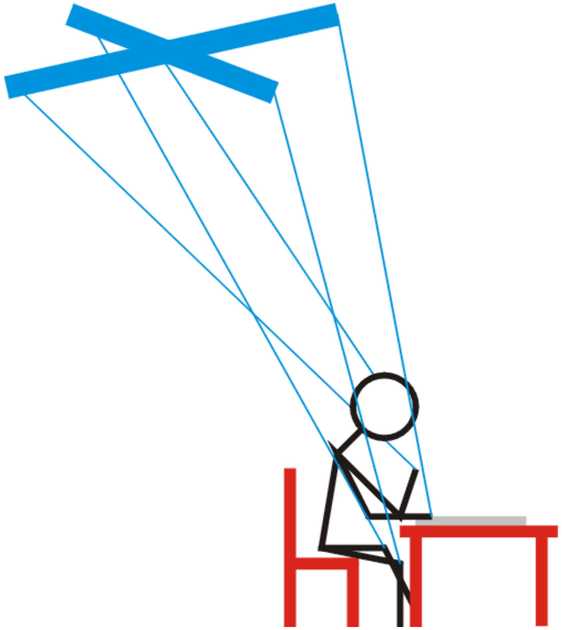
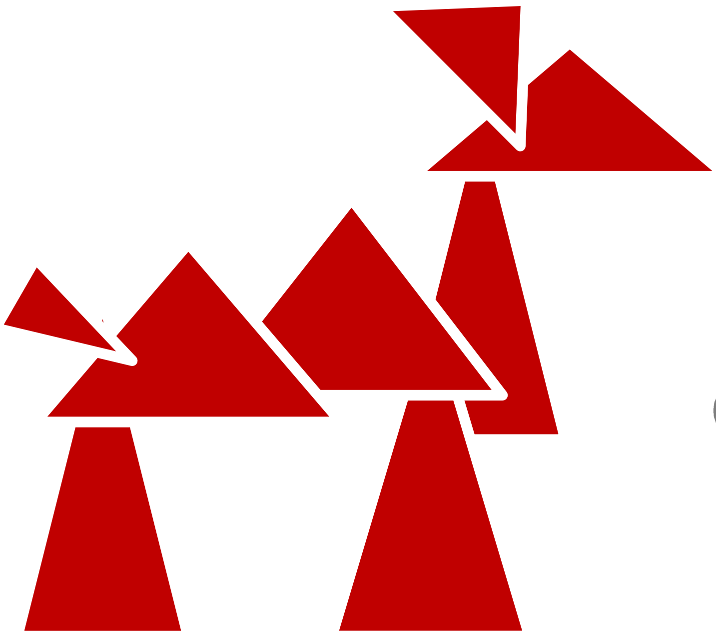


Local Hamiltonians & Quantum Complexity

Daniel Nagaj
universität wien

2014 | 4 | 11
CS lunch @ USC



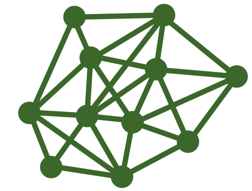
Local Hamiltonians & Quantum Complexity

Daniel Nagaj
universität wien
SAV

2014 | 4 | 11
CS lunch @ USC

1 Hamiltonians?

optimization & dynamics

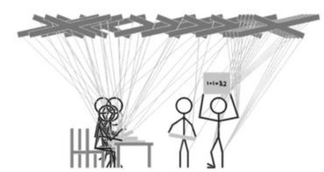


2 complexity

checking (quantum) proofs

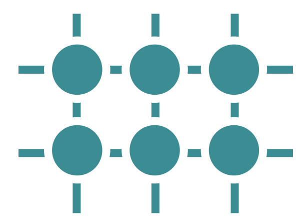
3 ground states?

