Entanglement, gravity and tensor networks

Review talk

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Strings 2016
Beijing
Motivation

• How does quantum gravity work?

Tool
Study patterns of entanglement.
Follow the qubit!
Motivation

• How does quantum gravity work?
• How are its degrees of freedom encoded?
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• How does holography work?
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• How does holography work?
• How do we describe the black hole interior?
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• Tool → Study patterns of entanglement.

→ Follow the qubit!
Outline

• Ancient concepts $\rightarrow$ quantum entropy
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• Ancient concepts → quantum entropy
• Quantum entropy in QFT.
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• Quantum entropy in QFT.
• Quantum entropy in semiclassical gravity
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- Ancient concepts ➔ quantum entropy
- Quantum entropy in QFT.
- Quantum entropy in semiclassical gravity
- Quantum entropy in holography
- Wormholes
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• Ancient concepts → quantum entropy
• Quantum entropy in QFT.
• Quantum entropy in semiclassical gravity
• Quantum entropy in holography
• Wormholes
• Tensor networks
Quantum entropy

- State $\rightarrow \rho$

\[ S = \text{Tr} \left[ \rho \log \rho \right] \]

$K = \log e = 1$
Quantum entropy

- State $\rightarrow \rho$
- Quantum entropy: $S = -Tr[\rho \log \rho]$
Quantum entropy

- State $\rightarrow \rho$
- Quantum entropy: $S = -Tr[\rho \log \rho]$

- Modular Hamiltonian.

$$K = -\log \rho \ , \quad \rho = e^{-K}$$

Makes the density matrix look "thermal"
• Relative entropy

\[ S(\rho|\sigma) = \text{Tr}[\rho \log \rho] - \text{Tr}[\rho \log \sigma] \]
• Relative entropy

\[
S(\rho|\sigma) = Tr[\rho \log \rho] - Tr[\rho \log \sigma]
\]

\[
= -\Delta S + \Delta K \sim \Delta F
\]

Looks like the “free energy”
Relative entropy

\[ S(\rho|\sigma) = Tr[\rho \log \rho] - Tr[\rho \log \sigma] \]

\[ = -\Delta S + \Delta K \sim \Delta F \]

Measure of the distinguishability of states

Looks like the "free energy"
• Relative entropy

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Looks like the "free energy"

Measure of the distinguishability of states

• Positivity \[ S(\rho|\sigma) \geq 0 \]
• Relative entropy

\[ S(\rho|\sigma) = Tr[\rho \log \rho] - Tr[\rho \log \sigma] = -\Delta S + \Delta K \sim \Delta F \]

Measure of the distinguishability of states

• Positivity \( S(\rho|\sigma) \geq 0 \)

• Monotonicity

\[ B \subset A \rightarrow S(\rho_B|\sigma_B) \leq S(\rho_A|\sigma_A) \]

Looking at less, we can distinguish less

Looks like the “free energy”
In quantum field theory
Entropy in QFT

• Quantum entropy of subregions.

\[ \text{A} = \text{Area} + \text{Finite results.} \]
Entropy in QFT

• Quantum entropy of subregions.

• Divergent

\[ S(A) = \frac{\text{Area}}{\epsilon^2} + \cdots + \text{Finite} \]
Entropy in QFT

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\[ S(A) = \frac{\text{Area}}{\varepsilon^2} + \cdots + \text{Finite} \]

• Interesting: Finite results.
Entropy in QFT

• Quantum entropy of subregions.

• Divergent

\[ S(A) = \frac{\text{Area}}{\varepsilon^2} + \cdots + \text{Finite} \]

• Interesting: Finite results.

