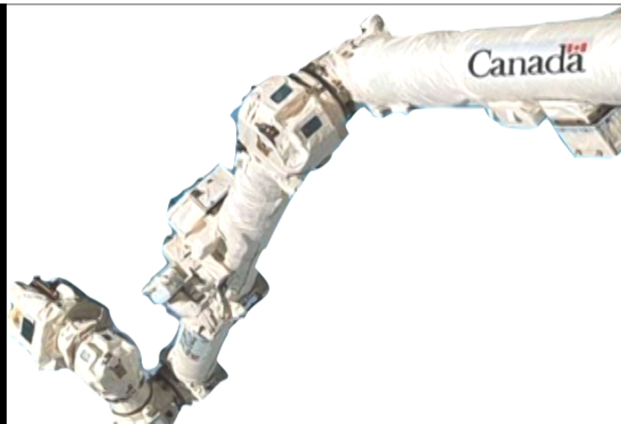
Title: Black Holes and Quantum Computation

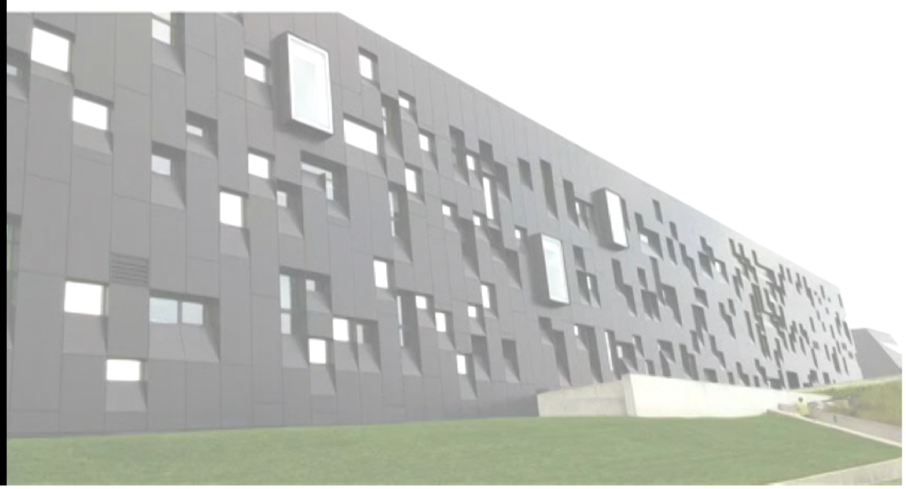
Date: Jan 17, 2018 02:00 PM

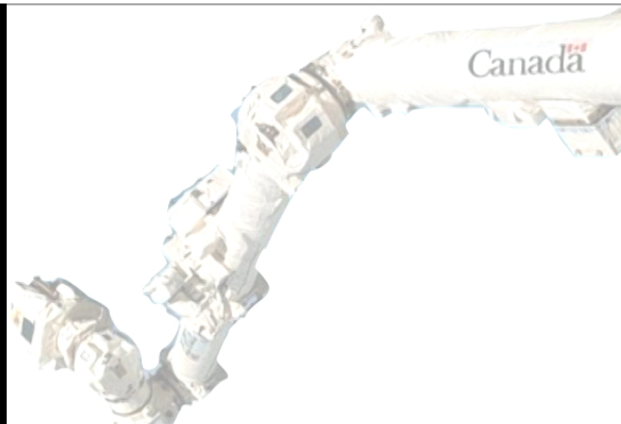
URL: http://pirsa.org/18010071

Abstract: <p>I will discuss the `holographic complexity conjecture', that seeks to relate the size of the wormhole that lies behind a black hole horizon to quantum computational complexity.</p>



Complexity and Spacetime





holographic
duality

Complexity and Spacetime

holographic duality

boundary (CFT)

bulk (AdS)

Complexity and Spacetime

holographic
duality

boundary (CFT)

bulk (AdS)

Complexity and Spacetime

classical property
gravitational theory

holographic
duality

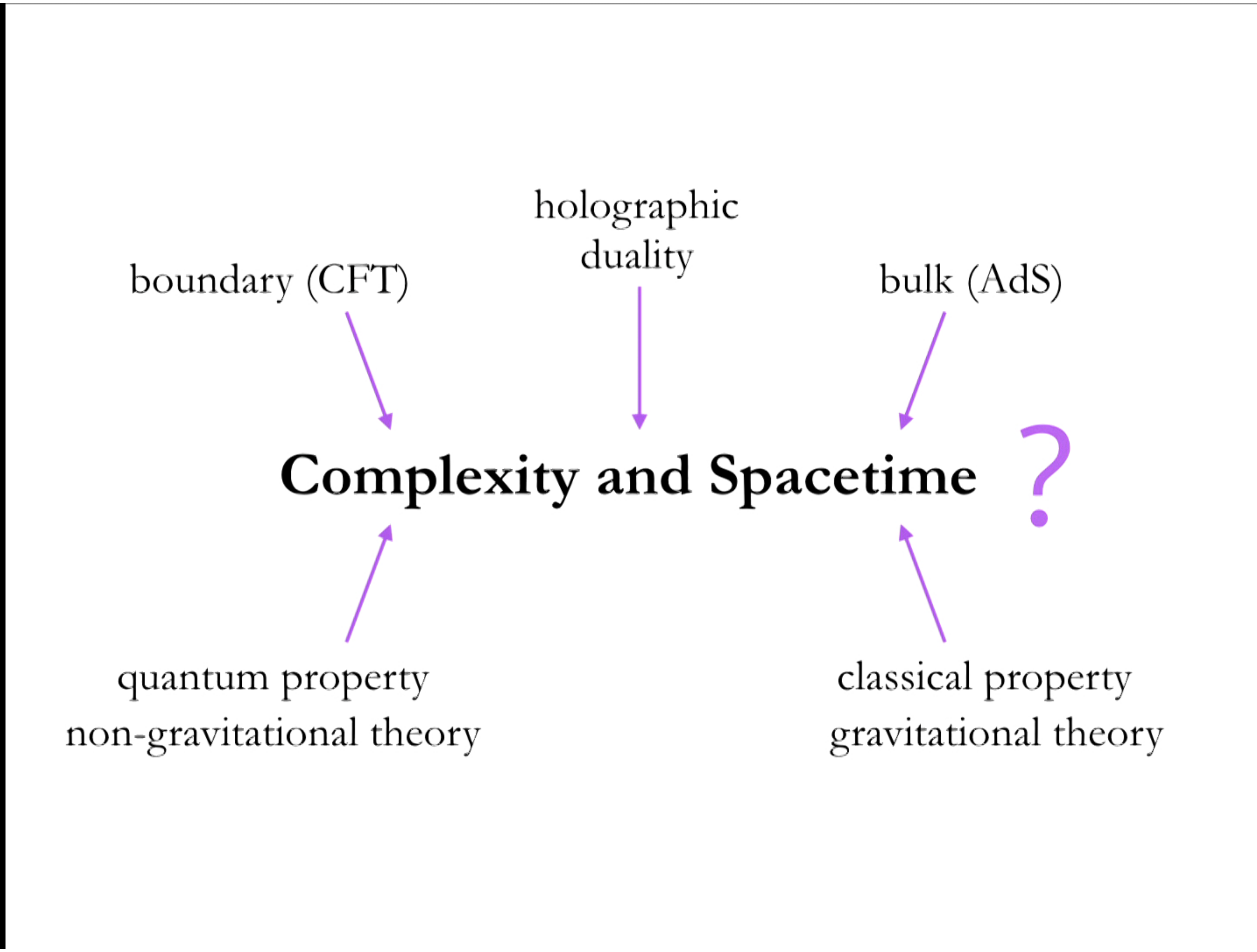
boundary (CFT)

bulk (AdS)

Complexity and Spacetime

quantum property
non-gravitational theory

classical property
gravitational theory


holographic duality
boundary (CFT)
bulk (AdS)
Complexity and Spacetime
?
quantum property
non-gravitational theory
classical property
gravitational theory

holographic duality

boundary (CFT)

bulk (AdS)

Complexity and Spacetime ?

quantum property
non-gravitational theory

classical property
gravitational theory

contributors include:

Leonard Susskind, Douglas Stanford, Daniel Roberts, Brian Swingle, Ying Zhao, Dean Carmi, Shira Chapman, Robert Jefferson, Luis Lehner, Hugo Marrochio, Rob Myers, Eric Poisson, Pratik Rath, Rafael Sorkin, Sotaro Sugishita, Beni Yoshida, Shan-Ming Ruan, Juan Pablo Hernandez

Complexity and Spacetime

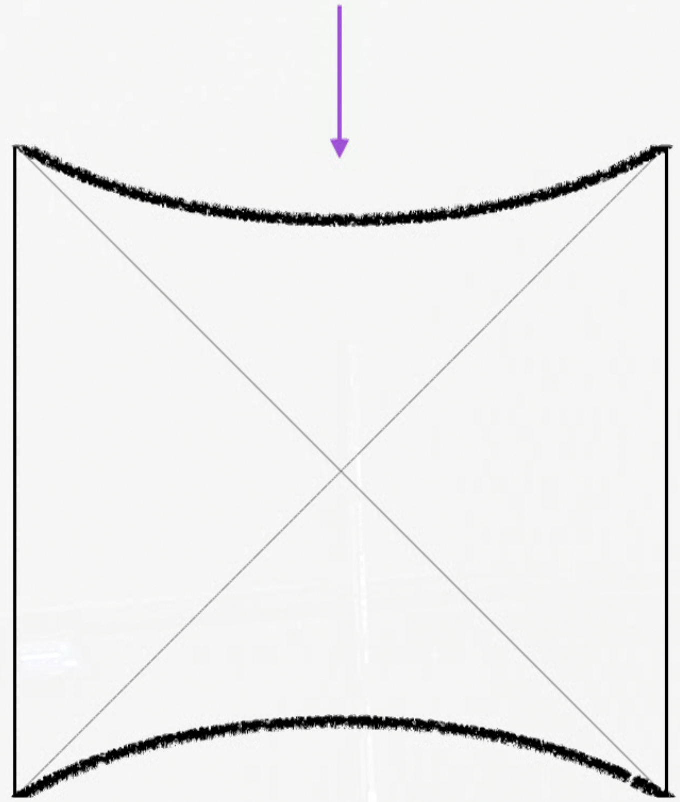
'size' of wormhole
for black hole in AdS

classical property
gravitational theory

contributors include:

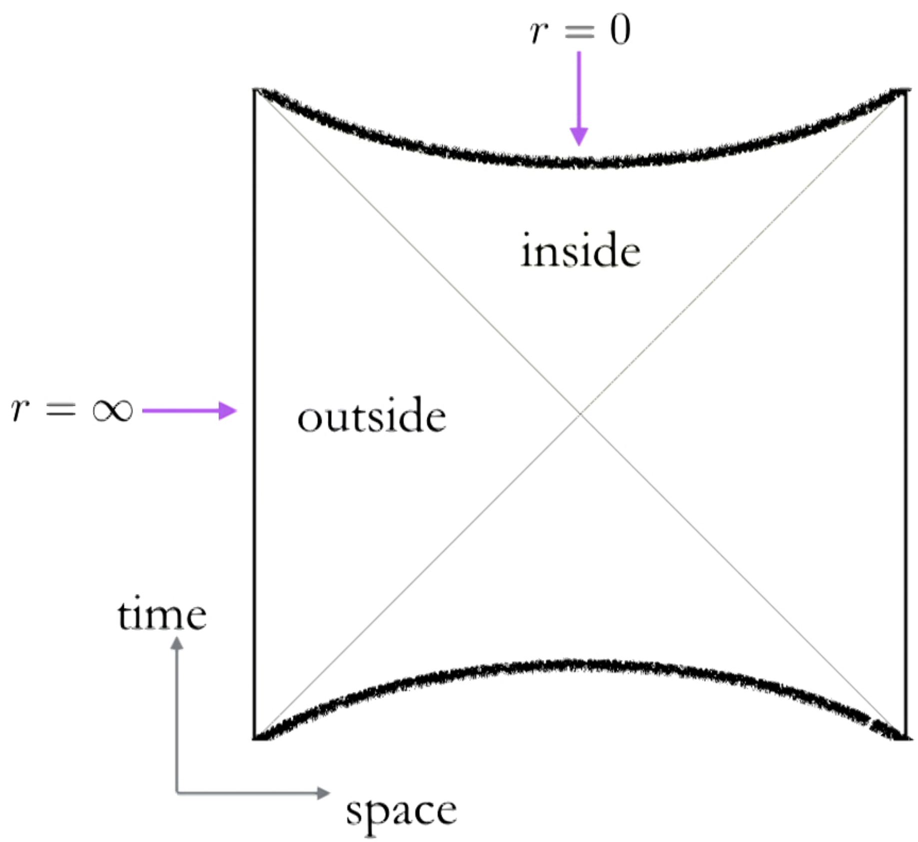
Leonard Susskind, Douglas Stanford, Daniel Roberts, Brian Swingle, Ying Zhao, Dean Carmi, Shira Chapman, Robert Jefferson, Luis Lehner, Hugo Marrochio, Rob Myers, Eric Poisson, Pratik Rath, Rafael Sorkin, Sotaro Sugishita, Beni Yoshida, Shan-Ming Ruan, Juan Pablo Hernandez

'size' of wormhole
for black hole in AdS



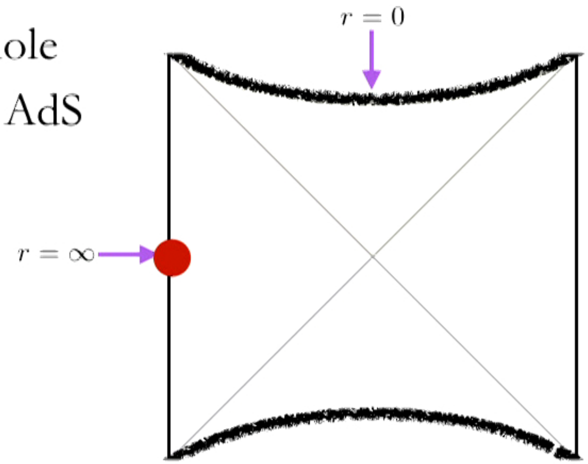
$$-\left(1-\frac{2GM}{r}+\frac{r^2}{L^2}\right)dt^2 + \frac{dr^2}{1-\frac{2GM}{r}+\frac{r^2}{L^2}} + r^2 d\Omega^2$$

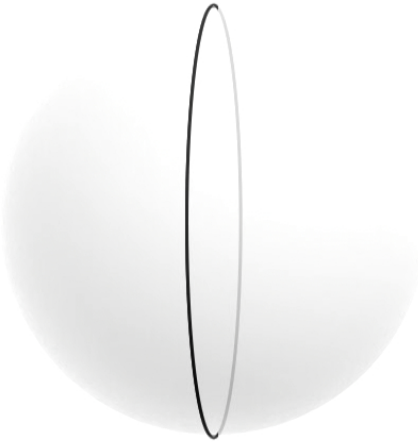
‘size’ of wormhole for black hole in AdS



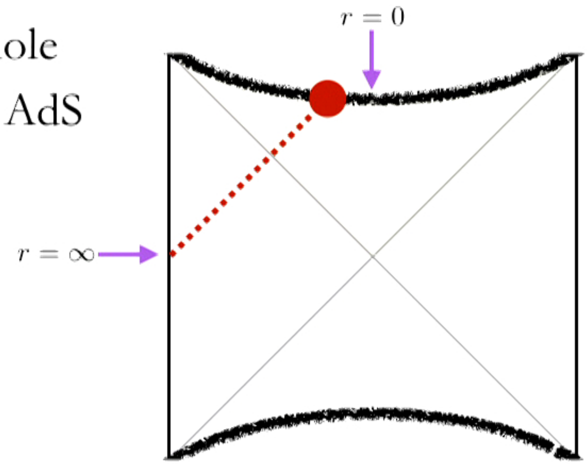
'size' of wormhole

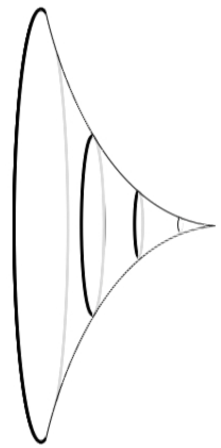
for black hole in AdS



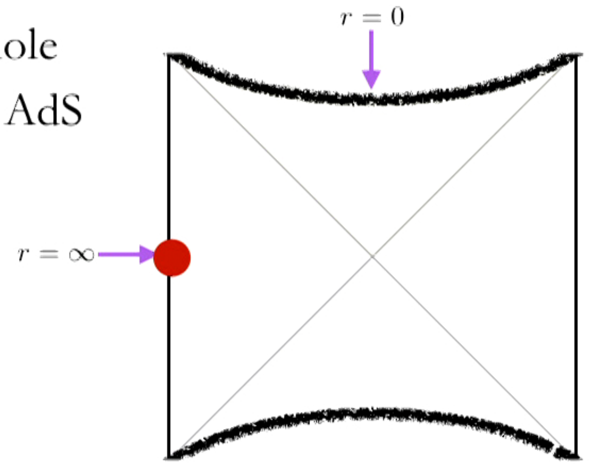


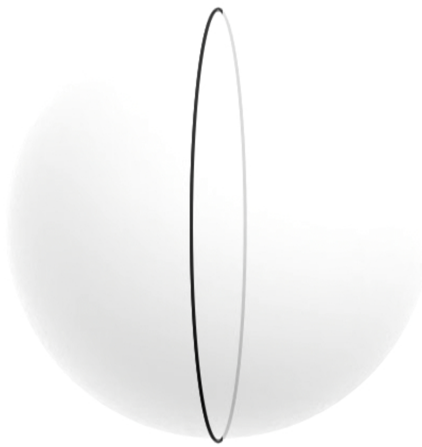
‘size’ of wormhole
for black hole in AdS