how hard is it to find them: QMA



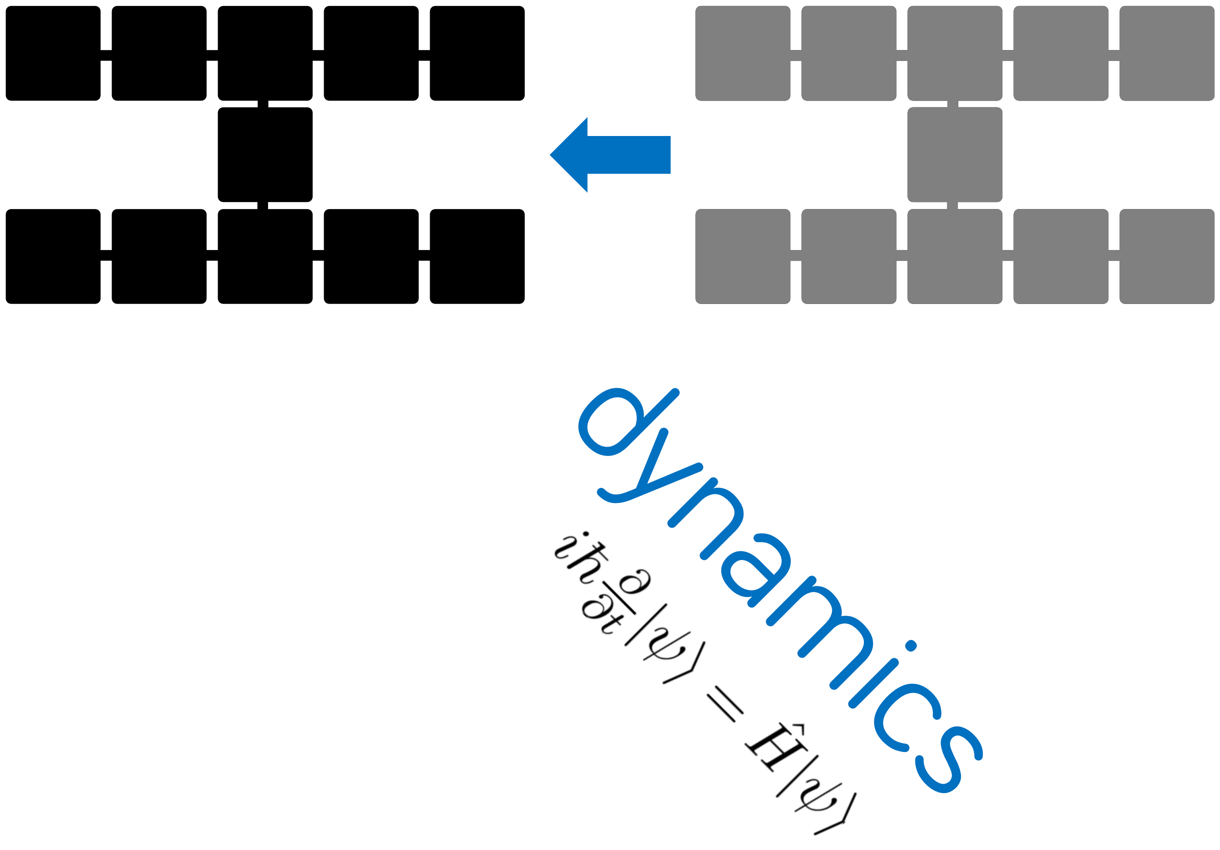
4 tensor networks

heuristics based on low entanglement



LH
QMA
[wisegeek.com]

Hamiltonians



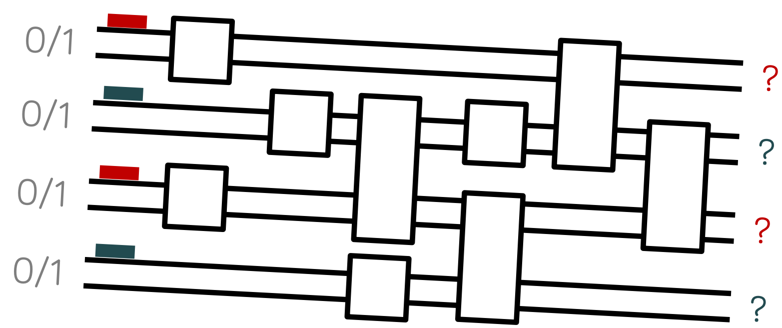
dynamics
$i\hbar\frac{\partial}{\partial t}|\psi\rangle = \hat{H}|\psi\rangle$


scattering
[fermilab]

