On sufficient conditions for holographic scattering

Caroline Lima, Sabrina Pasterski, and **Chris Waddell**

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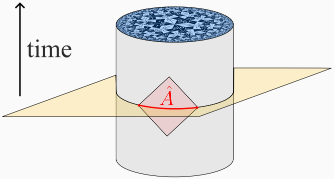
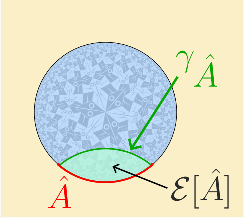
Quantum Information Theory and Holography

An information-theoretic perspective on AdS/CFT was initiated by the **Ryu-Takayanagi formula**:

Entropy $=$ **Area**[extremal surface]

$$S(\hat{A}) = \min_{\text{extremal } \gamma_{\hat{A}} \sim \hat{A}} \frac{\text{Area}[\gamma_{\hat{A}}]}{4G_N}$$





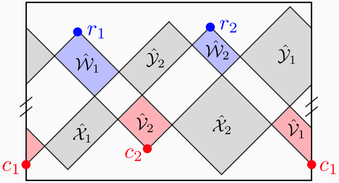
The Ryu-Takayanagi surface $\gamma_{\hat{A}}$ bounds a region called the **entanglement wedge** $\mathcal{E}[\hat{A}]$

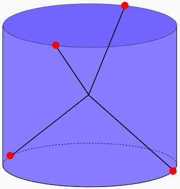
Conjecture: (Entanglement Wedge Reconstruction)

The bulk von Neumann algebra of $\mathcal{E}[\hat{A}]$ is isomorphic to the large N algebra of $\hat{A}$

[Ryu/Takayanagi '06], [Hubeny/Rangamani/Takayanagi '07],
[Czech/Karczmarek/Nogueira/Van Raamsdonk '12], [Wall '12], [Headrick/Hubeny/Lawrence/Rangamani '14]

Boundary entanglement turns out to be closely related to **bulk causal structure***

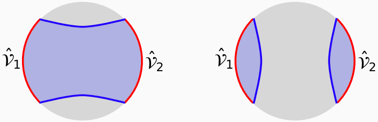




Connected Wedge Theorem: *Bulk-only scattering* $\Longrightarrow$ $\mathcal{E}[\hat{\mathcal{V}}_1 \cup \hat{\mathcal{V}}_2]$ *connected*
in asymptotically globally AdS$_3$ spacetime satisfying the null energy condition [May/Penington/Sorce '19]

$$I(\hat{\mathcal{V}}_1 : \hat{\mathcal{V}}_2) = S(\hat{\mathcal{V}}_1) + S(\hat{\mathcal{V}}_2) - S(\hat{\mathcal{V}}_1 \cup \hat{\mathcal{V}}_2)$$

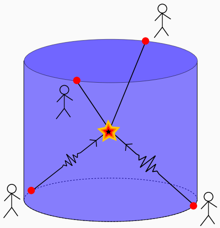
Connected | Disconnected



$I(\hat{\mathcal{V}}_1 : \hat{\mathcal{V}}_2) = O(1/G)$ | $I(\hat{\mathcal{V}}_1 : \hat{\mathcal{V}}_2) = O(1)$

*See also e.g. [Maldacena/Simmons-Duffin/Zhiboedov '15], [Engelhardt/Horowitz '16], [Caron-Huot/Chakravarty/Namjou '25] for alternative perspectives on bulk causal structure

Question: Suppose that agents act at the input points to introduce wavepackets in the bulk, these undergo some local interaction in the bulk, and the agents act at the output points to extract data from these wavepackets. How is it possible for the boundary theory to emulate this process?



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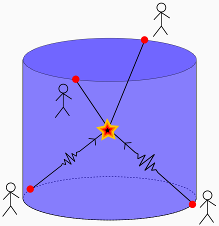
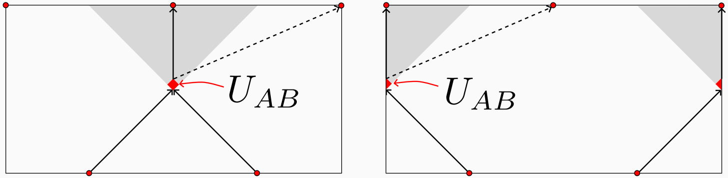
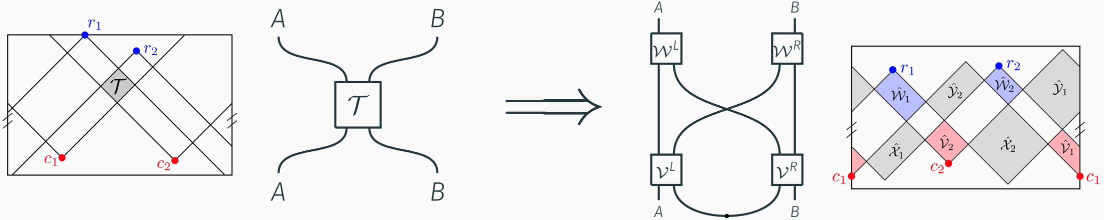