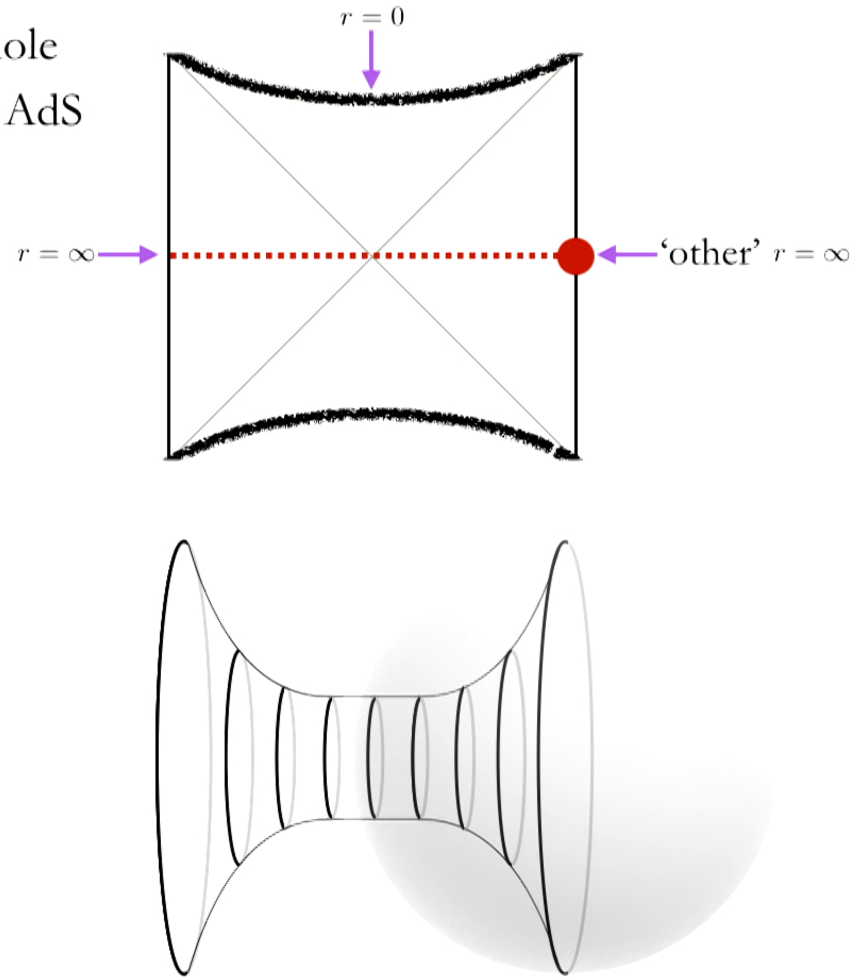


‘size’ of wormhole
for black hole in AdS

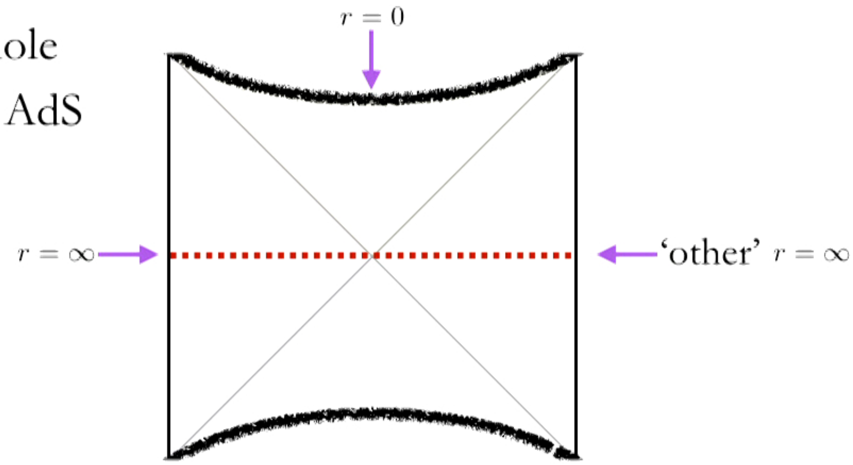


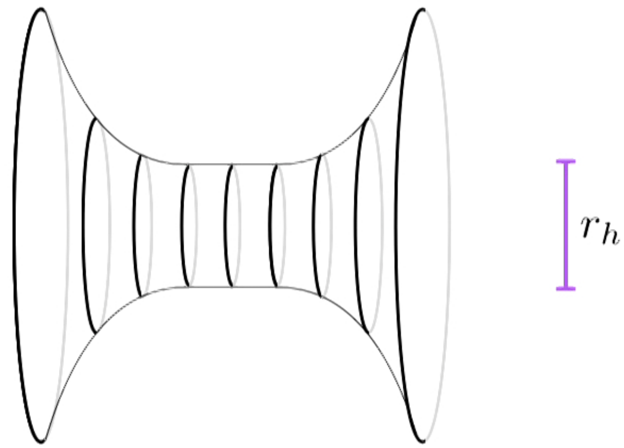


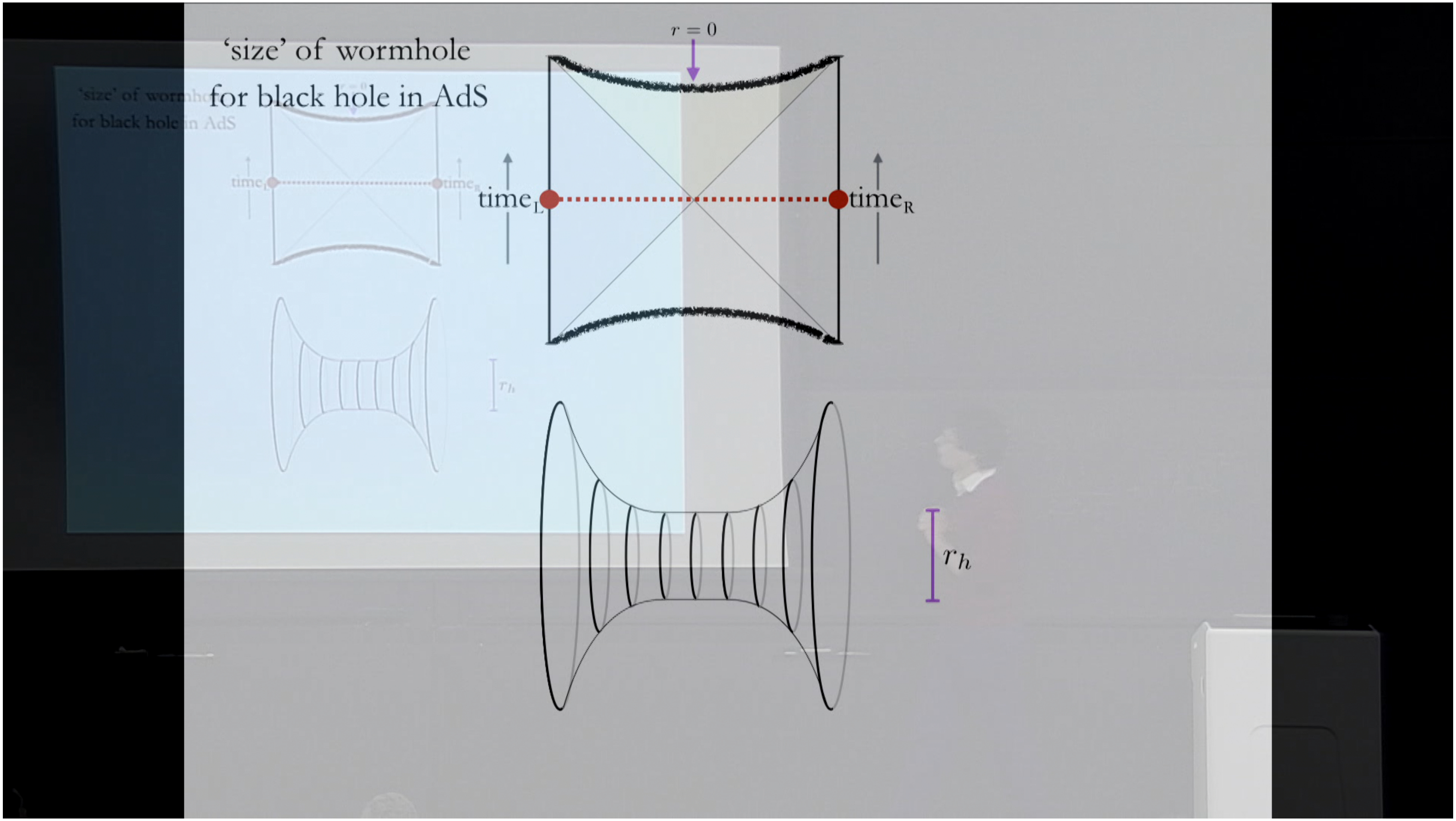
'size' of wormhole
for black hole in AdS



‘size’ of wormhole
for black hole in AdS

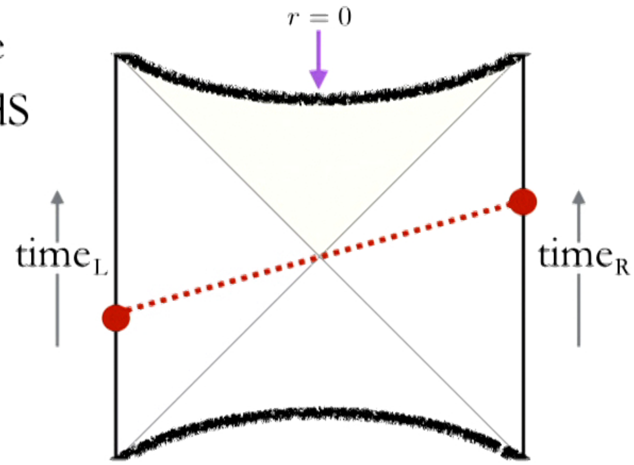


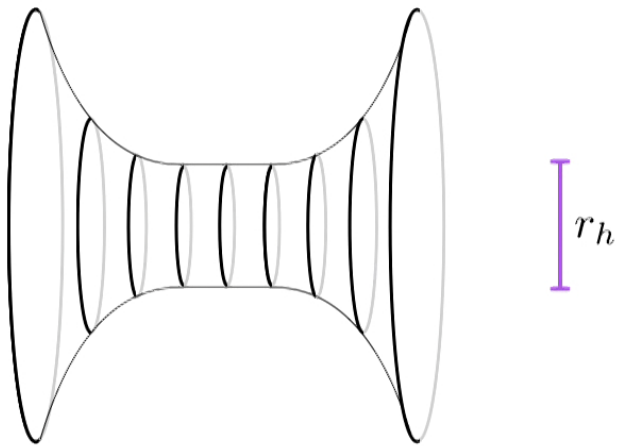




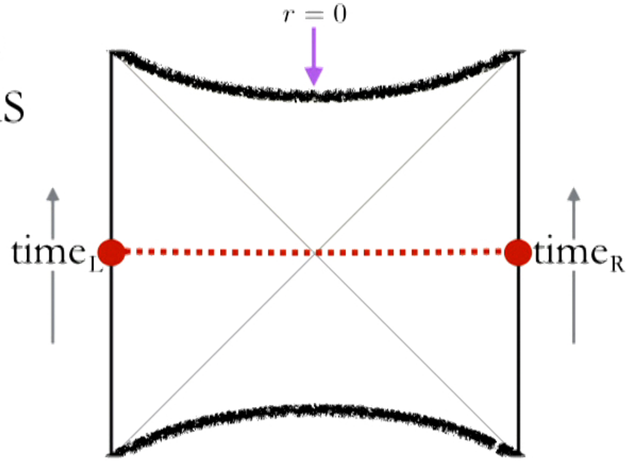
'size' of wormhole
for black hole in AdS
$r = 0$
time_L
time_R
r_h

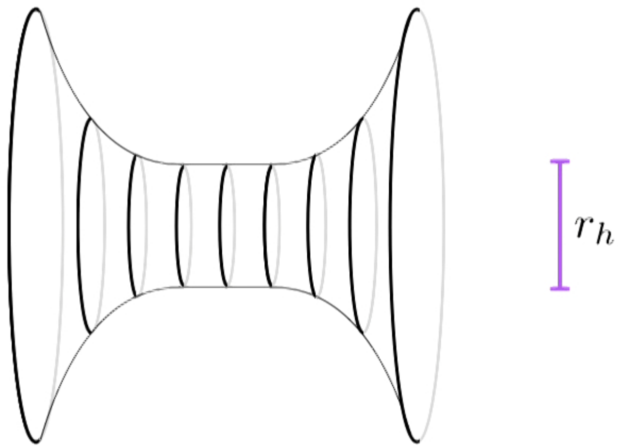
‘size’ of wormhole for black hole in AdS



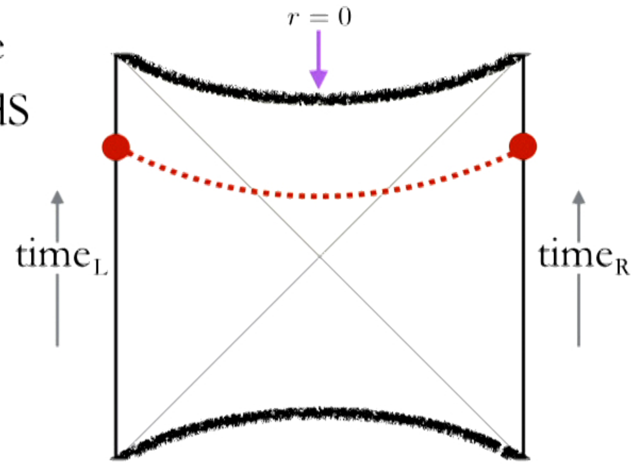


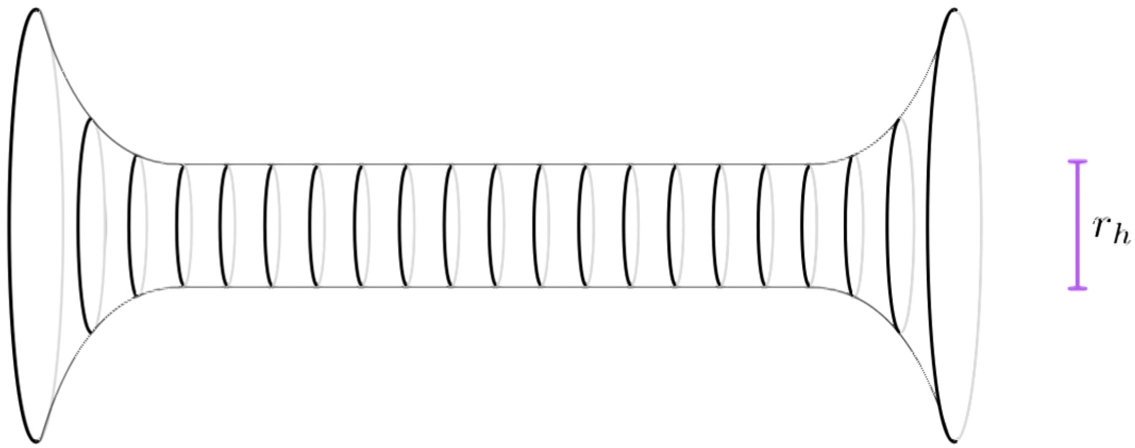
‘size’ of wormhole
for black hole in AdS





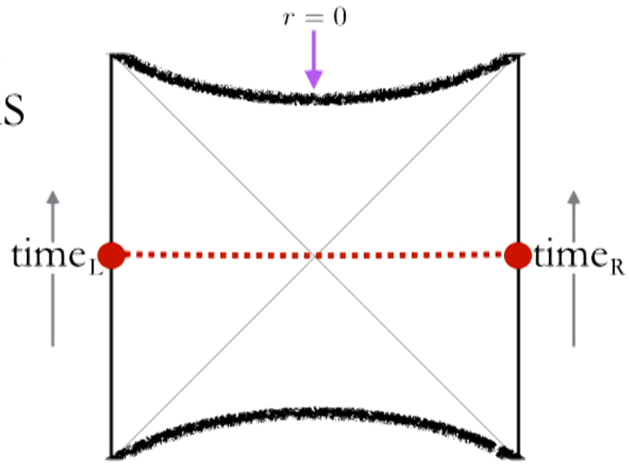
'size' of wormhole
for black hole in AdS

