von Neumann algebras via properties of the trace!

Type I von Neumann algebras

- We can prove that the trace is

1) Faithful $\mathrm{tr}(a) = 0 \text{ iff } a = 0$
2) Normal for any bounded increasing sequence a_n, tr $sup\ a_n = sup$ tr a_n
3) Semifinite $\forall a \in \mathcal{A}^+, \exists b < a$ such that $\mathrm{tr}(b) < \infty$

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Some known results on von Neumann algebras:

- Every von Neumann algebra is a direct sum or integral of factors (algebras with trivial center)
- These factors can be type I, II or III
- There is *no faithful, normal and semifinite trace on type III* ⇒ we cannot have type III
- on type II, for any faithful, normal and semifinite trace there are *nonzero projections with arbitrarily small trace*
  ⇒ we cannot have type II

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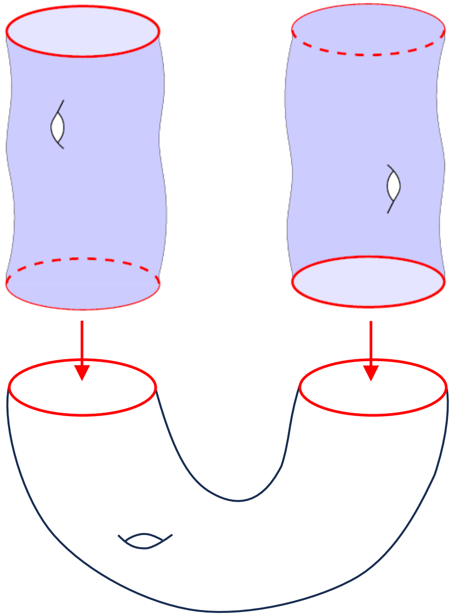
- Applying the trace inequality to $a = b = P \in \mathcal{A}_L$ gives $\mathrm{tr}(P) \geq 1$
- Therefore, $\mathcal{A}_{L/R}$ is a direct sum/integral of type I factors!
- The spectrum of $z \in \mathcal{Z}_L$ (center of $\mathcal{A}_L$) is discrete

$$\mathcal{A}_L = \bigoplus_{\mu} \mathcal{A}_{L,\mu}$$

Type I von Neumann algebras

- $\mathcal{A}_L, \mathcal{A}_R$ are each other commutants on $\mathcal{H}_{B\sqcup B}$, and so they have the same center $\mathcal{Z}$

$$\mathcal{A}_L = \bigoplus_\mu \mathcal{A}_{L,\mu}$$



$$\mathcal{A}_R = \bigoplus_\mu \mathcal{A}_{R,\mu}$$

- $\mathcal{H}_{B\sqcup B}$ can be decomposed into eigenspaces of $\mathcal{Z}$

$$\mathcal{H}_{B\sqcup B} = \bigoplus_\mu \mathcal{H}^\mu_{B\sqcup B}$$

with $\mathcal{H}^\mu_{B\sqcup B} = \mathcal{H}^\mu_{B\sqcup B,L} \otimes \mathcal{H}^\mu_{B\sqcup B,R}$

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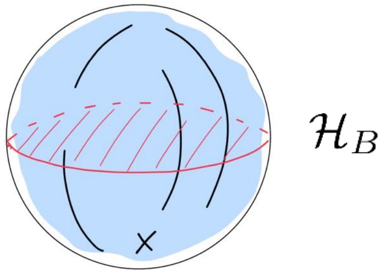