scattering

Universal computation by multi-particle quantum walk

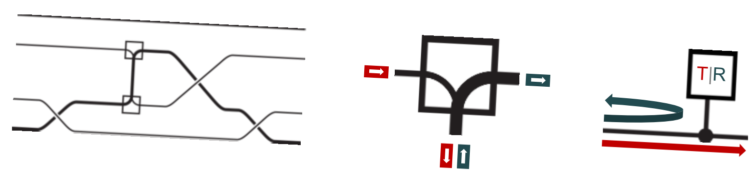
- dual-rail encoding
  N wavepackets



$$a_j^\dagger a_k + a_k^\dagger a_j$$

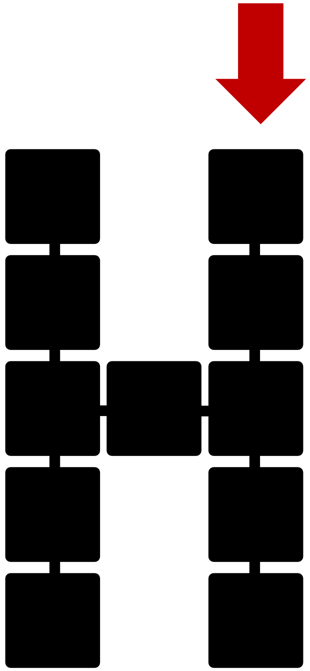