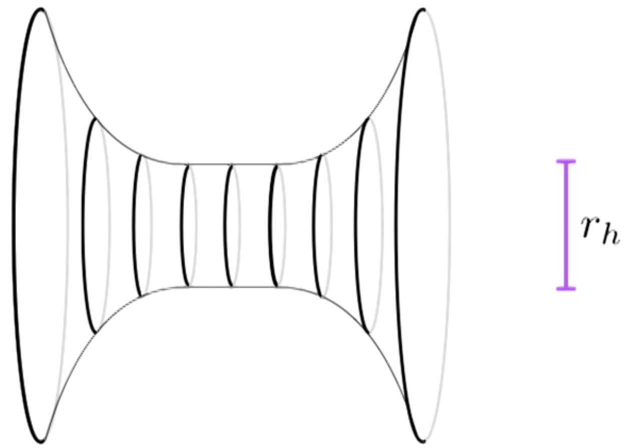




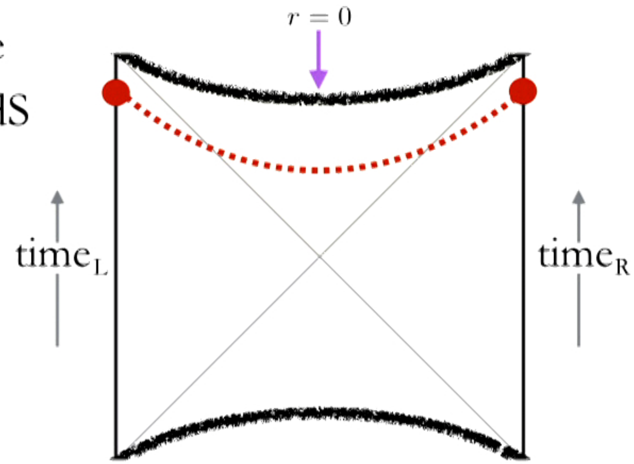
'size' of wormhole

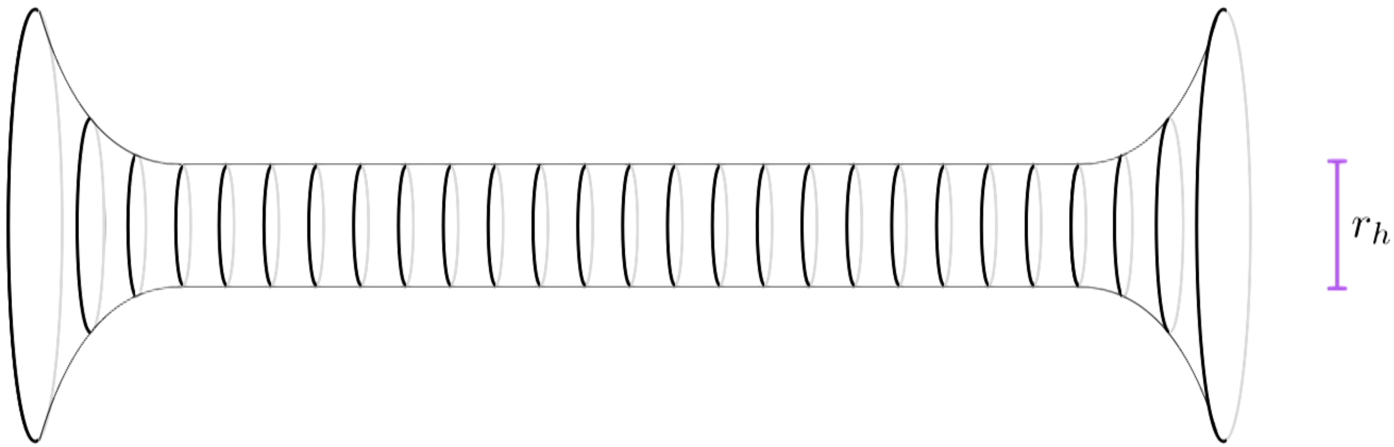
for black hole in AdS





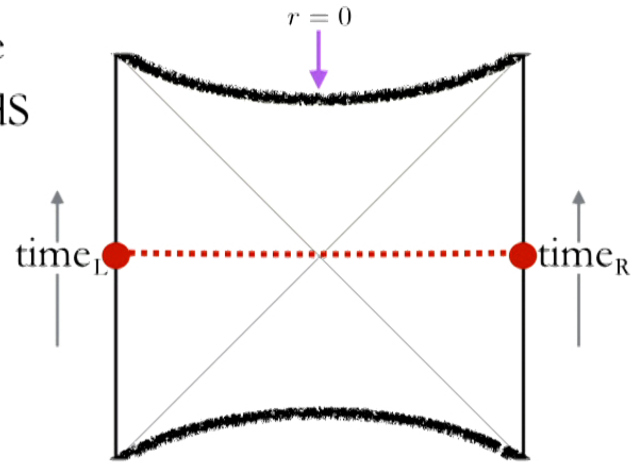
‘size’ of wormhole
for black hole in AdS

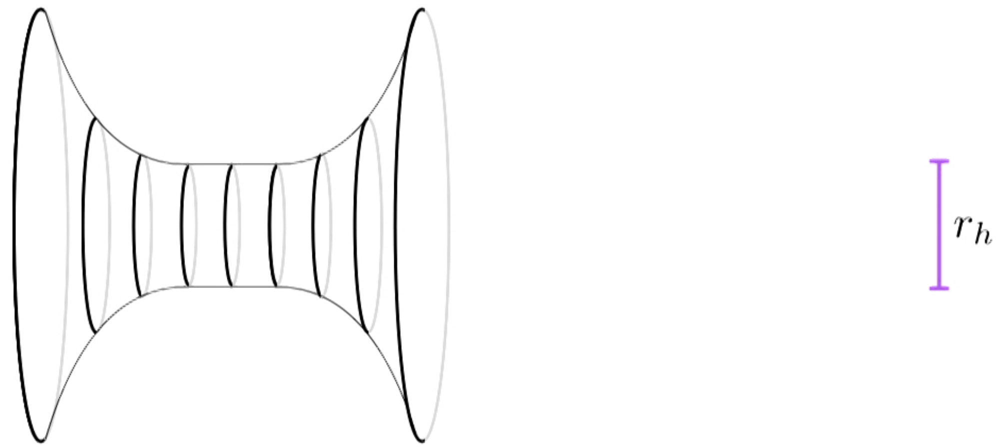




wormhole length $\sim t_L + t_R$

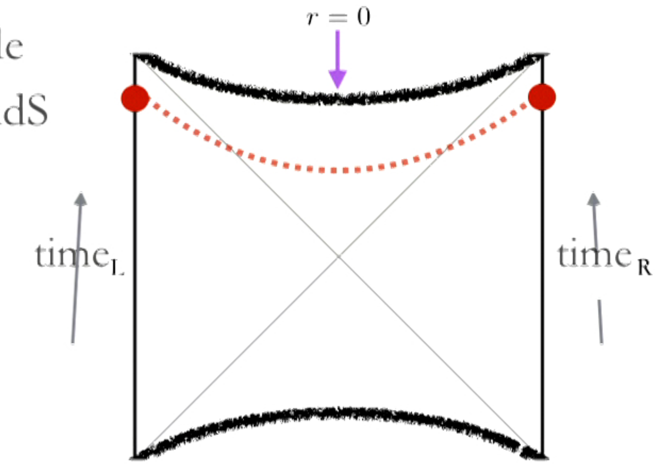
‘size’ of wormhole
for black hole in AdS

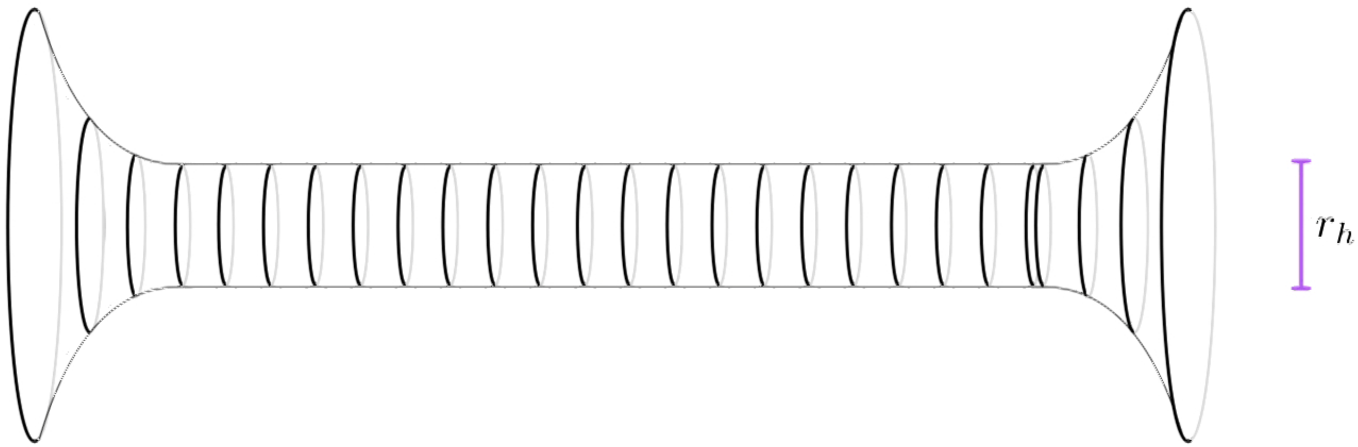




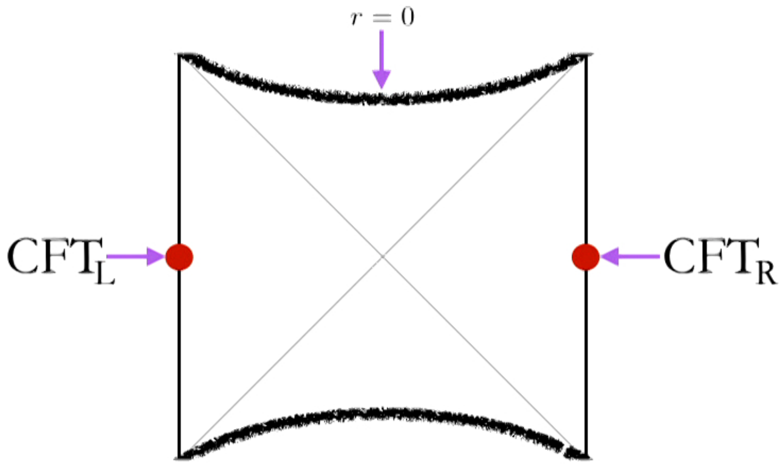
wormhole length $\sim t_L + t_R$

‘size’ of wormhole
for black hole in AdS

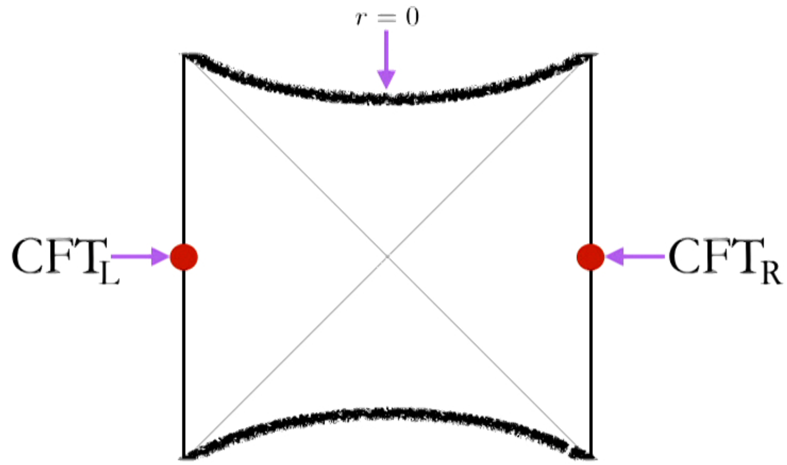




wormhole length $\sim t_L + t_R$

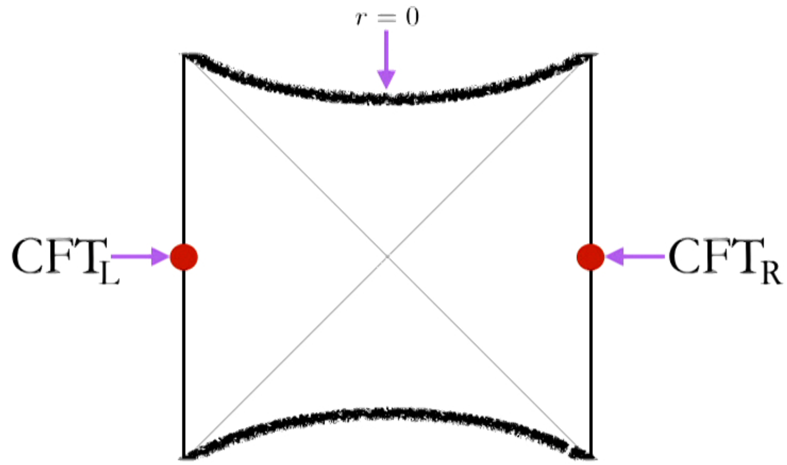


wormhole length $\sim t_L + t_R$



$$|\mathrm{TFD}\rangle = \sum_i e^{-\beta E_i/2}|E_i\rangle_L|E_i\rangle_R$$

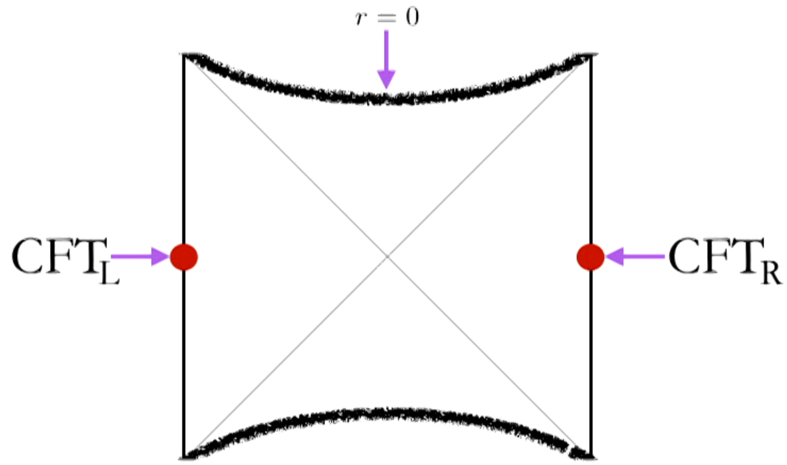
$$\text{wormhole length} \sim t_L + t_R$$



$$|\mathrm{TFD}\rangle = \sum_i e^{-\beta E_i/2}|E_i\rangle_L|E_i\rangle_R$$

$$|\psi(t_L,t_R)\rangle = \sum_i e^{-\beta E_i/2+iE_i(t_L+t_R)}|E_i\rangle_L|E_i\rangle_R$$

$$\text{wormhole length} \sim t_L + t_R$$



$$|\mathrm{TFD}\rangle = \sum_i e^{-\beta E_i/2} |E_i\rangle_L |E_i\rangle_R$$

$$|\psi(t_L, t_R)\rangle = \sum_i e^{-\beta E_i/2 + iE_i(t_L+t_R)} |E_i\rangle_L |E_i\rangle_R$$

What is CFT dual to linear growth of wormhole?

$$\text{wormhole length} \sim t_L + t_R$$

COMPLEXITY?

computational complexity of a quantum state

COMPLEXITY?

computational complexity of a quantum state

e.g. $|\psi(t_L, t_R)\rangle = \sum_i e^{-\beta E_i/2 + iE_i(t_L+t_R)} |E_i\rangle_L |E_i\rangle_R$

COMPLEXITY?

computational complexity of a quantum state

$$\text{e.g. } |\psi(t_L, t_R)\rangle = \sum_i e^{-\beta E_i/2 + iE_i(t_L+t_R)} |E_i\rangle_L |E_i\rangle_R$$

DEFINITION?