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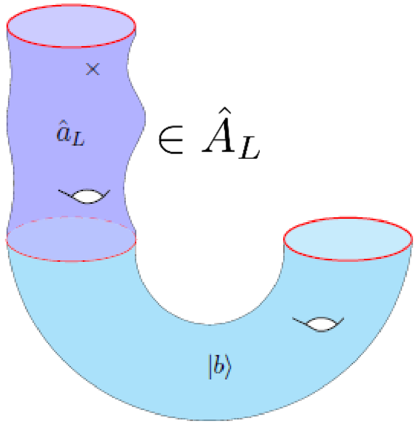
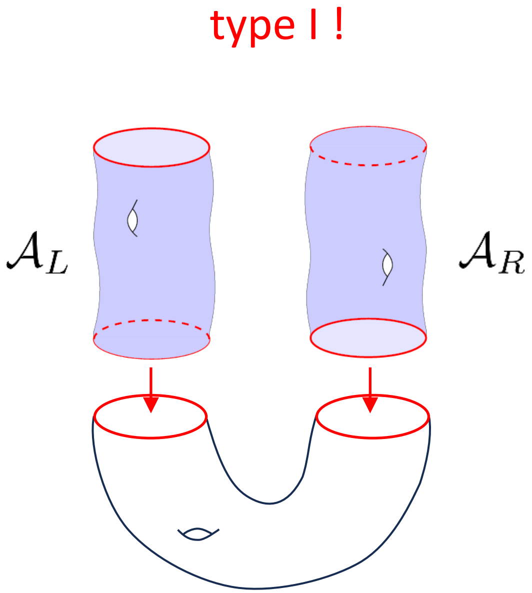


4. Type I von Neumann Factors ✓



5. Entropy (with state-counting interpretation) ⬅

Trace Normalization

- Faithful, normal, semifinite traces on type I algebras are unique up to an overall normalization constant. Therefore, on a given μ-sector

$$\mathrm{tr}(a) = n_\mu \mathrm{Tr}_\mu(a) = n_\mu \sum_i {}_L\langle i|a|i\rangle_L,$$

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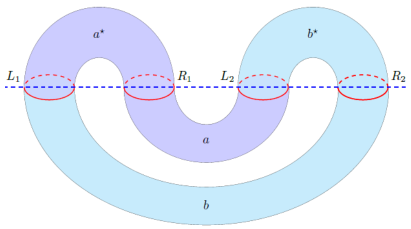
- For $a = P$ one-dimensional projection onto a state in $\mathcal{H}^\mu_{B\sqcup B,L}$ we have $\mathrm{Tr}_\mu(P) = 1$

$$1 \leq \mathrm{tr}(P) = n_\mu$$

trace inequality



positivity of the inner product on $\mathcal{H}_{B\sqcup B\sqcup B\sqcup B}$ | $\mathrm{tr}(P) \geq 1$ | $\mathrm{tr}(P) = 0$

positivity of the inner product on $\mathcal{H}_{\sqcup_{i=1}^n (B\sqcup B)}$ | $\mathrm{tr}(P) \geq n-1$ | $\mathrm{tr}(P) = 0, 1, \cdots, n-2$

$\Rightarrow$ n_μ is a positive integer!

Trace Normalization

- Therefore on a given μ-sector $\mathrm{tr} = n_\mu \mathrm{Tr}_\mu$ with $n_\mu \in \mathbb{Z}^+$

Trace Normalization

- Therefore on a given μ-sector $\mathrm{tr} = n_\mu \mathrm{Tr}_\mu$ with $n_\mu \in \mathbb{Z}^+$

- We define the extended Hilbert space factors:

$$\widetilde{\mathcal{H}}^{\mu}_{B\sqcup B,L/R} := \mathcal{H}^{\mu}_{B\sqcup B,L/R} \otimes \mathcal{H}_{n_\mu}$$

↓ "hidden sector"

where $\mathrm{tr} = \tilde{\mathrm{Tr}}_\mu$!

Trace Normalization

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↓

"hidden sector"

where $\mathrm{tr} = \tilde{\mathrm{Tr}}_\mu$!