- CPHASE: interaction

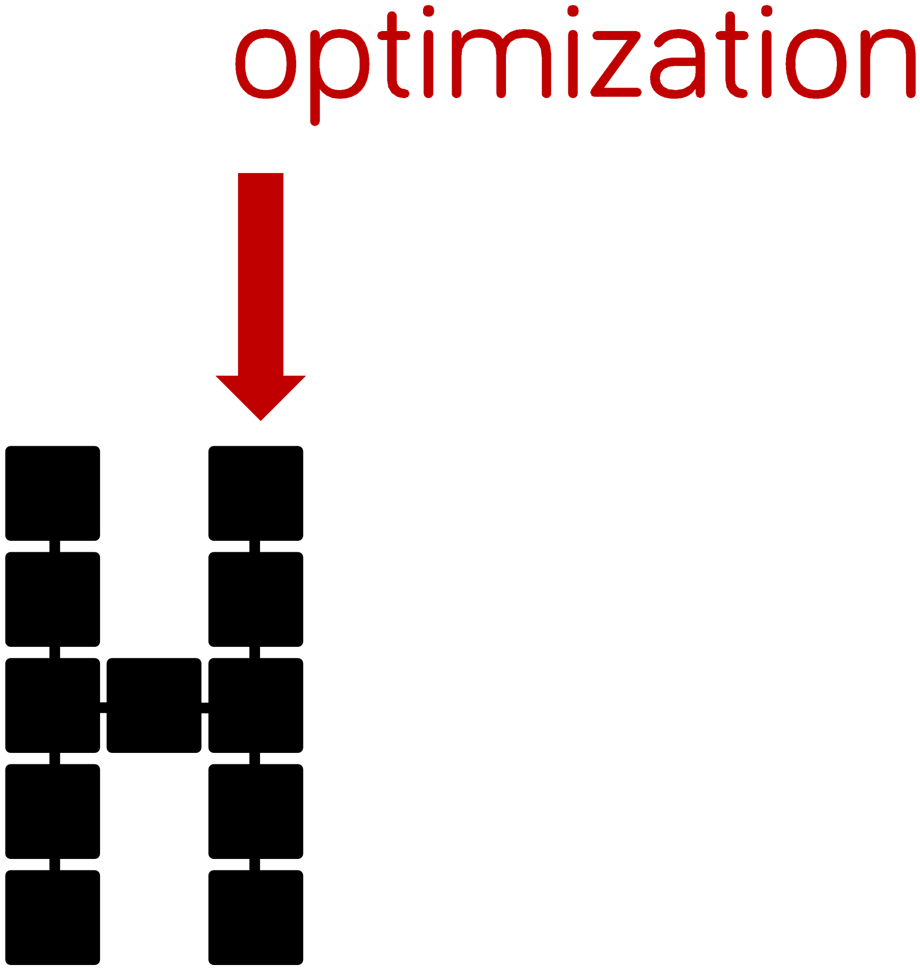
$$a_j^\dagger a_k^\dagger a_j a_k$$

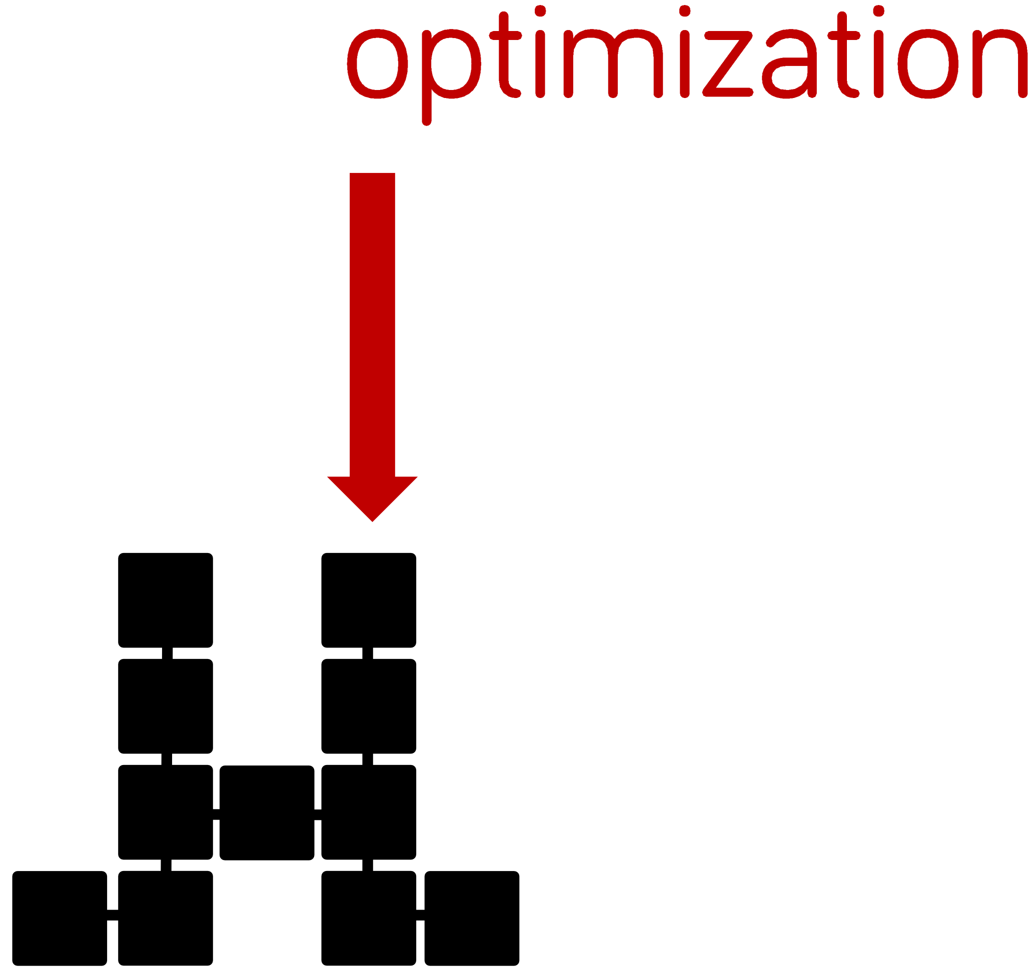


[Childs, Gosset, Webb, Science 339, 791 (2013)]