• Recall the QFT is a “target” for what we should approximately get in the bulk.
Half space in relativistic QFT

- Half space $\rightarrow$ Thermal in Rindler space
- Consequence of the Lorentz symmetry

$$\rho = e^{-2\pi B}$$

$$B = \int_0^\infty d^{D-2}y dx x T_{00} = E_{\text{Rindler}}$$

Local Energy for accelerating observer
Entanglement $\rightarrow$ useful results in QFT
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• Bekenstein-Casini bound:

$$S'(\rho|\rho_v) \geq 0 \rightarrow \Delta S \leq 2\pi \langle \Delta B \rangle = 2\pi \langle \Delta E_R \rangle$$

Relative entropy is UV finite

Sorkin
Marolf, Minic Ross Casini
Entanglement $\rightarrow$ useful results in QFT

- Bekenstein-Casini bound:

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Relative entropy is UV finite

- c and f theorems (in 1+1 and 2+1 dimensions)

Source:
- Sorkin
- Marolf, Minic Ross Casini
- Casini Huerta
Entanglement $\rightarrow$ useful results in QFT

- Bekenstein-Casini bound:

\[ S(\rho | \rho_v) \geq 0 \quad \rightarrow \quad \Delta S \leq 2\pi \langle \Delta B \rangle = 2\pi \langle \Delta E_R \rangle \]

Relative entropy is UV finite

- c and f theorems (in 1+1 and 2+1 dimensions)

Sorkin
Marolf, Minic Ross
Casini

- Integrated null energy condition (integrated along a null line)

\[ \langle \int dx^- T_{--} (x^-, x^+, \vec{y}) \rangle \geq 0 \]

Casini Huerta

Faulkner, Leigh, Parrikar, Wang
Idea of the argument

\[ A \implies A \]

\[ A \implies B \]

\[ S(A \implies B, B) \]

\[ S(A \implies A, A) \]

\[ S(A \implies A \implies A, A) \]

\[ h_B A i = h_P + i_B B c h_K B i h_K A c i \]
Idea of the argument

$A^c \quad A$

$B^c \quad B$

$h_B: A \rightarrow B$

$h_B: B^c \rightarrow A$

$h_B: A^c \rightarrow B$

$h_B: B \rightarrow A^c$

$h_B: P \rightarrow A^c \\
= h_B: A \rightarrow B$

$B^c : A \rightarrow B$

$A^c : B^c \rightarrow A$

$B : B \rightarrow A^c$

$P : A \rightarrow B$

$A^c : B \rightarrow A$

$B^c : A^c \rightarrow B$

$B : P \rightarrow A^c$

$A^c : B^c \rightarrow A$

$B^c : B \rightarrow A^c$

$P : B \rightarrow A^c$

$h_B: A \rightarrow B$

$h_B: B^c \rightarrow A$

$h_B: A^c \rightarrow B$

$h_B: B \rightarrow A^c$

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Idea of the argument

\[ B \subset A \]
\[ A^c \subset B^c \]

\[ S(\rho_B, \sigma_B) \leq S(\rho_A, \sigma_A) \]
\[ S(\rho_{A^c|\sigma_{A^c}}) \leq S(\rho_{B^c|\sigma_{B^c}}) \]
Idea of the argument

$B \subset A$

$A^c \subset B^c$

$S(\rho_B, \sigma_B) \leq S(\rho_A, \sigma_A)$

$S(\rho_{A^c} | \sigma_{A^c}) \leq S(\rho_{B^c} | \sigma_{B^c})$

$\langle K_B \rangle - \langle K_{B^c} \rangle \leq \langle K_A \rangle - \langle K_{A^c} \rangle$
Idea of the argument

\[ B \subseteq A \]
\[ A^c \subseteq B^c \]
\[ S(\rho_B, \sigma_B) \leq S(\rho_A, \sigma_A) \]
\[ S(\rho_{A^c}, \sigma_{A^c}) \leq S(\rho_{B^c}, \sigma_{B^c}) \]
\[ \langle K_B \rangle - \langle K_{B^c} \rangle \leq \langle K_A \rangle - \langle K_{A^c} \rangle \]
\[ 0 \leq \langle B_A \rangle - \langle B_B \rangle = -\langle P_+ \rangle \Delta X^+ \]
Real arguments uses...
Shape dependence of the entropy

Small deformation from a spherical surface.