 $\otimes |\uparrow\rangle$

 $\otimes |\downarrow\rangle$

COMPLEXITY?

computational complexity of a quantum state

e.g. $|\psi(t_L,t_R)\rangle = \sum_i e^{-\beta E_i/2 + iE_i(t_L+t_R)} |E_i\rangle_L |E_i\rangle_R$

DEFINITION? starting in a reference state

e.g. $|\mathrm{TFD}\rangle = \sum_i e^{-\beta E_i/2} |E_i\rangle_L |E_i\rangle_R$

how many fundamental gates

e.g. unitaries each of which
act only on two-qubits

are needed to make target state

e.g. to within an accuracy ϵ

COMPLEXITY?

computational complexity of a quantum state

e.g. $|\psi(t_L, t_R)\rangle = \sum_i e^{-\beta E_i/2 + iE_i(t_L+t_R)} |E_i\rangle_L |E_i\rangle_R$

DEFINITION? starting in a reference state

e.g. $|\mathrm{TFD}\rangle = \sum_i e^{-\beta E_i/2} |E_i\rangle_L |E_i\rangle_R$

how many fundamental gates

e.g. unitaries each of which act only on two-qubits

are needed to make target state

e.g. to within an accuracy ϵ

computational complexity of a quantum state

how many fundamental gates

starting in a reference state are needed to make target state

computational complexity of a classical state

how many fundamental gates

starting in a reference state are needed to make target state

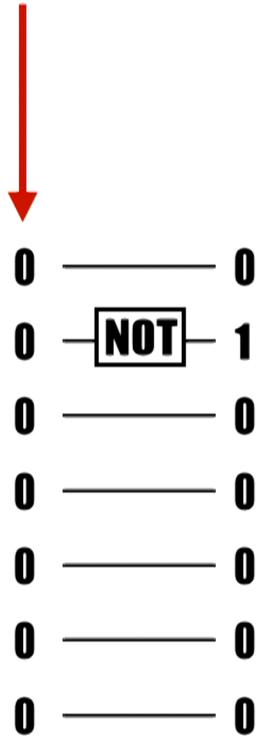
0
0
0
0
0
0
0

computational complexity of a classical state

how many fundamental gates

starting in a reference state

are needed to make target state

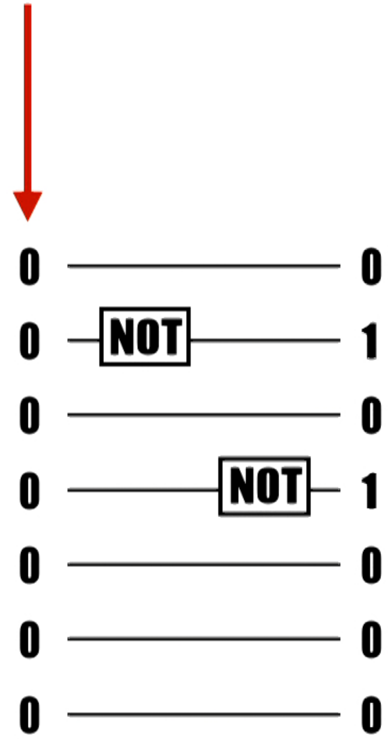


computational complexity of a classical state

how many fundamental gates

starting in a reference state

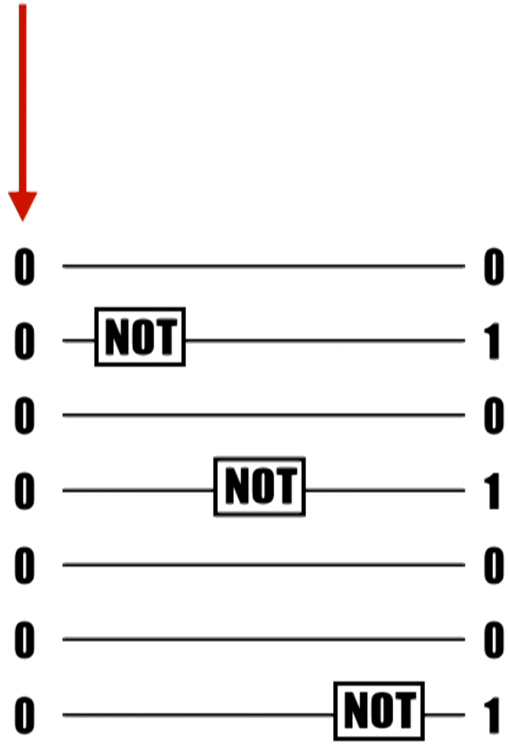
are needed to make target state



computational complexity of a classical state

how many fundamental gates

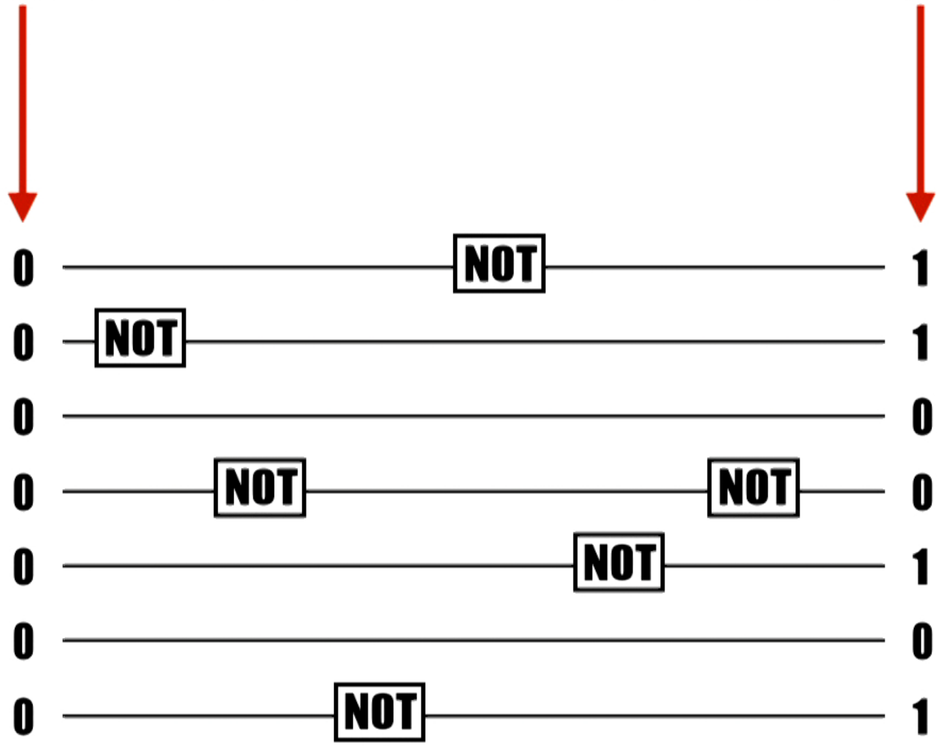
starting in a reference state are needed to make target state



computational complexity of a classical state

how many fundamental gates

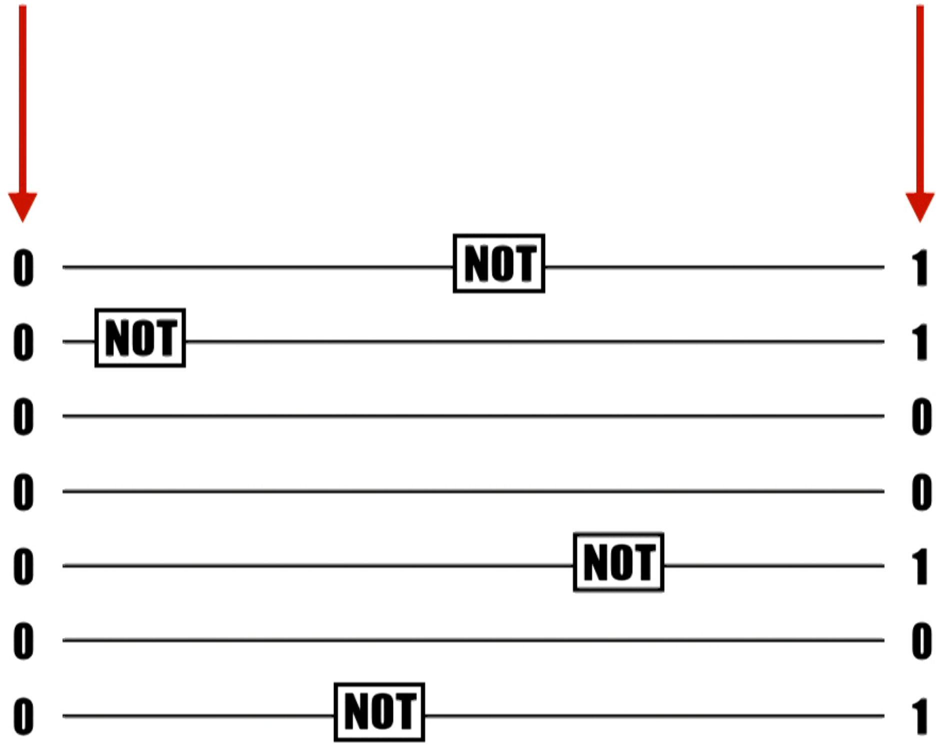
starting in a reference state   are needed to make target state



computational complexity of a classical state

how many fundamental gates

starting in a reference state are needed to make target state



computational complexity of a quantum state

how many fundamental gates

starting in a reference state

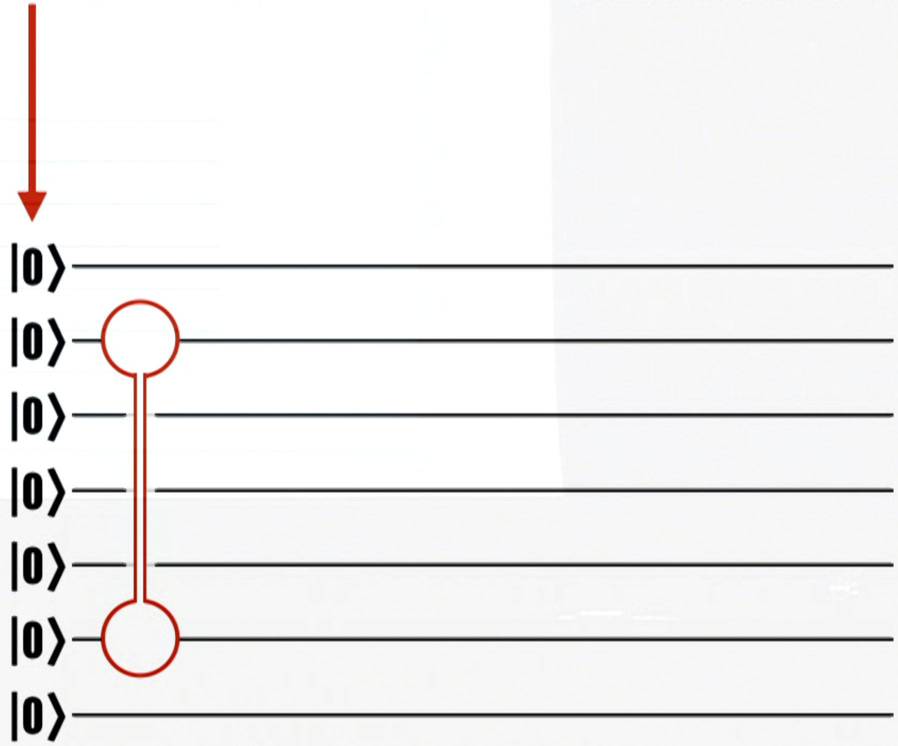
are needed to make target state (to within ϵ)

computational complexity of a quantum state

how many fundamental gates

starting in a reference state

are needed to make target state (to within ϵ)



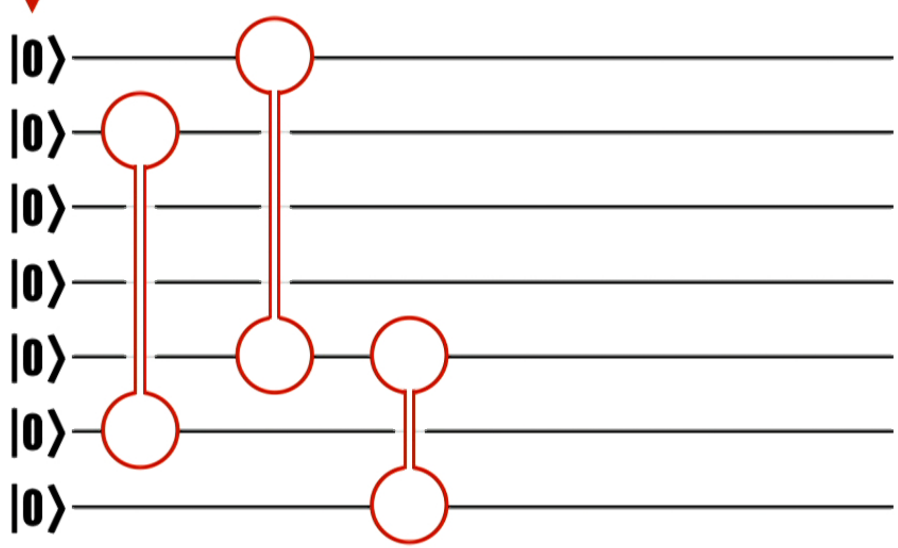
computational complexity of a quantum state

how many fundamental gates

starting in a reference state

are needed to make target state

(to within ϵ)



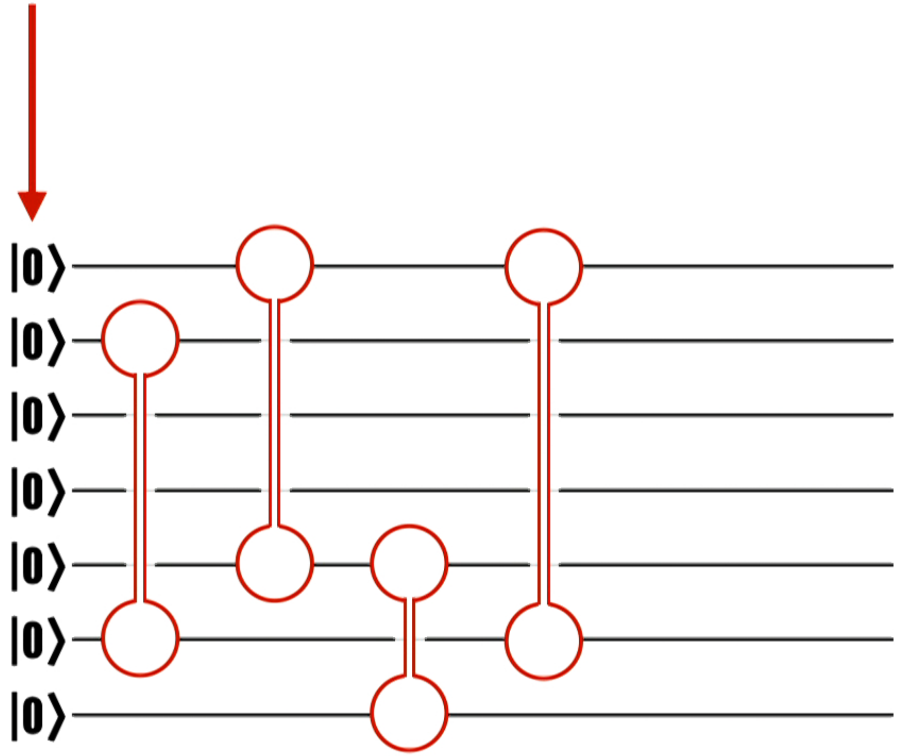
computational complexity of a quantum state

how many fundamental gates

starting in a reference state

are needed to make target state

(to within ϵ)

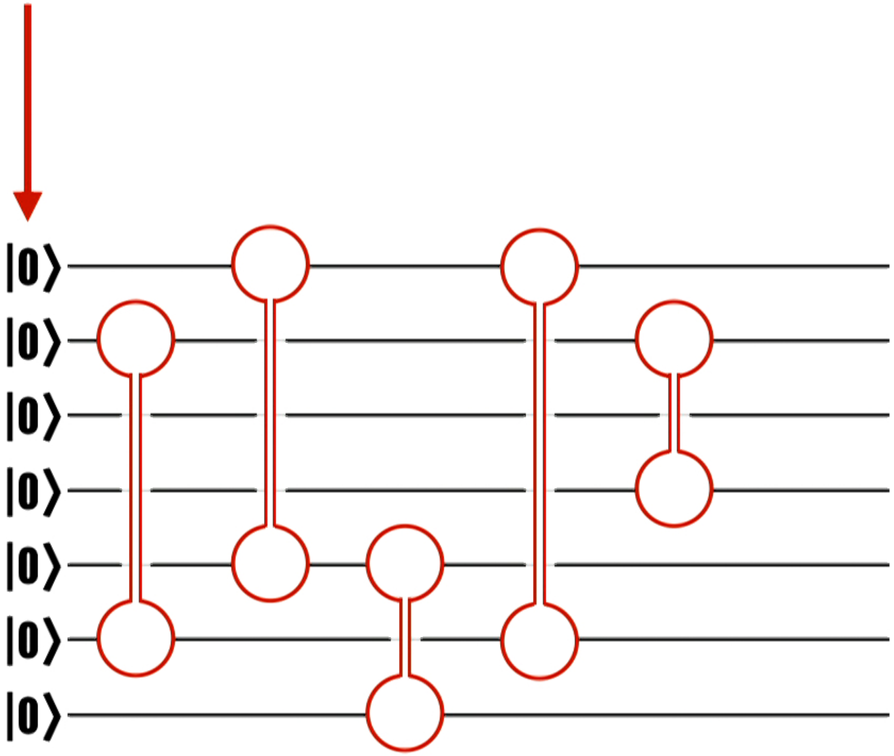


computational complexity of a quantum state

how many fundamental gates

starting in a reference state

are needed to make target state
(to within ϵ)

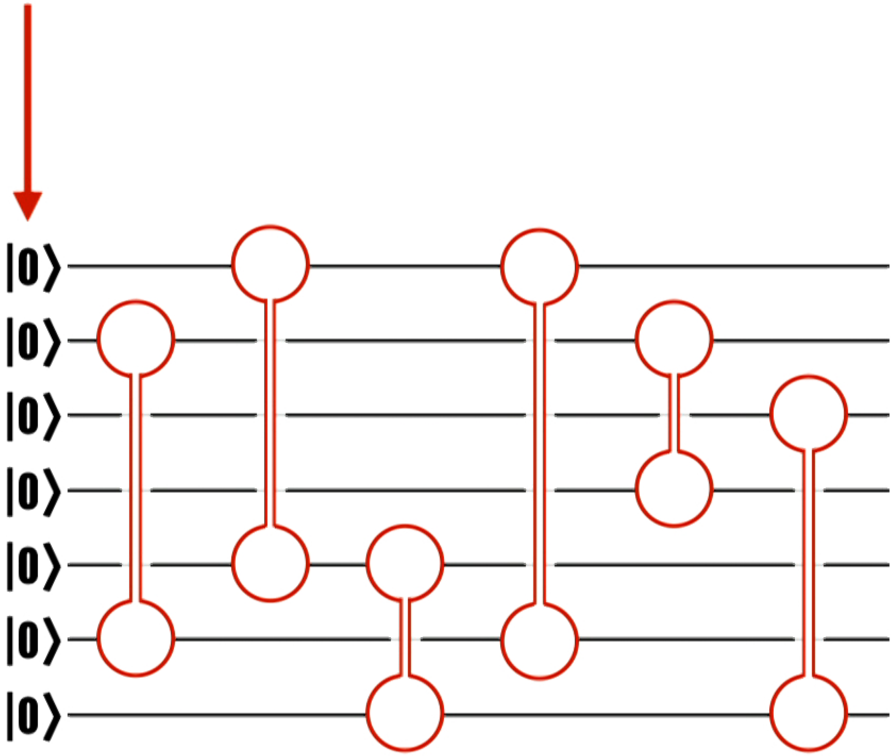


computational complexity of a quantum state

how many fundamental gates

starting in a reference state

are needed to make target state (to within ϵ)



computational complexity of a quantum state

e.g. $|\psi(t_L, t_R)\rangle = \sum_i e^{-\beta E_i/2 + iE_i(t_L+t_R)} |E_i\rangle_L |E_i\rangle_R$

DEFINITION: starting in a reference state

e.g. $|\mathrm{TFD}\rangle = \sum_i e^{-\beta E_i/2} |E_i\rangle_L |E_i\rangle_R$

how many fundamental gates

e.g. unitaries each of which act only on two-qubits

are needed to make target state

e.g. to within an accuracy ϵ

computational complexity of a quantum state

e.g. $|\psi(t_L, t_R)\rangle = \sum_i e^{-\beta E_i/2 + iE_i(t_L+t_R)} |E_i\rangle_L |E_i\rangle_R$

DEFINITION: starting in a reference state

e.g. $|\text{TFD}\rangle = \sum_i e^{-\beta E_i/2} |E_i\rangle_L |E_i\rangle_R$

how many fundamental gates

e.g. unitaries each of which act only on two-qubits

are needed to make target state

e.g. to within an accuracy ϵ

evolution of complexity?

evolution of complexity?