Observation: The process is *not* "**causal** propagation + **local** channel" in the CFT



AdS/CFT and Non-Local Quantum Computation

Instead, the CFT implements **non-local quantum computation (NLQC)** [May '19]



The local channel is emulated using local operations, **prior entanglement**, and a single round of **simultaneous quantum communication**

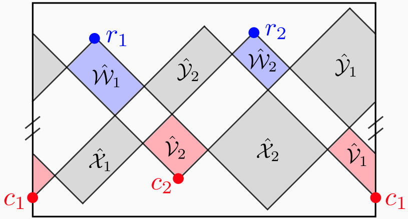
Fact: Some channels $\mathcal{T}$ are proven to require **correlation** $I_\Psi(L:R) \geq \Omega(\text{input size})$ to implement as an NLQC [Tomamichel, Fehr, Kaniewski, Wehner '13]

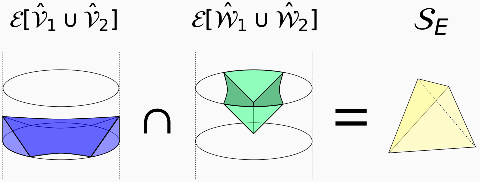
- This was the intuition behind the connected wedge theorem [May '19], [May/Penington/Sorce '19]

Inspired by recent progress on AdS/CFT from the algebraic viewpoint, Leutheusser and Liu have attempted to reformulate the connected wedge theorem as a statement about **large N CFT algebras**

Their conjecture involves a relaxation of the bulk scattering region

$$\mathcal{S} = \text{future}[c_1 \text{ and } c_2] \cap \text{past}[r_1 \text{ and } r_2] \to \boxed{\mathcal{S}_E \equiv \mathcal{E}[\hat{\mathcal{V}}_1 \cup \hat{\mathcal{V}}_2] \cap \mathcal{E}[\hat{\mathcal{W}}_1 \cup \hat{\mathcal{W}}_2] \supseteq \mathcal{S}}\,.$$





[Leutheusser/Liu '24]

The Generalized Connected Wedge Proposal

Conjecture (Leutheusser/Liu 2024)

(Informal) Define the $\mathcal{S}_E$-wedge by

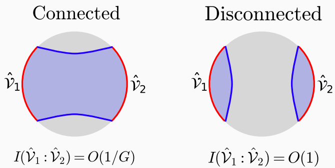
$$\mathcal{S}_E \equiv \mathcal{E}[\hat{\mathcal{V}}_1 \cup \hat{\mathcal{V}}_2] \cap \mathcal{E}[\hat{\mathcal{W}}_1 \cup \hat{\mathcal{W}}_2] \, .$$

Then $\mathcal{S}_E \neq \emptyset$ if and only if $\mathcal{E}[\hat{\mathcal{V}}_1 \cup \hat{\mathcal{V}}_2]$ and $\mathcal{E}[\hat{\mathcal{W}}_1 \cup \hat{\mathcal{W}}_2]$ are connected.

Interpretation: A connected entanglement wedge means a **superadditive** large N algebra

$$\mathcal{A}_{\hat{\mathcal{V}}_1} \vee \mathcal{A}_{\hat{\mathcal{V}}_2} \subsetneq \mathcal{A}_{\hat{\mathcal{V}}_1 \cup \hat{\mathcal{V}}_2} \, .$$

"The existence of non-locally generated operators and the ability to perform quantum tasks by a non-local protocol are equivalent."



Our work: We resolve Leutheusser and Liu's conjecture.

1. We prove the forward direction

$$\mathcal{E}[\hat{\mathcal{V}}_1 \cup \hat{\mathcal{V}}_2] \text{ and } \mathcal{E}[\hat{\mathcal{W}}_1 \cup \hat{\mathcal{W}}_2] \text{ connected } \implies \mathcal{S}_E \neq \emptyset$$

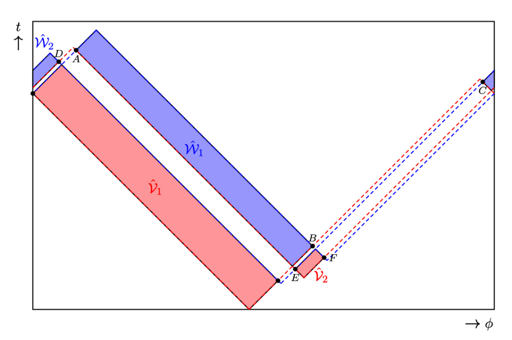
   using techniques from [May, Penington, Sorce '19]

2. We provide counter-examples for the reverse direction
3. We emphasize the difference in operational interpretation between bulk subregions $\mathcal{S}$ and $\mathcal{S}_E$

Reverse Direction: Counter-Examples

We consider the AdS$_3$ **conical defect**:

$$ds^2 = -(r^2 - M)dt^2 + \frac{dr^2}{r^2 - M} + r^2 d\phi^2 \,, \qquad -1 < M < 0$$