- The full extended Hilbert space:

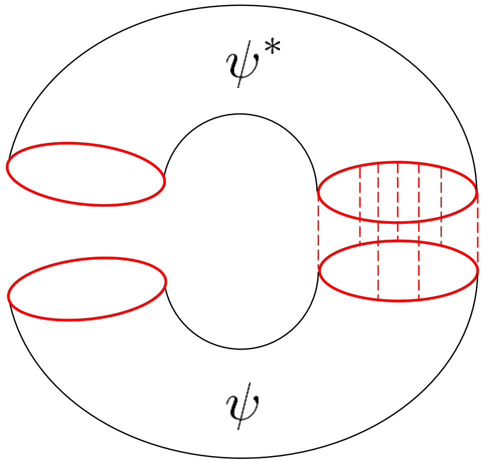
$$\widetilde{\mathcal{H}}_{B\sqcup B} := \bigoplus_{\mu\in\mathcal{I}} \left(\widetilde{\mathcal{H}}^{\mu}_{B\sqcup B,L} \otimes \widetilde{\mathcal{H}}^{\mu}_{B\sqcup B,R}\right)$$

⇒ The hidden sectors allow to interpret the path integral trace as a Hilbert space trace

Entropy

✓ The trace tr defines an entropy on the left/right B

- Given a state $|\psi\rangle \in \mathcal{H}_{B\sqcup B}$ we can define a reduced density operator $\rho_\psi \in \mathcal{A}_L$



- The von Neumann entropy is $S^L_{vN}(\psi) = \mathrm{tr}(-\rho_\psi \ln \rho_\psi)$

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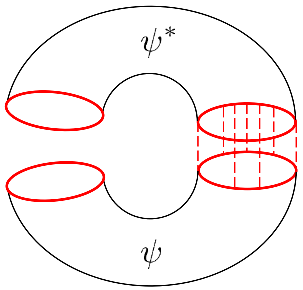

$$S^L_{vN}(\psi) = \mathrm{tr}(-\rho_\psi \ln \rho_\psi)$$

✓ Thanks to the relation $\mathrm{tr} = \tilde{\mathrm{Tr}}_\mu$ this entropy has a state-counting interpretation as left entropy on the extended Hilbert space $\widetilde{\mathcal{H}}_{B\sqcup B}$

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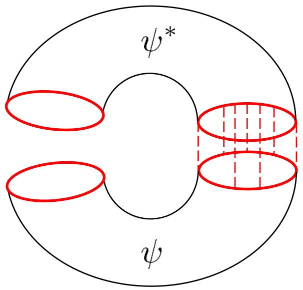


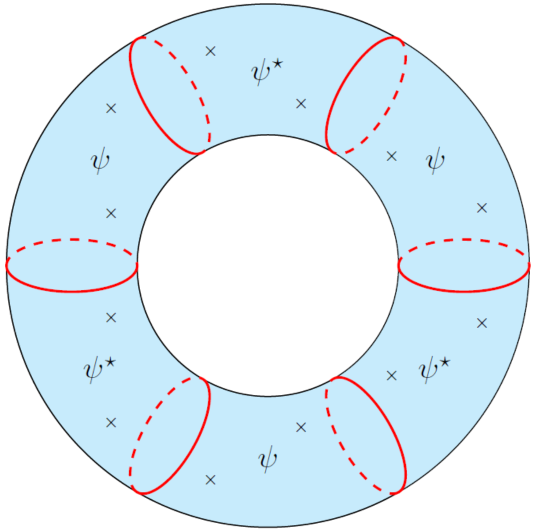
$$S^L_{vN}(\psi) = \mathrm{tr}(-\rho_\psi \ln \rho_\psi)$$

- ✓ Thanks to the relation $\mathrm{tr} = \widetilde{\mathrm{Tr}}_\mu$ this entropy has a state-counting interpretation as left entropy on the extended Hilbert space $\widetilde{\mathcal{H}}_{B\sqcup B}$