CLASSICAL (N bits)

e.g. 01110100

CLASSICAL (N bits)

e.g. 01110100

$\#$ classical states $= 2^N$

CLASSICAL (N bits)

e.g. 01110100

$\#$ classical states $= 2^N$

$$\mathcal{C}_{\max} = N$$

CLASSICAL (N bits)

e.g. 01110100

$$\#\ \text{classical states} = 2^N$$

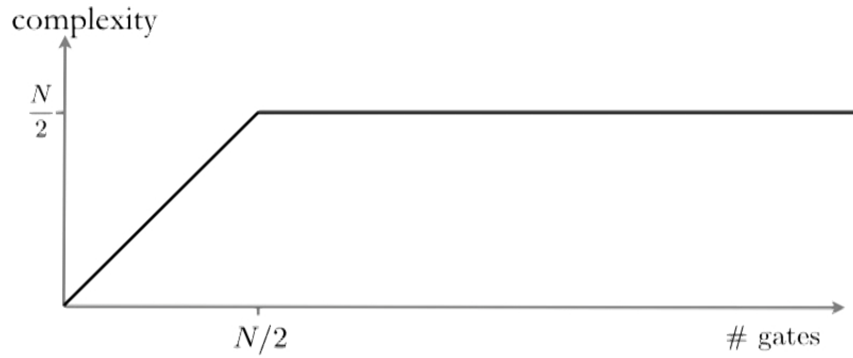
$$\mathcal{C}_{\max} = N$$

CLASSICAL (N bits)

e.g. 01110100

$$\#\text{ classical states} = 2^N$$

$$\mathcal{C}_{\max} = N$$

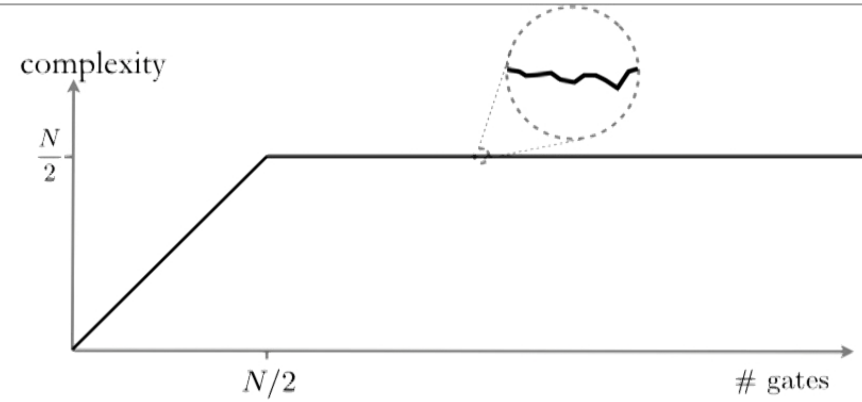


CLASSICAL (N bits)

e.g. 01110100

$\#$ classical states $= 2^N$

$\mathcal{C}_{\max} = N$

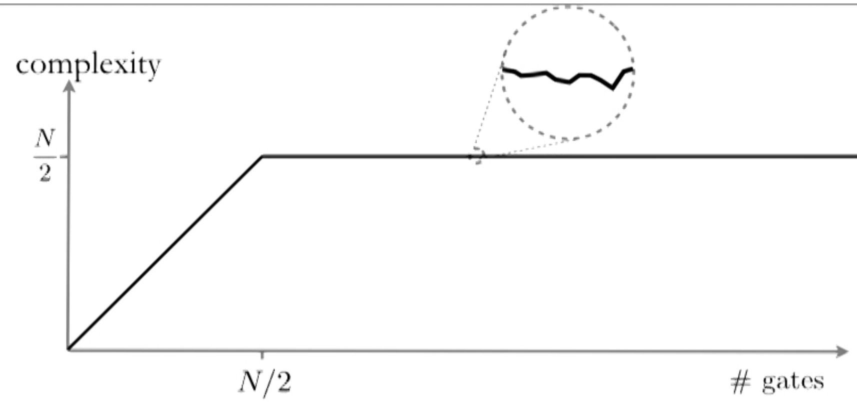


CLASSICAL (N bits)

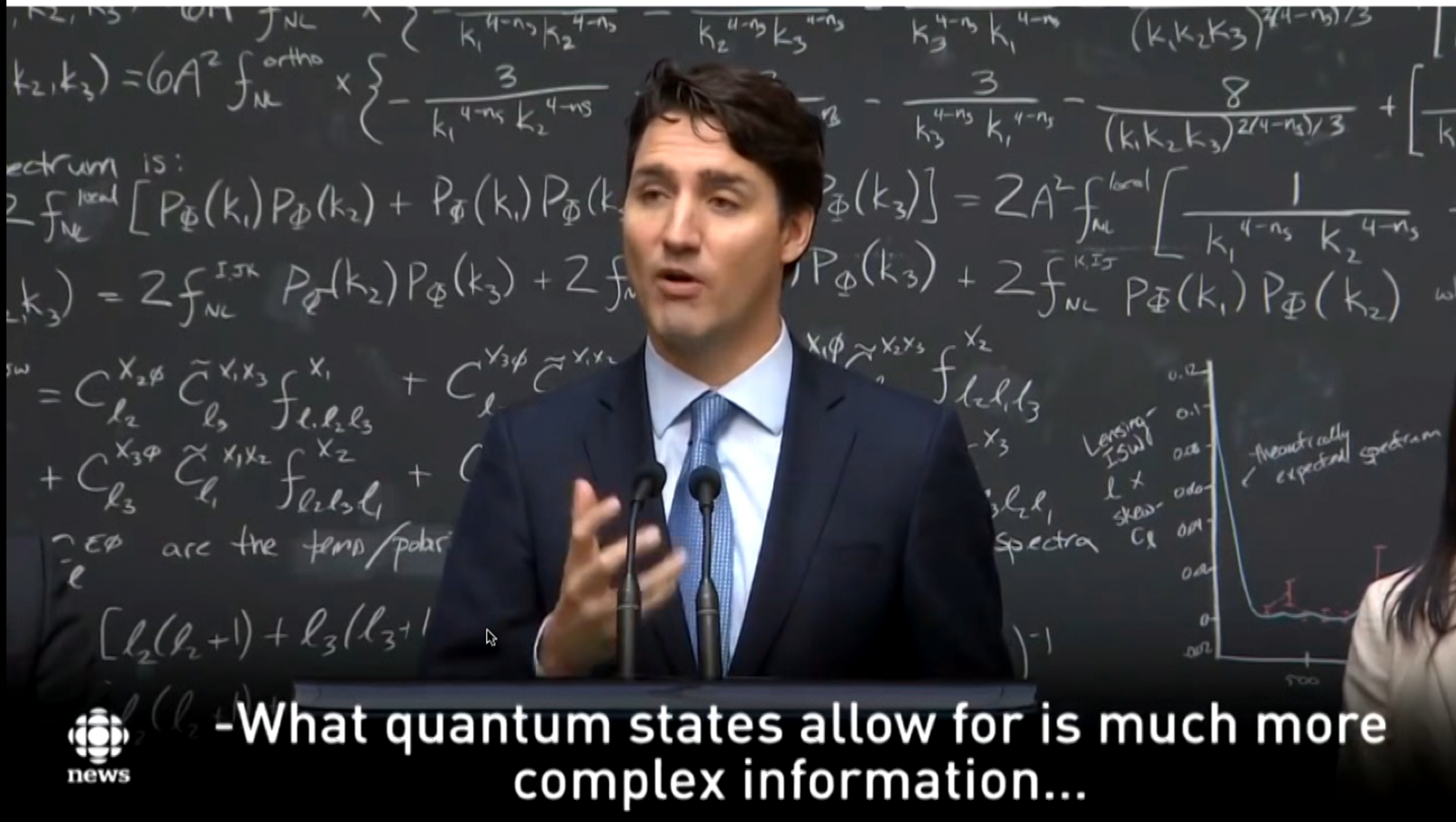
e.g. 01110100

$\#$ classical states $= 2^N$

$\mathcal{C}_{\max} = N$



QUANTUM (N qubits)

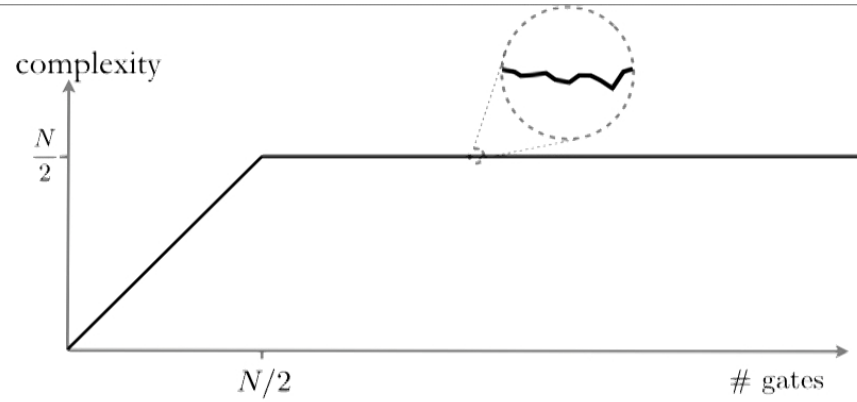

news
-What quantum states allow for is much more complex information...

CLASSICAL (N bits)

e.g. 01110100

$\#$ classical states $= 2^N$

$\mathcal{C}_{\max} = N$



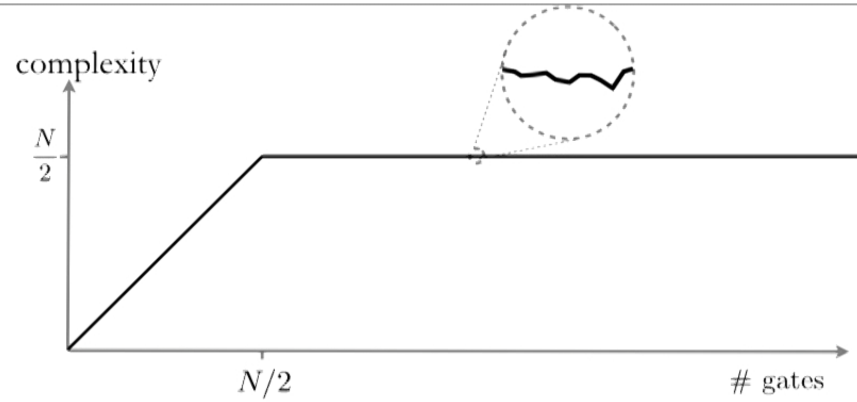
QUANTUM (N qubits)

CLASSICAL (N bits)

e.g. 01110100

$\#$ classical states $= 2^N$

$\mathcal{C}_{\max} = N$



QUANTUM (N qubits)

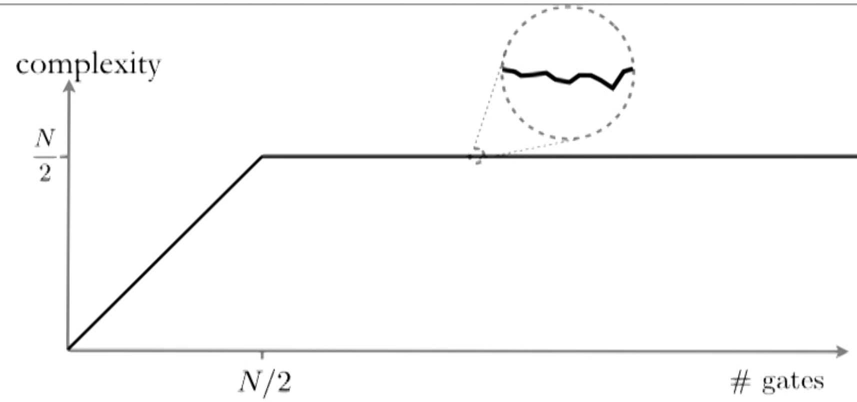
$$\text{e.g.} \quad \alpha_1 |00000000\rangle + \ldots$$
$$\ldots + \alpha_{2^N} |11111111\rangle$$

CLASSICAL (N bits)

e.g. 01110100

$$\#\ \text{classical states} = 2^N$$

$$\mathcal{C}_{\max} = N$$



QUANTUM (N qubits)

$$\text{e.g.} \quad \alpha_1|00000000\rangle + \ldots \\ \ldots + \alpha_{2^N}|11111111\rangle$$

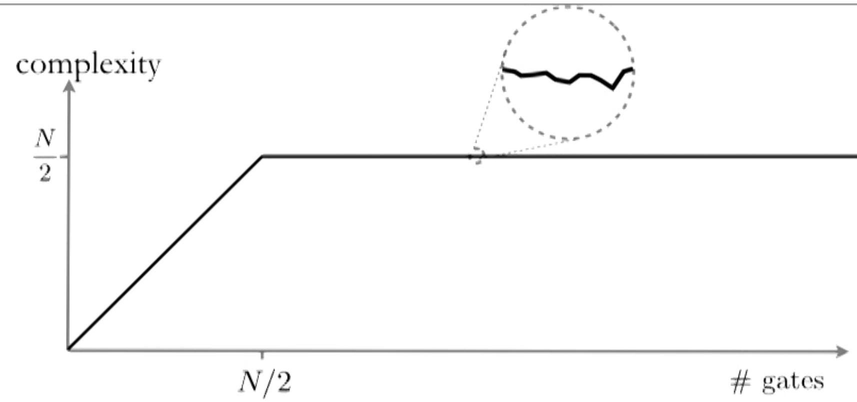
$$\#\ \text{exactly orthogonal states} = 2^N$$

CLASSICAL (N bits)

e.g. 01110100

$\#$ classical states $= 2^N$

$\mathcal{C}_{\max} = N$



QUANTUM (N qubits)

e.g. $\alpha_1 |00000000\rangle + \dots$
$\dots + \alpha_{2^N} |11111111\rangle$

$\#$ exactly orthogonal states $= 2^N$

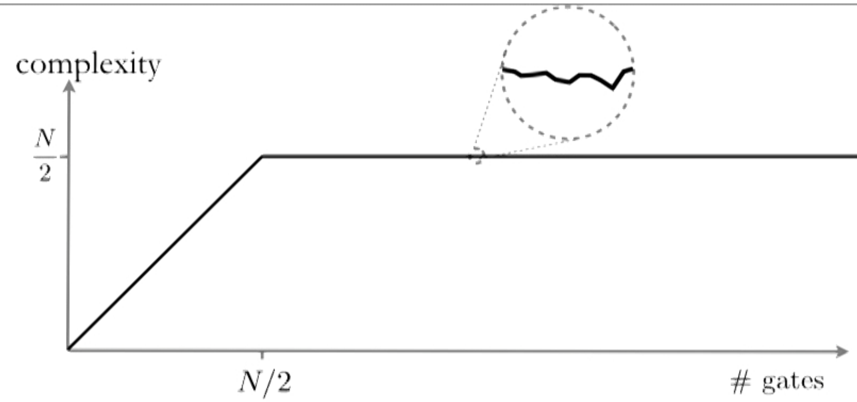
$\#$ almost orthogonal states $\sim 2^{2^N}$

CLASSICAL (N bits)

e.g. 01110100

$$\# \text{ classical states} = 2^N$$

$$\mathcal{C}_{\max} = N$$



QUANTUM (N qubits)

$$\text{e.g.} \quad \alpha_1|00000000\rangle + \ldots$$
$$\ldots + \alpha_{2^N}|11111111\rangle$$

$$\# \text{ exactly orthogonal states} = 2^N$$

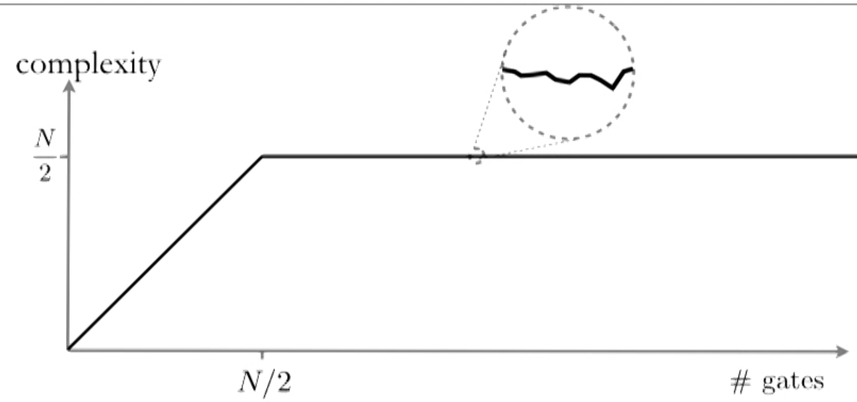
$$\# \text{ almost orthogonal states} \sim 2^{2^N} \longleftarrow \frac{1}{2^{N/2}}\Big(\pm|00000000\rangle \pm |00000001\rangle \pm \ldots$$
$$\ldots \pm |11111110\rangle \pm |11111111\rangle\Big)$$