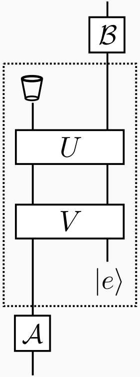


M	ϕ_B	ϕ_D	$\mathcal{E}[\hat{\mathcal{V}}_1 \cup \hat{\mathcal{V}}_2]$	$\mathcal{E}[\hat{\mathcal{W}}_1 \cup \hat{\mathcal{W}}_2]$	$\mathcal{S}_E$
-0.25	3.8	0.27	disc	disc	nonempty
-0.9	3.9	0.28	disc	disc	empty
-0.25	3.8	0.28	disc	conn	nonempty
-0.9	3.9	0.29	disc	conn	empty
-0.25	4.2	0.27	conn	disc	nonempty
-0.9	4.3	0.29	conn	disc	empty

The only logical dependence between predicates "$\mathcal{E}[\hat{\mathcal{V}}_1 \cup \hat{\mathcal{V}}_2]$ is connected", "$\mathcal{E}[\hat{\mathcal{W}}_1 \cup \hat{\mathcal{W}}_2]$ is connected", "$\mathcal{S}_E = \emptyset$", and their negations is the one we have proven.

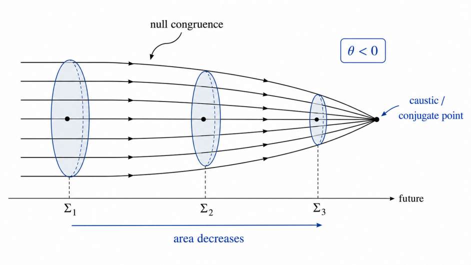
Interpretation & Outlook

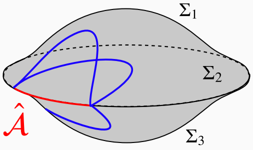
- Despite the close relationship between $\mathcal{S}$ and $\mathcal{S}_E$, they have **different operational interpretations**
- Suppose that Alice has access to $\hat{\mathcal{V}}_1 \cup \hat{\mathcal{V}}_2$, Bob has access to $\hat{\mathcal{W}}_1 \cup \hat{\mathcal{W}}_2$, and Eve has access to $\hat{\mathcal{X}}_1 \cup \hat{\mathcal{X}}_2 = (\hat{\mathcal{V}}_1 \cup \hat{\mathcal{V}}_2)'$
- As long as Eve can only apply **low-energy EFT operations**, she cannot interfere with information in the region $\mathcal{S}_E$, so Alice and Bob can use operators in the algebra of this region to encode/decode information when $\mathcal{S}_E \neq \emptyset$
- Our result: When Alice and Bob **both** have access to **non-locally generated operators**, they can do QEC for this class of low-energy error channels
- There appears to be an interesting connection between **causal structure** and **quantum error correction** in holography.



Proof Ingredients

Ingredient 1: The **focusing theorem** quantifies how light rays converge due to gravity, and gives rise to an **area theorem** for spatial slices of null surfaces





Ingredient 2: The **maximin prescription** of [Wall '12] identifies the Ryu-Takayanagi surface with the surface $m(\hat{\mathcal{A}})$ realizing

$$\max_{\Sigma} \min_{X_{\hat{\mathcal{A}}} \subset \Sigma} \text{Area}[X_{\hat{\mathcal{A}}}] \, ,$$

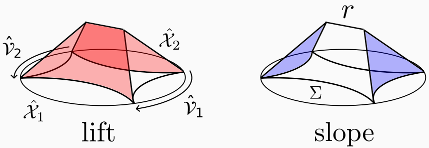
with Σ Cauchy slices and $X_{\hat{\mathcal{A}}} \sim \hat{\mathcal{A}}$ on Σ

Proof Sketch

Suppose by contradiction that $\mathcal{E}[\hat{\mathcal{V}}_1 \cup \hat{\mathcal{V}}_2]$ and $\mathcal{E}[\hat{\mathcal{W}}_1 \cup \hat{\mathcal{W}}_2]$ are connected but $\mathcal{S}_E$ is empty

Then one can construct a **null membrane** as follows:

- Shoot forward null sheets from the boundary of $\mathcal{E}[\hat{\mathcal{V}}_1 \cup \hat{\mathcal{V}}_2]$
- Shoot backward null sheets from the boundary of $\mathcal{E}[\hat{\mathcal{W}}_1 \cup \hat{\mathcal{W}}_2]$
- When points on two of these sheets are causally separated, keep only the past-most point
- Only keep points above the maximin slice Σ



The forward sheets will meet at a “ridge” r before being cut off by the backward sheets

Proof Sketch

The proof then proceeds as follows:

- Begin with the RT surface γ_1
- Focusing upward on the lift, Area$[\gamma_1] \geq$ Area$[\gamma_2]$
- Remove the "ridge" to obtain γ_2' with Area$[\gamma_2] >$ Area$[\gamma_2']$
- Focusing downward on the slope, Area$[\gamma_2'] \geq$ Area$[\gamma_3]$
- This contradicts the assumption that Σ is maximin