Leading quadratic dependence on the deformation:

Faulkner, Leigh, Parrikar

Shape dependence of the entropy

Small deformation from a spherical surface.

Leading quadratic dependence on the deformation:

Fixed by conformal symmetry and $C_T$, the vacuum two point function of the stress tensor.

Idea: Changing shape $\rightarrow$ changing metric $\rightarrow$ insertions of stress tensor

Faulkner, Leigh, Parrikar

Shape dependence of the entropy

Small deformation from a spherical surface.

Leading quadratic dependence on the deformation:

Fixed by conformal symmetry and $C_T$, the vacuum two point function of the stress tensor.

Idea: Changing shape $\rightarrow$ changing metric $\rightarrow$ insertions of stress tensor

Universality of corner entropy.

Faulkner, Leigh, Parrikar

Gauge fields and Edge Modes

Center variables = Electric field on the separating surface.
Gauge fields and Edge Modes

\[ H = \sum_q H^q_L \times H^{-q}_R \]

Splitting of Hilbert space in each charge sector.

\[ S = \sum_q -p_q Tr[\rho_q \log \rho_q] - p_q \log p_q \]

Donelly Wall Radicevic
Casini Huerta Rosabal
Hawking, Strominger, Perry Harlow

\[ \rho \rightarrow \rho_q, \rho_q \]
Gauge fields and Edge Modes

\[ H = \sum_q H^q_L \times H^{-q}_R \]

Splitting of Hilbert space in each charge sector.

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\[ S = \sum_q -p_q Tr[\rho_q \log \rho_q] - p_q \log p_q \]

Donelly Freidel

Expect a similar story for gravity: Electric field \( \rightarrow \) geometry of the surface
Gauge fields and Edge Modes

\[
H = \sum_q H^q_L \times H^{-q}_R
\]

Splitting of Hilbert space in each charge sector.

\[
\rho \rightarrow \rho_q, \rho^{-q}_q, \quad S = \sum_q \rho_q Tr[\rho_q \log \rho_q] - \rho_q \log \rho_q
\]

Consequences of this for UV finite quantities remain to be seen...
Quantum entropy in semiclassical gravity
Results in semiclassical gravity

• QFT in a gravitational background.
Results in semiclassical gravity

- QFT in a gravitational background.

- Corrections to black hole entropy. BPS, non BPS...

See eg. Sen et al
Results in semiclassical gravity

• QFT in a gravitational background.

• Corrections to black hole entropy. BPS, non BPS...

\[ S_{gen} = \frac{\text{Area}}{4G_N} + S_{ent} \]

See eg. Sen et al

Bombelli, Koul, Lee, Sorkin
Srednicki
Callan Wilzcek Larsen Holzey
Susskind Uglum
Solodhukin, Frolov, Fursaev ...

UV finite
Results in semiclassical gravity

- QFT in a gravitational background.

- Corrections to black hole entropy. BPS, non BPS...  
  \[ S_{gen} = \frac{\text{Area}}{4G_N} + S_{ent} \]

- Second law of thermodynamics, S increases (monotonicity of relative entropy)

See eg. Sen et al
Bombelli, Koul, Lee, Sorkin
Srednicki
Callan Wilzcek Larsen Holzey
Susskind Uglum
Solodhukin, Frolov,Fursaev .... 
UV finite

Hawking, Wall
Results in semiclassical gravity

- Better understanding of the quantum Bousso bound.
Classical Bousso bound

Set of null rays with negative expansion

\[ \theta = \frac{1}{A} \frac{dA}{d\lambda} \leq 0 \]
Classical Bousso bound

\[ \theta = \frac{1}{A} \frac{dA}{d\lambda} \leq 0 \]

\[ S \leq \frac{A_i - A_f}{4G_N} \]