CLASSICAL (N bits)

e.g. 01110100

$$\#\ \text{classical states} = 2^N$$

$$\mathcal{C}_{\max} = N$$



QUANTUM (N qubits)

e.g. $\alpha_1|00000000\rangle + \ldots$

$\ldots + \alpha_{2^N}|11111111\rangle$

$$\#\ \text{exactly orthogonal states} = 2^N$$

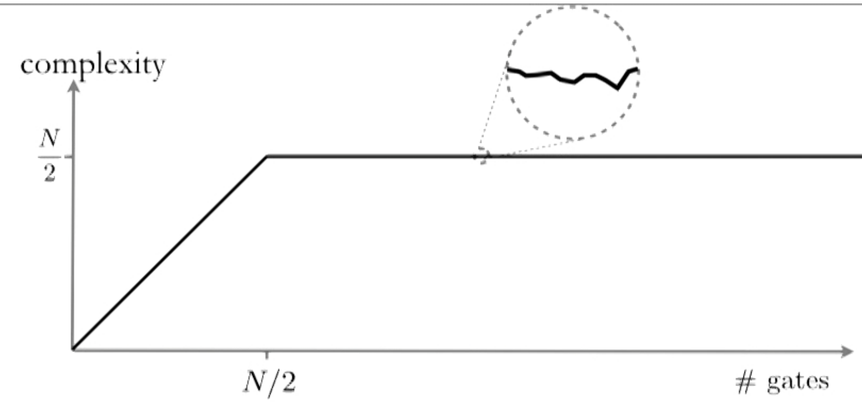
$$\#\ \text{almost orthogonal states} \sim 2^{2^N} \leftarrow \frac{1}{2^{N/2}}\Big(\pm|00000000\rangle \pm |00000001\rangle \pm \ldots$$
$$\ldots \pm |11111110\rangle \pm |11111111\rangle\Big)$$

CLASSICAL (N bits)

e.g. 01110100

$\#$ classical states $= 2^N$

$\mathcal{C}_{\max} = N$



QUANTUM (N qubits)

e.g. $\alpha_1|00000000\rangle + \ldots$
$\ldots + \alpha_{2^N}|11111111\rangle$

$\#$ exactly orthogonal states $= 2^N$

$\#$ almost orthogonal states $\sim 2^{2^N}$ ← $\frac{1}{2^{N/2}}\Big(\pm|00000000\rangle \pm |00000001\rangle \pm \ldots$
$\ldots \pm |11111110\rangle \pm |11111111\rangle\Big)$

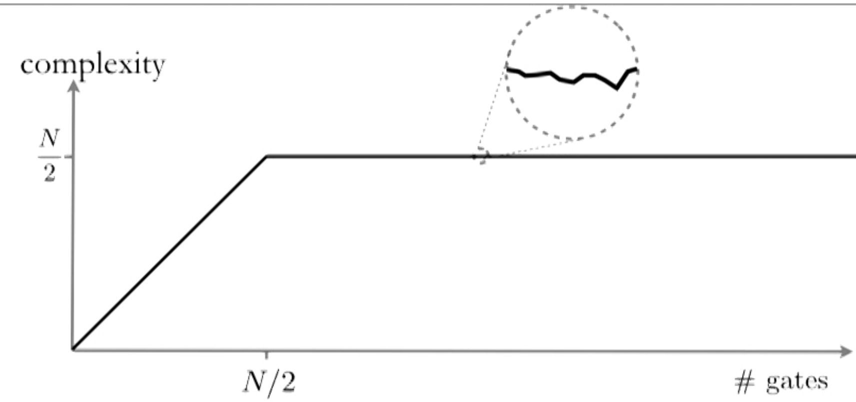
HILBERT SPACE IS HUGE

CLASSICAL (N bits)

e.g. 01110100

$\#$ classical states $= 2^N$

$\mathcal{C}_{\max} = N$



QUANTUM (N qubits)

e.g. $\alpha_1 |00000000\rangle + \ldots$
$\ldots + \alpha_{2^N} |11111111\rangle$

$\#$ exactly orthogonal states $= 2^N$

$\#$ almost orthogonal states $\sim 2^{2^N}$ $\leftarrow$ $\frac{1}{2^{N/2}}\Big(\pm|00000000\rangle \pm |00000001\rangle \pm \ldots$
$\ldots \pm |11111110\rangle \pm |11111111\rangle\Big)$

$\#$ circuits $\sim (N^2)^{\#\mathrm{gates}}$

$\downarrow$

$\mathcal{C}_{\max} \sim 2^N$

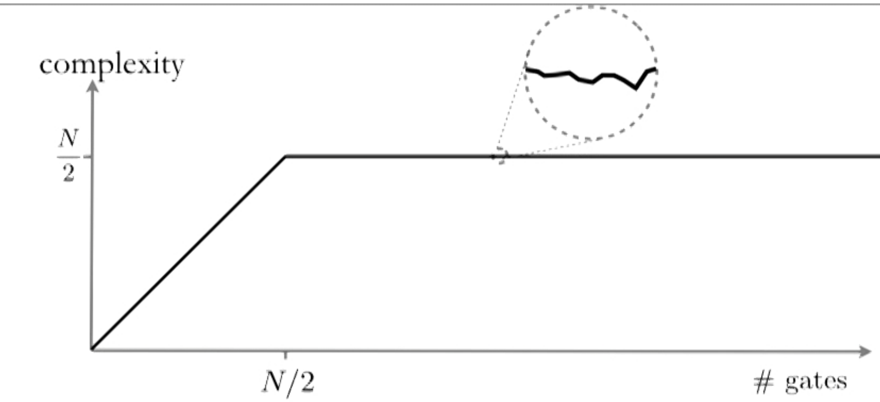
HILBERT SPACE IS HUGE

CLASSICAL (N bits)

e.g. 01110100

$\#$ classical states $= 2^N$

$\mathcal{C}_{\max} = N$



QUANTUM (N qubits)

e.g. $\alpha_1|00000000\rangle + \ldots$
$\ldots + \alpha_{2^N}|11111111\rangle$

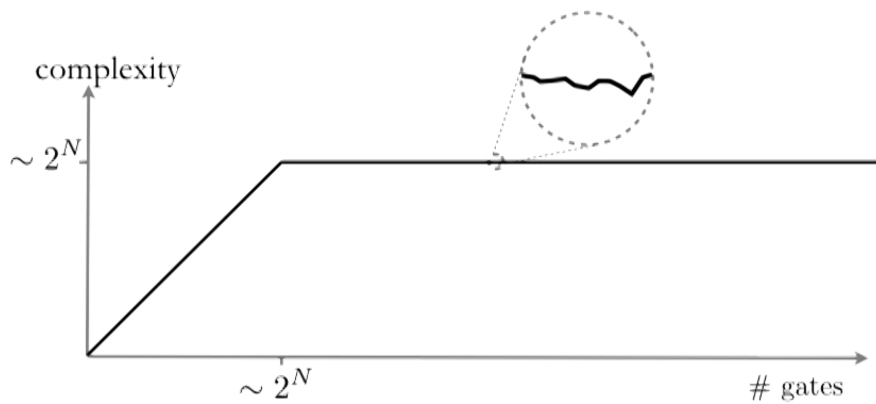
$\#$ exactly orthogonal states $= 2^N$

$\#$ almost orthogonal states $\sim 2^{2^N}$

$\#$ circuits $\sim (N^2)^{\# \text{gates}}$

$\downarrow$

$\mathcal{C}_{\max} \sim 2^N$



HILBERT SPACE IS HUGE

complexity ~ size of wormhole?

EVIDENCE:

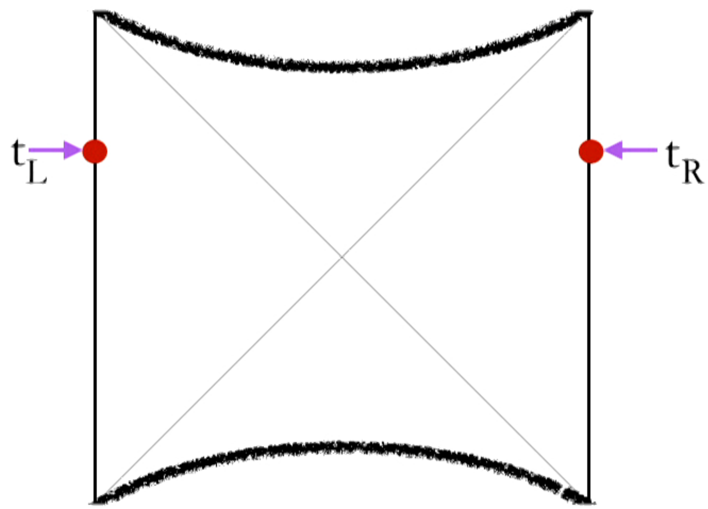
complexity ~ size of wormhole?

EVIDENCE:
- both expected to grow linearly (at early times)
- both can be exponentially large

complexity ~ size of wormhole?

EVIDENCE: • both expected to grow linearly (at early times)
• both can be exponentially large

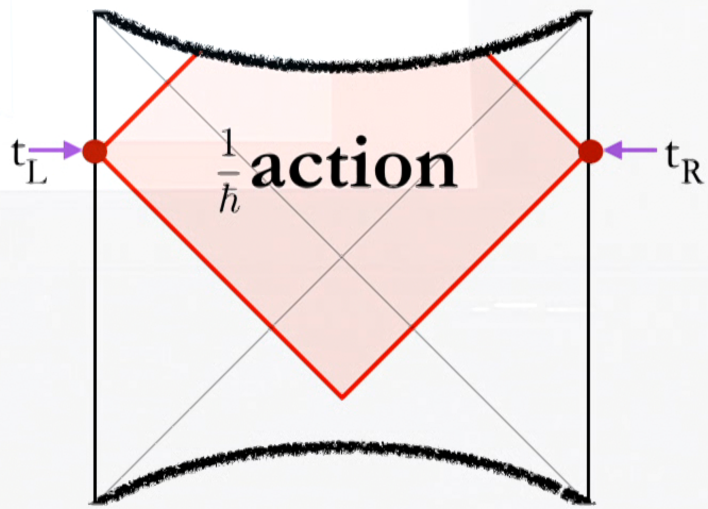
how to characterize "size" of wormhole?



complexity ~ size of wormhole?

EVIDENCE:
- both expected to grow linearly (at early times)
- both can be exponentially large

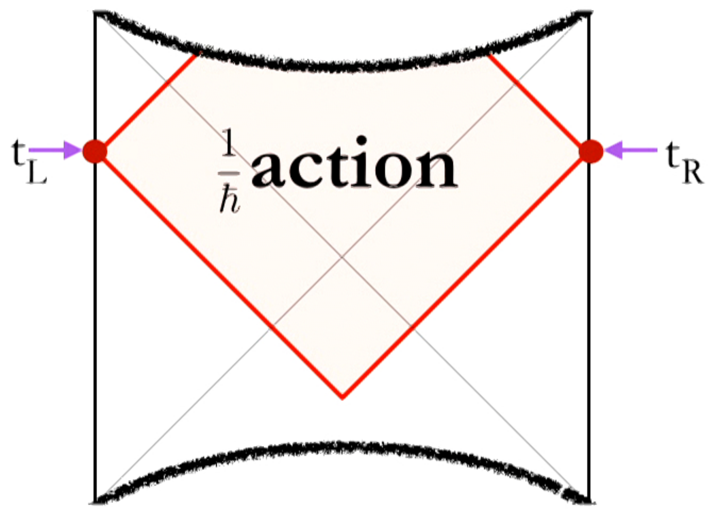
how to characterize "size" of wormhole?



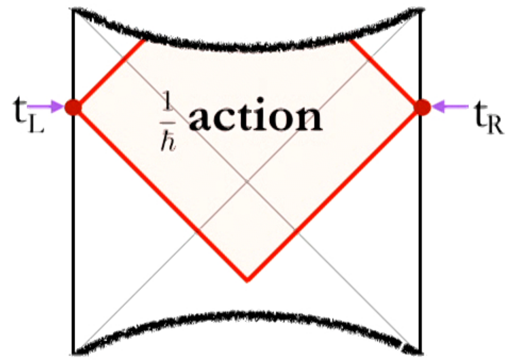
complexity ~ size of wormhole?

EVIDENCE: • both expected to grow linearly (at early times)
• both can be exponentially large

how to characterize "size" of wormhole?

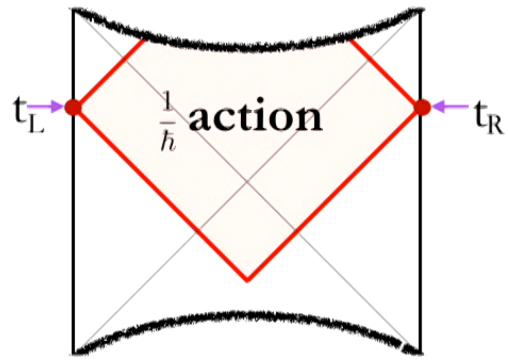


complexity ~ size of wormhole?



$$\text{Complexity} \sim \frac{\text{Action}}{\hbar}$$

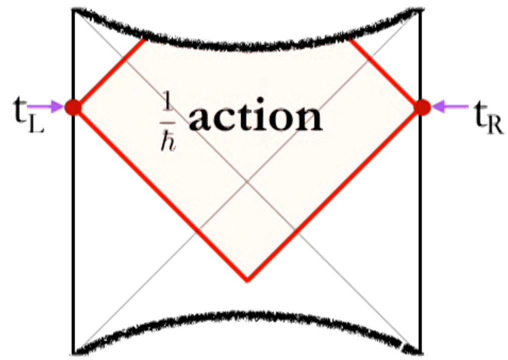
complexity ~ size of wormhole?



$$\text{Complexity} \sim \frac{\text{Action}}{\hbar}$$

how to fix constant of proportionality?

complexity ~ size of wormhole?



$$\text{Complexity} \sim \frac{\text{Action}}{\hbar}$$

how to fix constant of proportionality?

bound on rate of complexification?

bound on rate of complexification?

$$\Delta p \, \Delta x \geq \frac{\hbar}{2}$$

with $(\Delta x)^2 \equiv \langle\psi|\hat{x}^2|\psi\rangle - \langle\psi|\hat{x}|\psi\rangle^2$

bound on rate of complexification?

$$\Delta p \, \Delta x \geq \frac{\hbar}{2}$$

with $(\Delta x)^2 \equiv \langle\psi|\hat{x}^2|\psi\rangle - \langle\psi|\hat{x}|\psi\rangle^2$

bound on rate of complexification?

$$\Delta p \, \Delta x \geq \frac{\hbar}{2}$$

with $(\Delta x)^2 \equiv \langle \psi | \hat{x}^2 | \psi \rangle - \langle \psi | \hat{x} | \psi \rangle^2$

$$\Delta E \, \Delta t \geq \frac{\hbar}{2}$$

bound on rate of complexification?

$$\Delta p \, \Delta x \geq \frac{\hbar}{2}$$

with $(\Delta x)^2 \equiv \langle\psi|\hat{x}^2|\psi\rangle - \langle\psi|\hat{x}|\psi\rangle^2$

$$\Delta E \, \Delta t \geq \frac{\hbar}{2} \quad ???$$

with $(\Delta t)^2 \equiv \langle\psi|\hat{t}^2|\psi\rangle - \langle\psi|\hat{t}|\psi\rangle^2 \quad ???$

how rapidly can one state evolve to an orthogonal state?

$$\langle\psi(t)|\psi(0)\rangle = 0 \quad ?$$

how rapidly can one state evolve to an orthogonal state?

$$\langle\psi(t)|\psi(0)\rangle = 0 \quad ?$$

$E = \delta$

$E = 0$

$$|\psi(0)\rangle = \frac{|0\rangle + |\delta\rangle}{\sqrt{2}}$$

how rapidly can one state evolve to an orthogonal state?

$$\langle \psi(t) | \psi(0) \rangle = 0 \quad ?$$

$$E = \delta$$

$$E = 0$$

$$|\psi(t)\rangle = \frac{|0\rangle + e^{i\delta t/\hbar}|\delta\rangle}{\sqrt{2}}$$

$$|\langle \psi(t) | \psi(0) \rangle| = \cos(\delta t / 2\hbar)$$

how rapidly can one state evolve to an orthogonal state?

$$\langle \psi(t) | \psi(0) \rangle = 0 \quad ?$$

$E = \delta$

$E = 0$

$$|\psi(t)\rangle = \frac{|0\rangle + e^{i\delta t/\hbar}|\delta\rangle}{\sqrt{2}}$$

$$|\langle \psi(t) | \psi(0) \rangle| = \cos(\delta t / 2\hbar)$$

$$= 0 \;\rightarrow\; t = \frac{\pi}{\delta} = \frac{\pi \hbar}{2\langle E \rangle}$$

how rapidly can one state evolve to an orthogonal state?

$$\langle\psi(t)|\psi(0)\rangle = 0 \quad ?$$

$$\downarrow$$

Margolus-Levitin theorem: $\Delta t \geq \dfrac{\pi\hbar}{2\langle E\rangle}$

how rapidly can one state evolve to an orthogonal state?

$$\langle\psi(t)|\psi(0)\rangle = 0 \quad ?$$

$$\downarrow$$

Margolus-Levitin theorem: $\Delta t \geq \dfrac{\pi\hbar}{2\langle E\rangle}$

$$\downarrow ?$$

Lloyd conjecture: $\dfrac{d\#\text{ops}}{d\text{t}} \leq \dfrac{2\langle E\rangle}{\pi\hbar}$

how rapidly can one state evolve to an orthogonal state?

$$\langle \psi(t) | \psi(0) \rangle = 0 \quad ?$$

$$\downarrow$$

Margolus-Levitin theorem: $\Delta t \geq \dfrac{\pi \hbar}{2 \langle E \rangle}$

$$\downarrow ?$$

Lloyd conjecture: $\dfrac{d\#\mathrm{ops}}{d\mathrm{t}} \leq \dfrac{2 \langle E \rangle}{\pi \hbar}$

$100g$ CPU performs 10^{12} FLOPS $\ll 10^{50}$ FLOPS

how rapidly can one state evolve to an orthogonal state?

$$\langle\psi(t)|\psi(0)\rangle = 0 \quad ?$$

$$\downarrow$$

Margolus-Levitin theorem: $\Delta t \geq \dfrac{\pi\hbar}{2\langle E\rangle}$

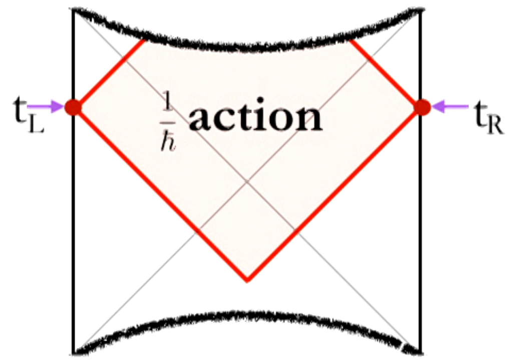
$$\downarrow ?$$

Lloyd conjecture: $\dfrac{d\#\text{ops}}{dt} \leq \dfrac{2\langle E\rangle}{\pi\hbar}$

$100g$ CPU performs 10^{12} FLOPS $\ll 10^{50}$ FLOPS

do black holes saturate this bound?

complexity ~ size of wormhole?



$$\text{Complexity} \sim \frac{\text{Action}}{\hbar}$$

$$\boxed{\text{Complexity} = \frac{\text{Action}}{\pi\hbar}}$$

ASSUME a conjectured bound on rate of computation
AND that black holes saturate that bound

complexity ~ size of wormhole?