- ✓ We can compute this entropy via the replica trick:

$$\mathrm{tr}(\rho^n_\psi) = \zeta\left(M([\psi\psi^\star]^n)\right)$$

$$S^L_{vN}(\psi) = (1 - n\partial n) \log \mathrm{tr}(\rho^n_\psi)\Big|_{n=1}$$



Entropy

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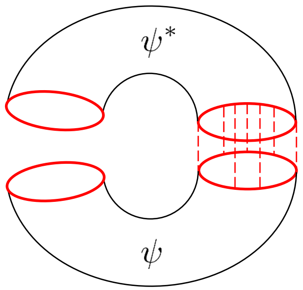


$$S^L_{vN}(\psi) = \mathrm{tr}(-\rho_\psi \ln \rho_\psi)$$

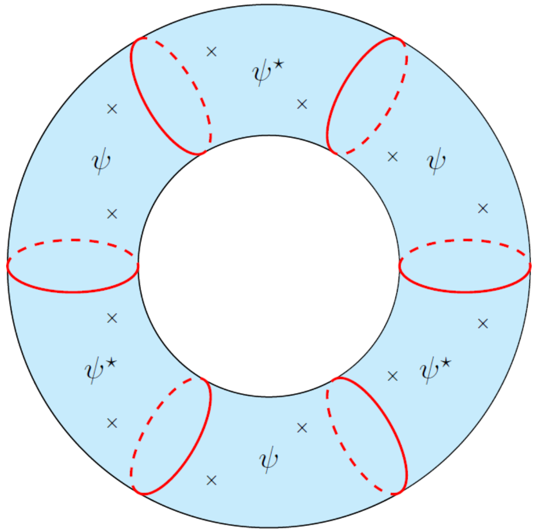
- ✓ Thanks to the relation $\mathrm{tr} = \tilde{\mathrm{Tr}}_\mu$ this entropy has a state-counting interpretation as left entropy on the extended Hilbert space $\widetilde{\mathcal{H}}_{B\sqcup B}$

- ✓ We can compute this entropy via the replica trick:

$$\mathrm{tr}(\rho_\psi^n) = \zeta\left(M([\psi\psi^\star]^n)\right)$$

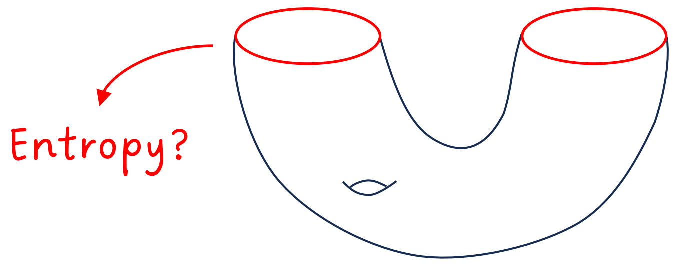
$$S^L_{vN}(\psi) = (1 - n\partial n)\log \mathrm{tr}(\rho_\psi^n)\big|_{n=1}$$

$$= \frac{A(\gamma)}{4G} \quad \textbf{RT}$$



- ✓ If the theory admits a semiclassical limit described by Einstein-Hilbert or JT gravity, we can argue (by following Lewkowycz-Maldacena) that in such a limit the entropy is given by the Ryu-Takayanagi entropy

Conclusions



$$\mathcal{H}_{B\sqcup B} \overset{?}{\neq} \mathcal{H}_B \otimes \mathcal{H}_B$$

- A gravitational path integral satisfying a simple and familiar set of axioms defines type I von Neumann algebras of observables associated with codimension-2 boundaries.

- The path integral also defines a trace and entropy on these algebras.

- The Hilbert space on which the algebras act decomposes as

$$\mathcal{H}_{B\sqcup B} = \bigoplus_{\mu} \mathcal{H}^{\mu}_{B\sqcup B,L} \otimes \mathcal{H}^{\mu}_{B\sqcup B,R}$$

- The path integral trace is equivalent to a standard trace on an extended Hilbert space: $\mathrm{tr} = \tilde{\mathrm{Tr}}_{\mu}$.

- This provides a state-counting interpretation of the entropy, even when the gravitational theory is not known to have a holographic dual.

- In the semiclassical limit, the entropy is given by the Ryu-Takayanagi formula.

Thanks for the attention!