Bousso
Flanagan, Marolf, Wald
Quantum Bousso Bound

• 2 versions

1) Bousso, Casini, Fischer, JM

2) Strominger, Thompson
   Bousso, Fischer, Leichenauer,
   Wall + Koeller
Quantum Bousso Bound

- Quantum focusing conjecture

Strominger, Thompson, Bousso, Fischer, Leichenauer, Wall + Koeller
• Classical focusing theorem

\[ \theta \equiv \frac{1}{A} \frac{dA}{d\lambda} \]

\[ \frac{d\theta}{d\lambda} \leq 0 , \quad \text{since} \quad T_{\lambda\lambda} \geq 0 \]
Quantum Focusing conjecture

- Define the "quantum expansion"

\[ \Theta \equiv \frac{1}{A} \frac{dS_{gen}}{d\lambda} \]  

Bousso, Fischer, Leichenauer, Wall + Koeller
Quantum Focusing conjecture

- Define the "quantum expansion"

\[ \Theta \equiv \frac{1}{A} \frac{dS_{gen}}{d\lambda} \]

- Conjecture

\[ \frac{d\Theta}{d\lambda} \leq 0 \]
Quantum Focusing conjecture

\[ S_{2,\text{gen}} \]

\[ S_{1,\text{gen}} \]

\[ \Theta \leq 0 \]

\[ \lambda \]

\[ \Delta S \leq \frac{\Delta A}{4G_N} \]

Classical Bousso bound

Bousso, Fischer, Leichenauer, Wall + Koeller
Quantum Focusing conjecture

\[ S_{2, \text{gen}} \]
\[ S_{1, \text{gen}} \]
\[ \Theta \leq 0 \]

Bousso, Fischer, Leichenauer, Wall + Koeller

\[ \implies \Delta S \leq \frac{\Delta A}{4G_N} \]

Classical Bousso bound

Weak gravity:

\[ \langle T_{--} \rangle \geq \frac{1}{2\pi} \lim_{A \to 0} \frac{S''_{out}}{A} \]

Quantum null energy condition. Proven in some cases.
Entanglement and holography
Entanglement in theories with gravity duals

\[ S = \frac{(\text{Area})_{\text{min}}}{4G_N} \]

Ryu Takayanagi
Hubeny, Rangamani, Takayanagi
Entanglement in theories with gravity duals

\[ S = \frac{(\text{Area})_{\text{min}} + \alpha'(\text{curvature}) + \cdots}{4G_N} + S_{\text{bulk}} + o(G_N) \]

Wald, Myers, Jacobson, …, Dong

Faulkner, Lewkowicz, JM Barrella, Dong, Hartnoll, Martin
Relative entropy

\[ S(\rho, \sigma) = S_{\text{bulk}}(\rho, \sigma) \]

\[ K = \frac{A}{4G_N} + K_{\text{bulk}} \]
Relative entropy

\[ S(\rho, \sigma) = S_{\text{bulk}}(\rho, \sigma) \]

\[ K = \frac{A}{4G_N} + K_{\text{bulk}} \]

Two points of view:

1- Only holds for restricted semiclassical states...

2 - All dof are visible in the bulk (cutoff independent indication that all of black hole entropy comes from the atmosphere)
Qualitative idea for black hole entropy

\[ S_{gen} = \frac{\text{Area}}{4G_N} + S_{ent} \]

As \( \varepsilon \to 0 \), area term goes to zero and all entropy is entanglement.

Is all of black hole entropy just bulk entanglement entropy, with a suitable cutoff?

This happens in "induced gravity theories" (not well defined)...

Conservative: do not mix the leading order with the subleading order...