EVIDENCE:

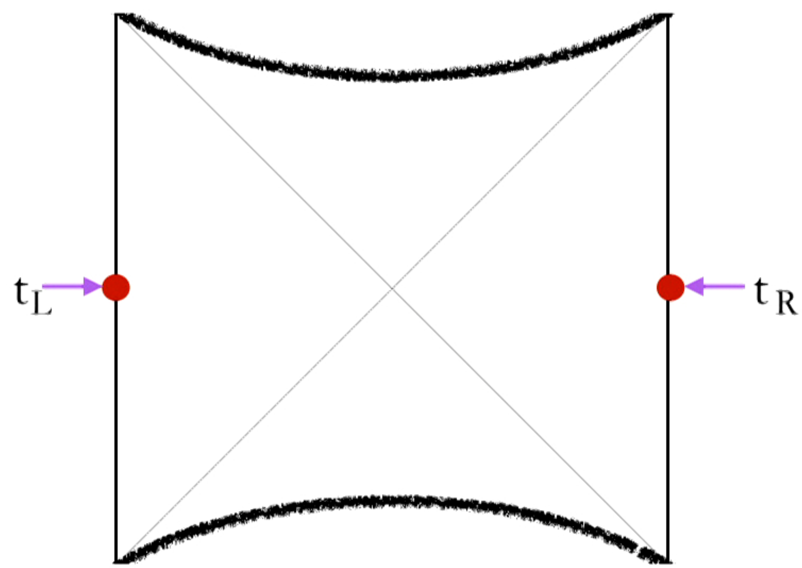
- both expected to grow linearly (at early times)
- both can be exponentially large
- perturb black hole with boundary operator
  - in CFT, leads to increase in complexity (chaos)
  - in wormhole, leads to shockwave, increases size

the two increases match
including delicate cancellations!

- perturb black hole with boundary operator
  - in CFT, leads to increase in complexity (chaos)
  - in wormhole, leads to shockwave, increases size

the two increases match -1

including delicate cancellations!

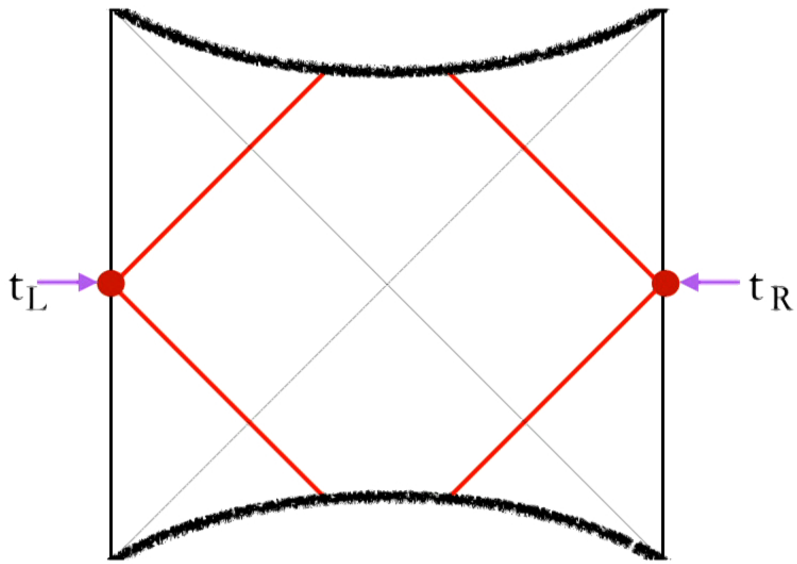


- perturb black hole with boundary operator
  - in CFT, leads to increase in complexity (chaos)
  - in wormhole, leads to shockwave, increases size

the two increases match

including delicate cancellations!

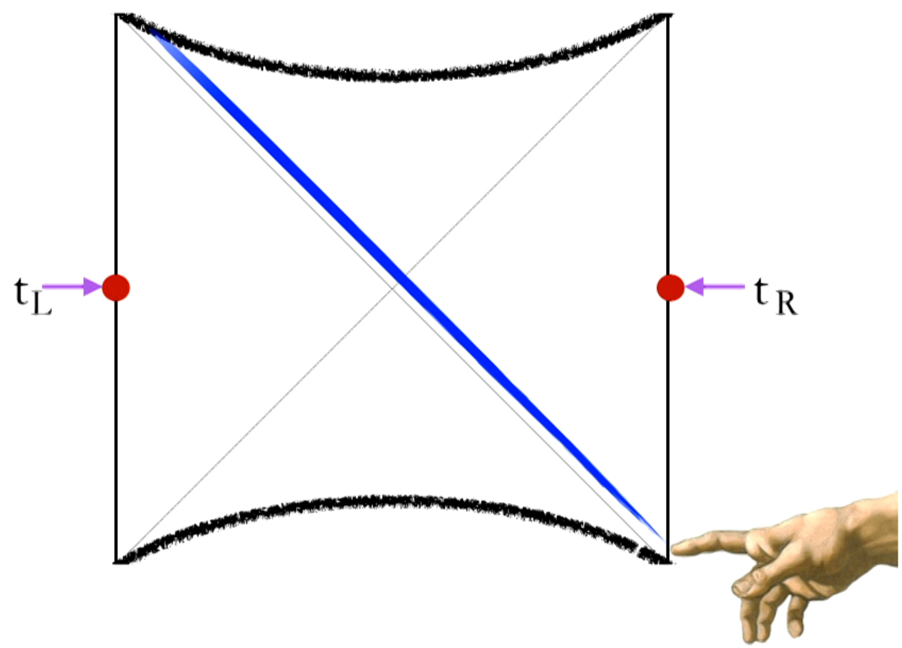
-1



- perturb black hole with boundary operator
  - in CFT, leads to increase in complexity (chaos)
  - in wormhole, leads to shockwave, increases size

the two increases match
including delicate cancellations!

-1

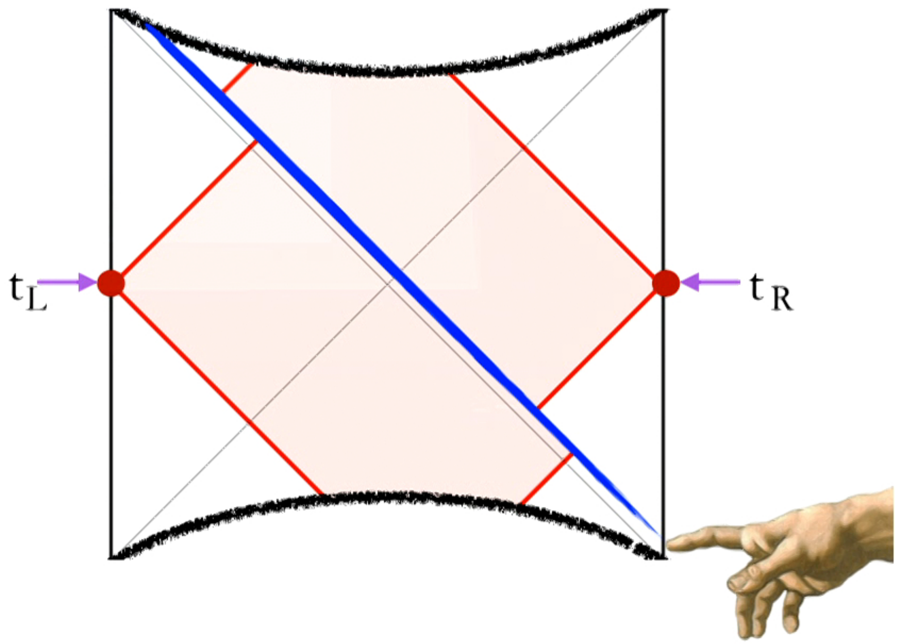


- perturb black hole with boundary operator
  - in CFT, leads to increase in complexity (chaos)
  - in wormhole, leads to shockwave, increases size

the two increases match

including delicate cancellations!

-1



complexity ~ size of wormhole?

EVIDENCE:
- both expected to grow linearly (at early times)
- both can be exponentially large
- perturb black hole with boundary operator
  - in CFT, leads to increase in complexity (chaos)
  - in wormhole, leads to shockwave, increases size

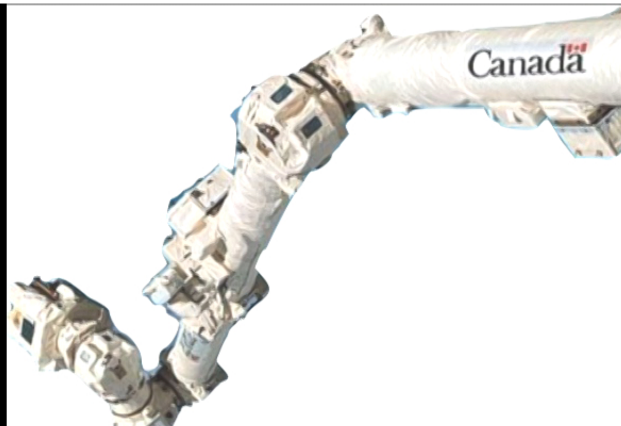
  the two increases match
  including delicate cancellations!
- single/multiple/localized perturbations

complexity ~ size of wormhole?

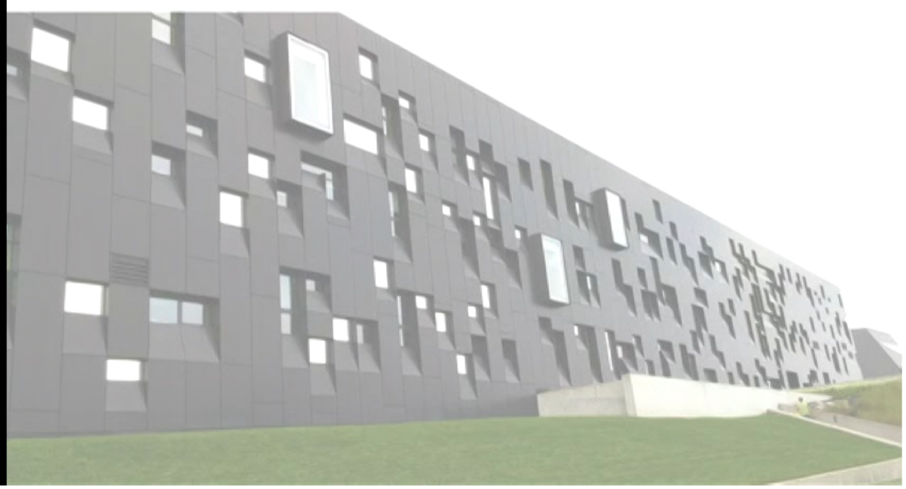
EVIDENCE:

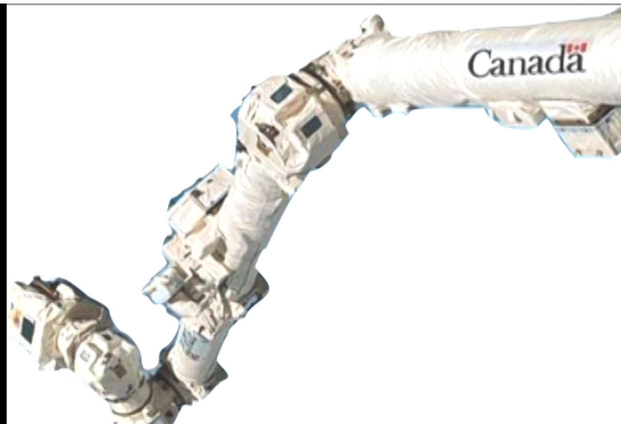
- both expected to grow linearly (at early times)
- both can be exponentially large
- perturb black hole with boundary operator
  - in CFT, leads to increase in complexity (chaos)
  - in wormhole, leads to shockwave, increases size

  the two increases match
  including delicate cancellations!
- single/multiple/localized perturbations
- entomb black hole in inert shell