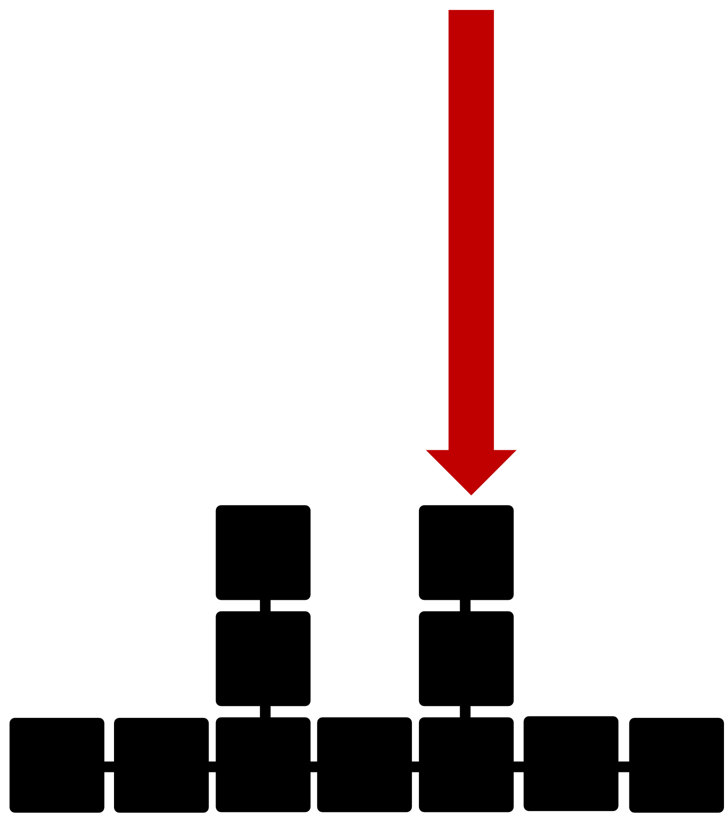
optimization



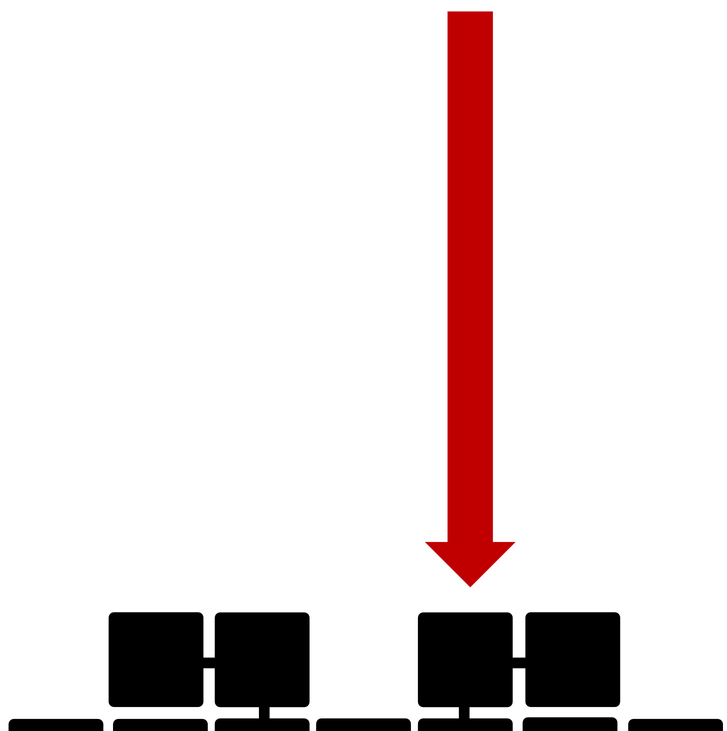

optimization


optimization

optimization

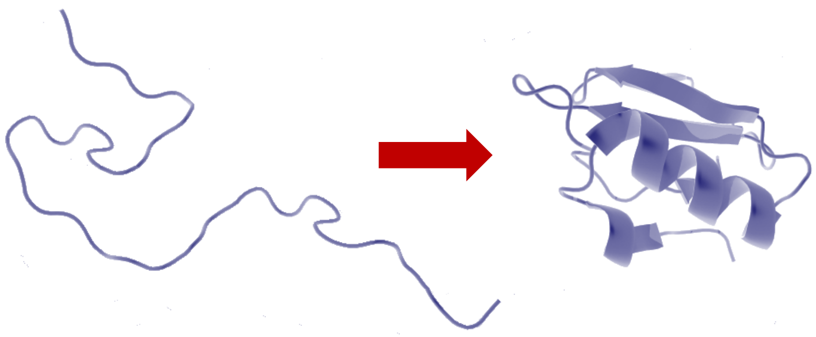


optimization

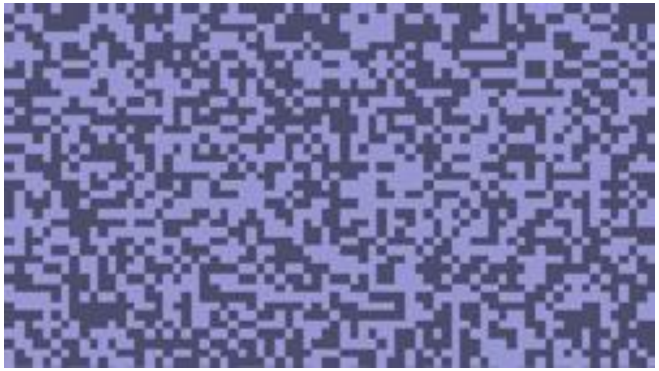


protein folding

spin glasses



[wikipedia]