Dreamer: figure out in what sense this is true....

\[ S(\rho, \sigma) = S_{\text{bulk}}(\rho, \sigma) \] Is a cutoff independent indication of this.
Einstein equations from the entanglement formula

Initially

Ryu-Takayanagi formula

Einstein’s equations
Einstein equations from the entanglement formula

Can go in the other direction

Ryu-Takayanagi formula $\rightarrow$ Einstein’s equations

Lashkari, McDermott, Van Raamsdonk, Faulkner, Guica, Hartman, Myers, Swingle
Jacobson (not in full generality yet...)
Wormholes
Wormholes and entangled states

Full Schwarzschild-AdS Geometry

\[ \text{Entangled state in two non-interacting CFT's.} \]

\[ |\Psi\rangle = \sum_n e^{-\beta E_n/2} |E_n\rangle^CPT_L \times |E_n\rangle^R \]
Wormhole physics

• Integrated null energy condition $\Rightarrow$ no signal propagation. (recall recent entanglement based proof)
Wormhole physics

• Integrated null energy condition $\rightarrow$ no signal propagation. (recall recent entanglement based proof)

• Allowing interactions between the two sides $\rightarrow$ can have negative energy $\rightarrow$ can get signal propagation.

Gao Jafferis Wall
Wormholes and entangled states

Interaction between the two sides for some time.

$$\lambda \int dt O_L(t) O_R(t)$$

Gao Jafferis Wall
Wormholes and entangled states

Gao Jafferis Wall

Interaction between the two sides for some time.

\[ \lambda \int dt O_L(t) O_R(t) \]
Wormholes and entangled states

Gao Jafferis

Interaction between the two sides for some time.

$$\lambda \int dt O_L(t) O_R(t)$$
• Connected with “black holes as mirrors”

Hayden Preskill

• If one has access to a state that is maximally entangled with a black hole, then information that is sent into the black hole can be recovered by looking at a small amount of Hawking radiation.
Wormholes and entangled states

Extracted Information

2\textsuperscript{nd} side is the quantum computer that extracts the information from the radiation
Not just entanglement entropy...
Entanglement wedge vs. causal wedge

\[ \frac{A_{RT}}{4G_N} \leq \frac{A_{\text{Causal wedge}}}{4G_N} \leq \frac{A_{\text{final}}}{4G_N} \]
Entanglement wedge vs. causal wedge

\[ \frac{A_{RT}}{4G_N} + S_{bulk} \leq \frac{A_{\text{Causal wedge}}}{4G_N} + S_{bulk} \leq \frac{A_{\text{final}}}{4G_N} + S_{bulk} \]

2nd Law
Different notions of entropy

\[
\frac{A_{RT}}{4G_N} + S_{bulk} \leq \frac{A_{\text{Causal wedge}}}{4G_N} + S_{bulk} \leq \frac{A_{\text{final}}}{4G_N} + S_{bulk}
\]

Fine grained entropy

These should be coarse grained entropies
Different notions of entropy

\[ \frac{A_{RT}}{4G_N} + S_{bulk} \leq \frac{A_{\text{Causal wedge}}}{4G_N} + S_{bulk} \leq \frac{A_{\text{final}}}{4G_N} + S_{bulk} \]

Fine grained entropy

These should be coarse grained entropies

Restrict the algebra of observables to gravity fields. Simple operators acting within a scrambling time

Entropy of the maximal entropy state compatible with the density matrix of the simple algebra...

Kelly, Wall, Papadodimas, Raju,....
Tensor Networks
Tensor Networks

• Method to write wavefunctions. Ansatz for the wavefunction.
Tensor Networks

• Method to write wavefunctions. Ansatz for the wavefunction.
• Wavefunction constructed out of simpler objects, out of simpler tensors.
Tensor Networks

- Method to write wavefunctions. Ansatz for the wavefunction.
- Wavefunction constructed out of simpler objects, out of simpler tensors.
- Originated as a numerical method.
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• Method to write wavefunctions. Ansatz for the wavefunction.
• Wavefunction constructed out of simpler objects, out of simpler tensors.
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• They embody the renormalization group.
Tensor Networks

• Method to write wavefunctions. Ansatz for the wavefunction.
• Wavefunction constructed out of simpler objects, out of simpler tensors.
• Originated as a numerical method.
• They embody the renormalization group.
• There are some qualitative similarities with gravity.
Examples