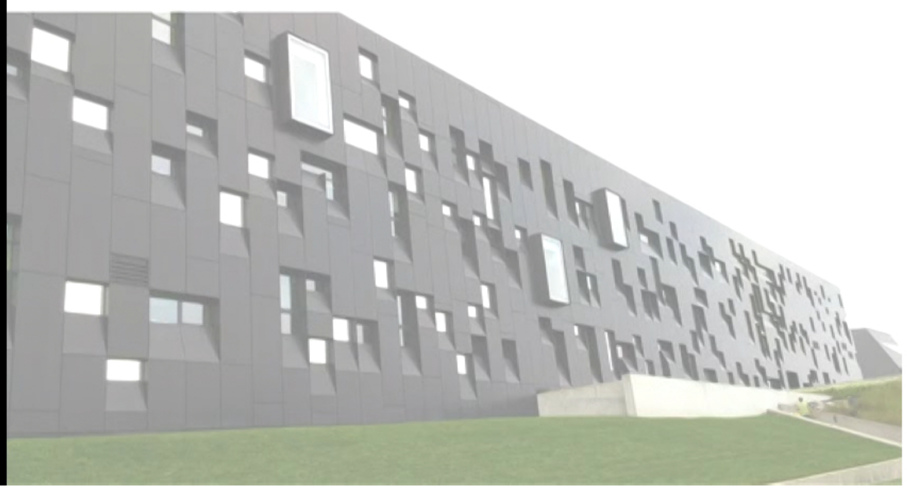


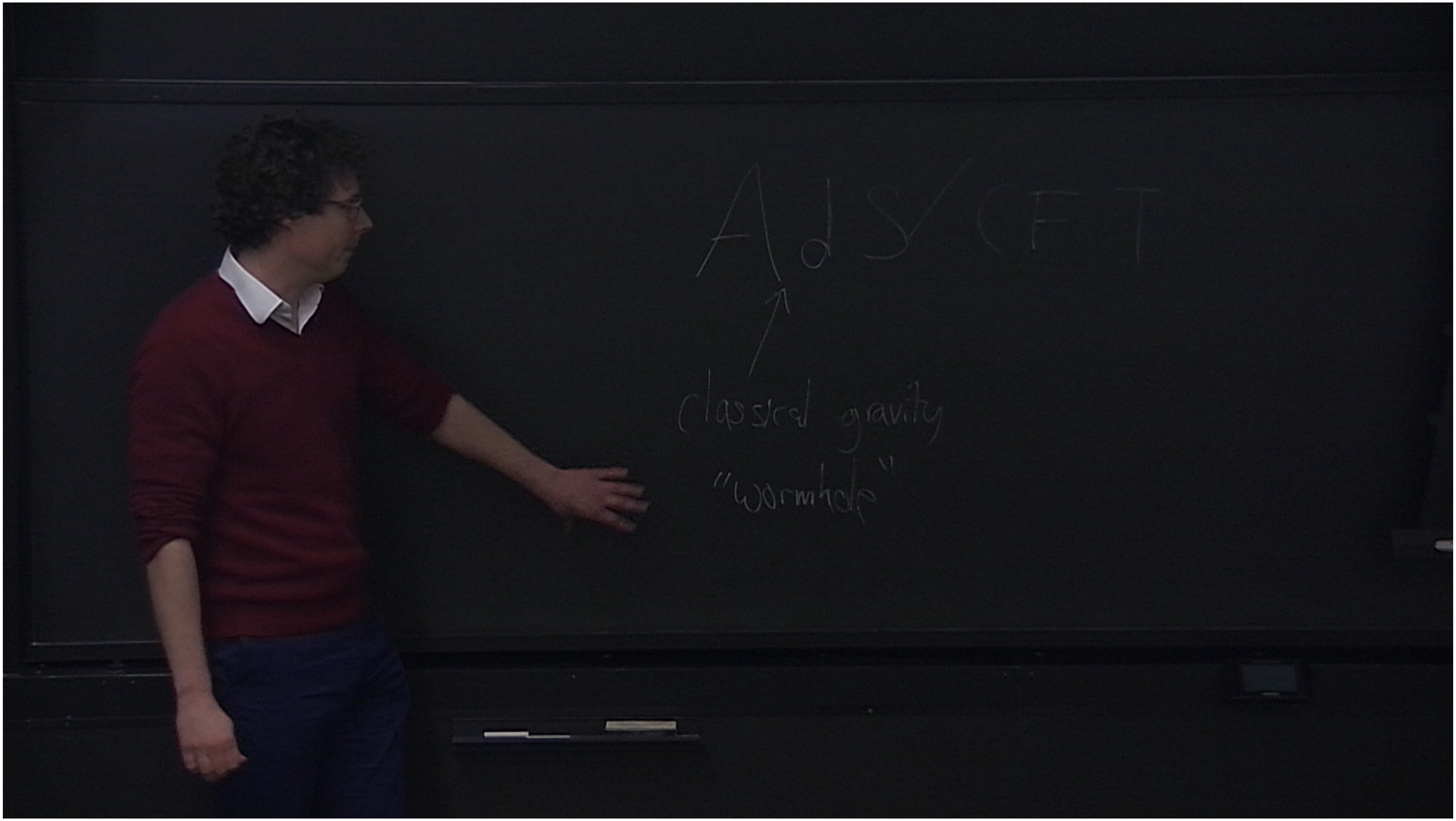
Complexity and Spacetime

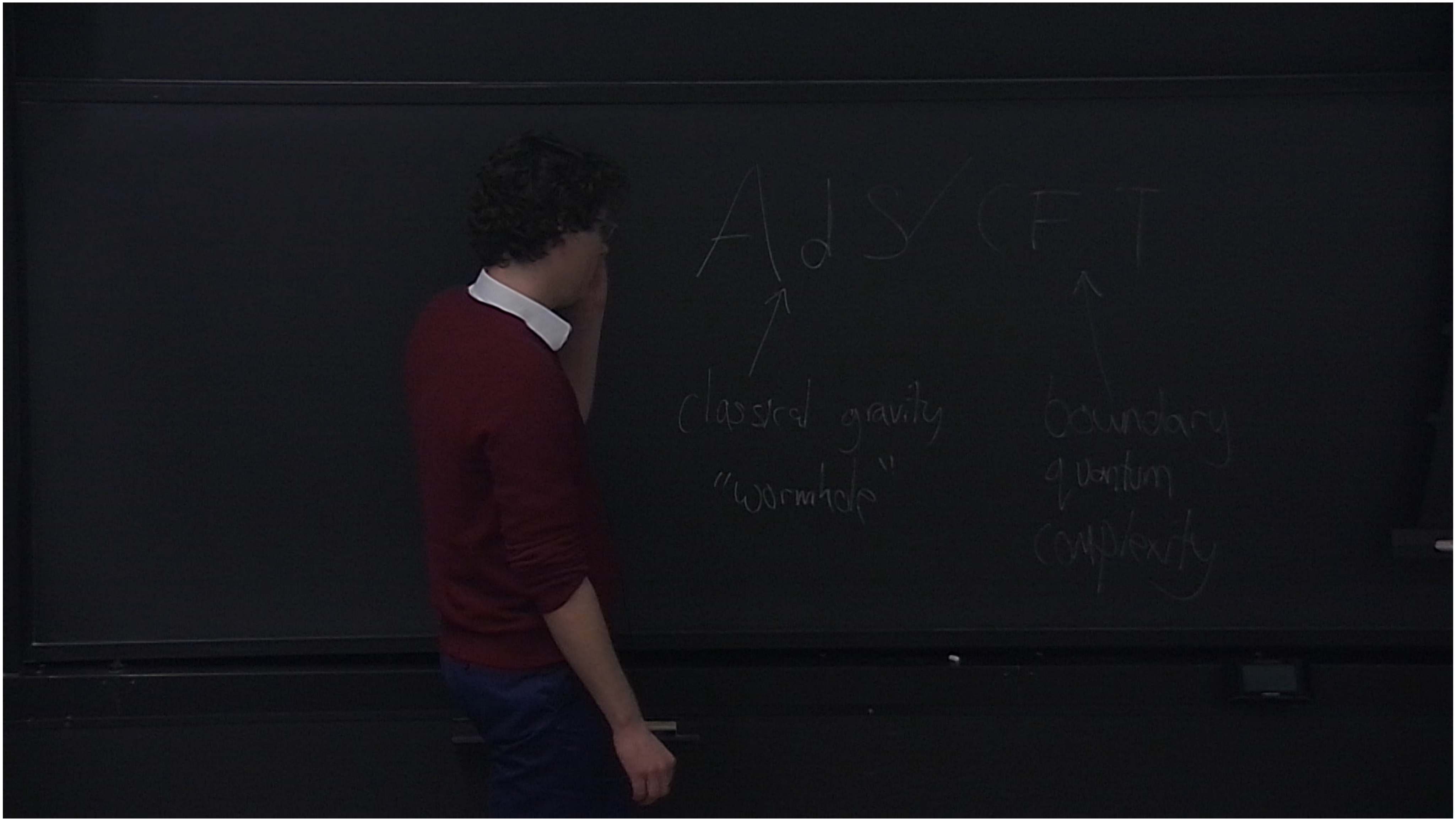


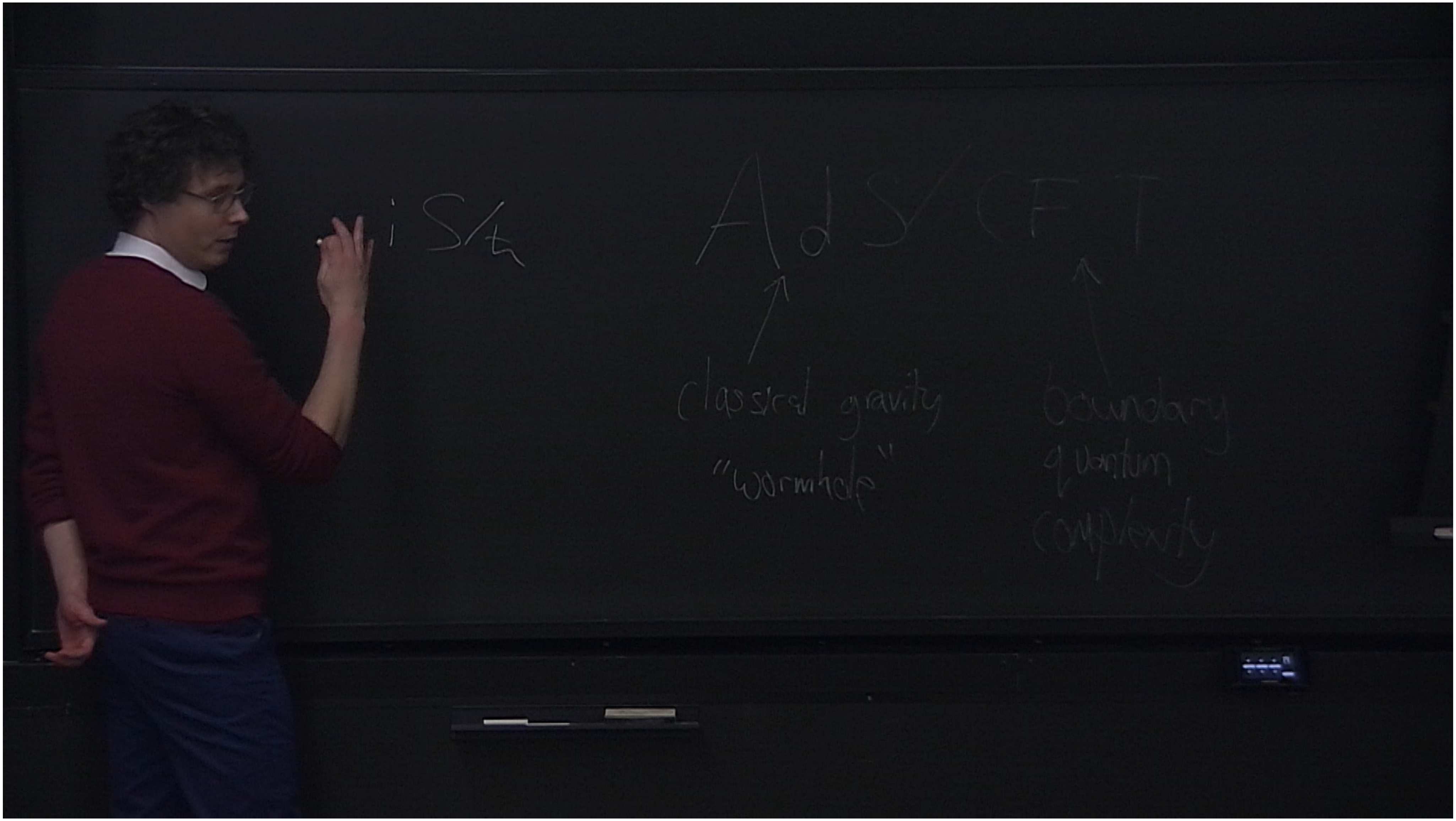


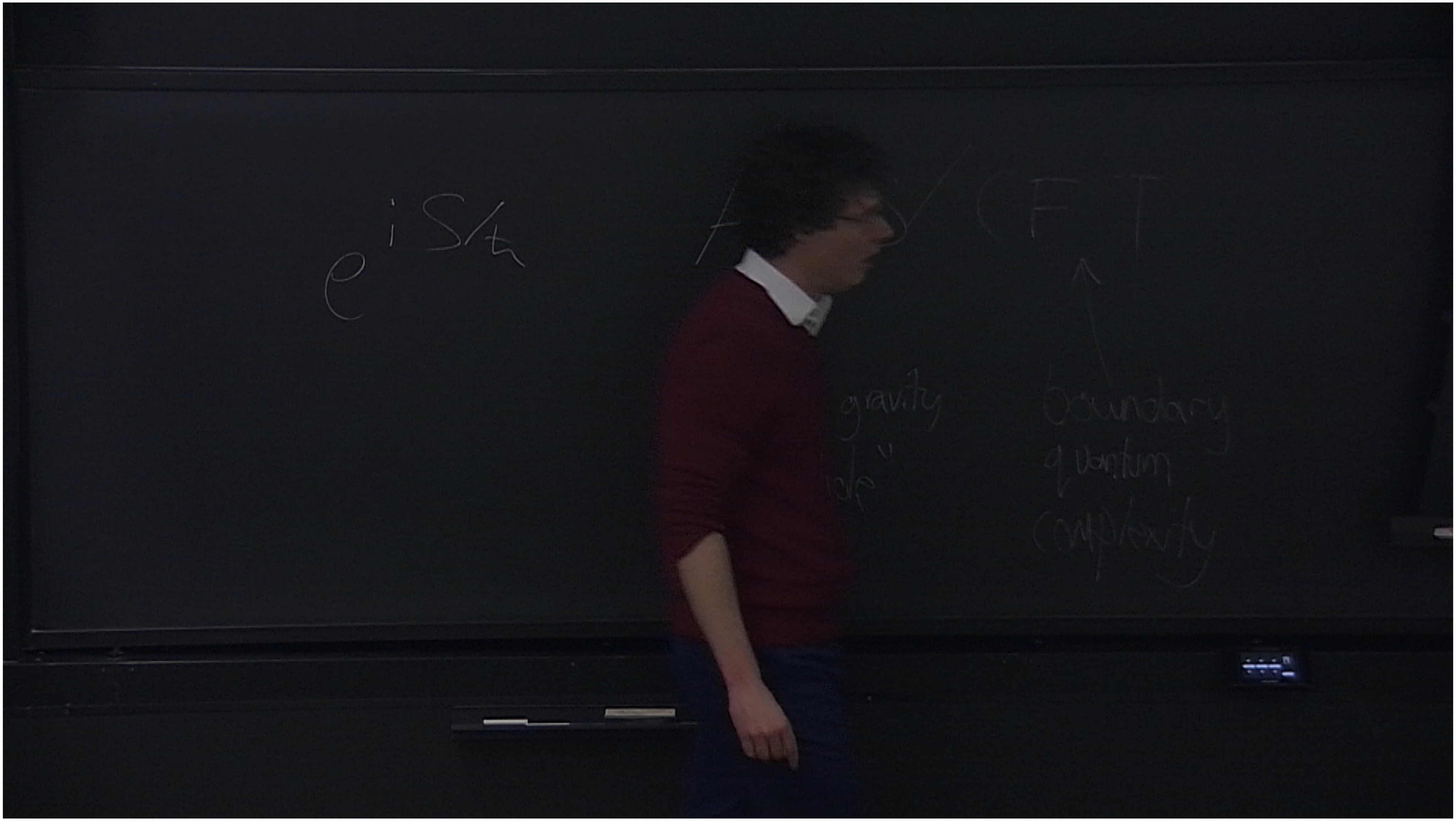
Complexity “=” Spacetime

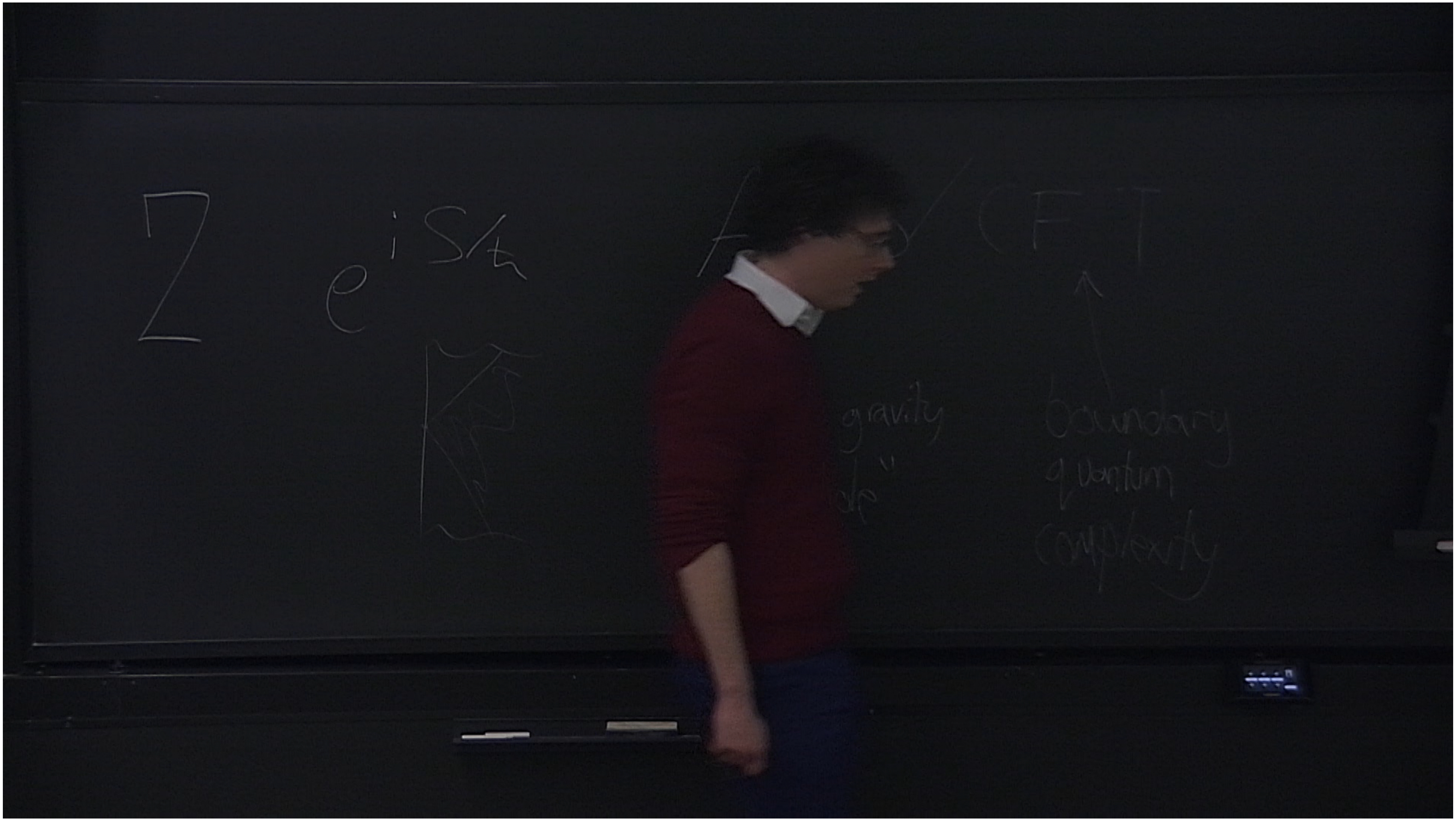



AdS/CFT
classical gravity
"wormhole"


AdS/CFT
classical gravity
"wormhole"
boundary
quantum
complexity


iS/ħ
AdS/CFT
classical gravity
"wormhole"
boundary
quantum
complexity


$e^{iS/\hbar}$
CFT
gravity
boundary
quantum
complexity


CFT
gravity
boundary
quantum
complexity