• Matrix product states.

\[ \Psi(s_1, s_2, \cdots, s_N) = Tr[T_{s_1} T_{s_2} \cdots T_{s_n}] \]

\[ T_{s_i} = (T_{s_i})^k \quad D \times D \text{ matrix} \]
Examples

- Matrix product states.

\[ \Psi(s_1, s_2, \cdots, s_N) = \text{Tr}[T_{s_1} T_{s_2} \cdots T_{s_N}] \]

\[ T_{s_i} = (T_{s_i})^k_l \quad D \times D \quad \text{matrix} \]

\[ 2D^2, \quad \text{or} \quad 2ND^2 \ll 2^N \]

Works for states with finite Amount of long range entanglement

Vertex = tensor
Open line = open index
Link = contracted index
Scale invariant wavefunctions

Each vertex is a five index tensor. Each line is an index contraction.
Can give rise to
The RT formula.

Does work for some
Tensors. Works too
well \rightarrow all Renyi entropies

Qualitatively similar to the bulk in AdS/CFT

Random tensors:
Hayden, Nezami, Qi, Thomas,
Walter, Yang

Swingle
As a unitary transformation
As a unitary transformation

Looks like de Sitter evolution.

Is expected: CFT in de Sitter conformal frame

\[ -dt^2 + dx^2 \rightarrow \frac{-dt^2 + dx^2}{t^2} \]

Connection to "kinematic space" (space of pairs of points)  

Could also use it as a representation of the cosmological wavefunction...

Czech, Lamrou, McCandish, Sully
Peeking into the interior
Thermal states

Spatial direction along horizon
Time evolution of thermofield double

Similar to the stretching of the geometry behind the horizon.

Hartman JM
What networks to choose?

• Choose "simple" elementary tensors = small tensors
What networks to choose?

• Choose ``simple” elementary tensors = small tensors
• View network as preparing the state by simple operations from a simple product state.
What networks to choose?

• Choose "simple" elementary tensors = small tensors

• View network as preparing the state by simple operations from a simple product state.

• Complexity = number of simple gates
Complexity = Action?

- Complexity = action of the WdW patch?

Brown, Roberts, Susskind, Swingle, Zhao

Wheeler de Wit patch

$\mathcal{L}_R \rightarrow \mathcal{L}_L$
Complexity = Action?

- Complexity = action of the WdW patch?

Wheeler de Wit patch

\[ t_R \quad t_L \]

Brown, Roberts, Susskind, Swingle, Zhao

Nice qualitative agreement → time dependence

Singularity?

Other physical interpretation?
Tensor networks and the holographic encoding

Tensor network is an encoding of the bulk into the boundary

$\mathcal{H}_{\text{Bulk}} \rightarrow \mathcal{H}_{\text{Boundary}}$
• Capture many qualitative features!

• Local lorentz invariance in the bulk?
Conclusions

• Quantum entropy is a tool to prove general results in QFTs (lorentz invariance is non-trivial!).
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• Gravity + QFT $\rightarrow$ interesting entropy statements, which are being proved. $2^{\text{nd}}$ Law. Bousso bound. Holographic entanglement formulas...
Conclusions

• Quantum entropy is a tool to prove general results in QFTs (lorentz invariance is non-trivial!).

• Gravity + QFT → interesting entropy statements, which are being proved. 2nd Law. Bousso bound. Holographic entanglement formulas...

• Weird wormholes → help constrain how spacetime emerges.
Conclusions

• Quantum entropy is a tool to prove general results in QFTs (lorentz invariance is non-trivial!).

• Gravity + QFT → interesting entropy statements, which are being proved. 2\textsuperscript{nd} Law. Bousso bound. Holographic entanglement formulas...

• Weird wormholes → help constrain how spacetime emerges.

• Tensor networks capture interesting properties of black hole geometries. (But not local bulk lorentz invariance, so far...)
End