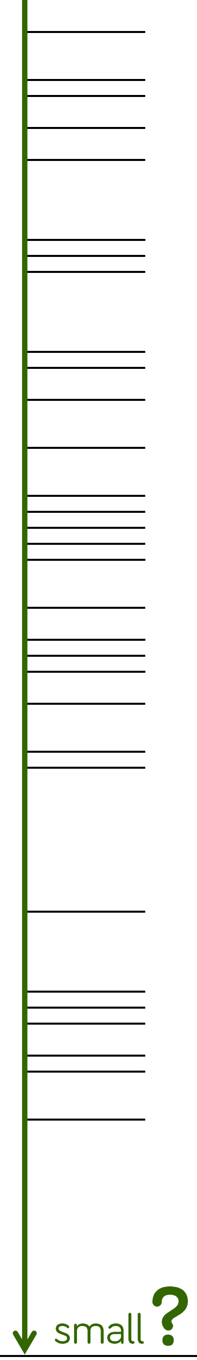


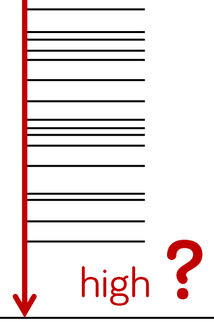
[uni-koeln.de]

local Hamiltonians

1 Hamiltonians and their ground states

Is the ground state energy of a **LH**



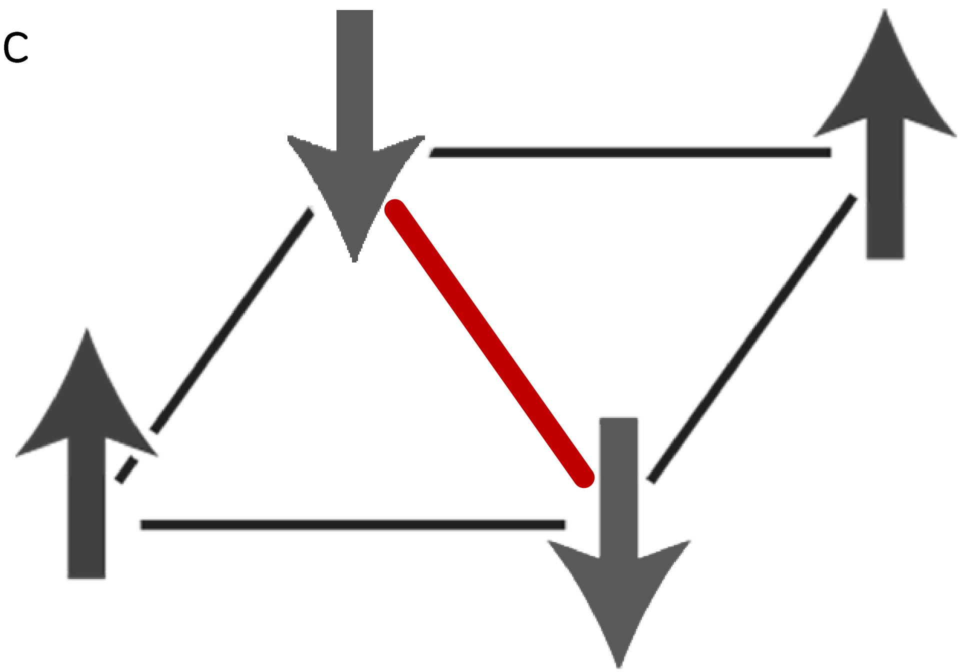


Is the ground state energy of a **LH**

1 Frustrated systems

Everybody can't be happy.

antiferromagnetic
spin glass

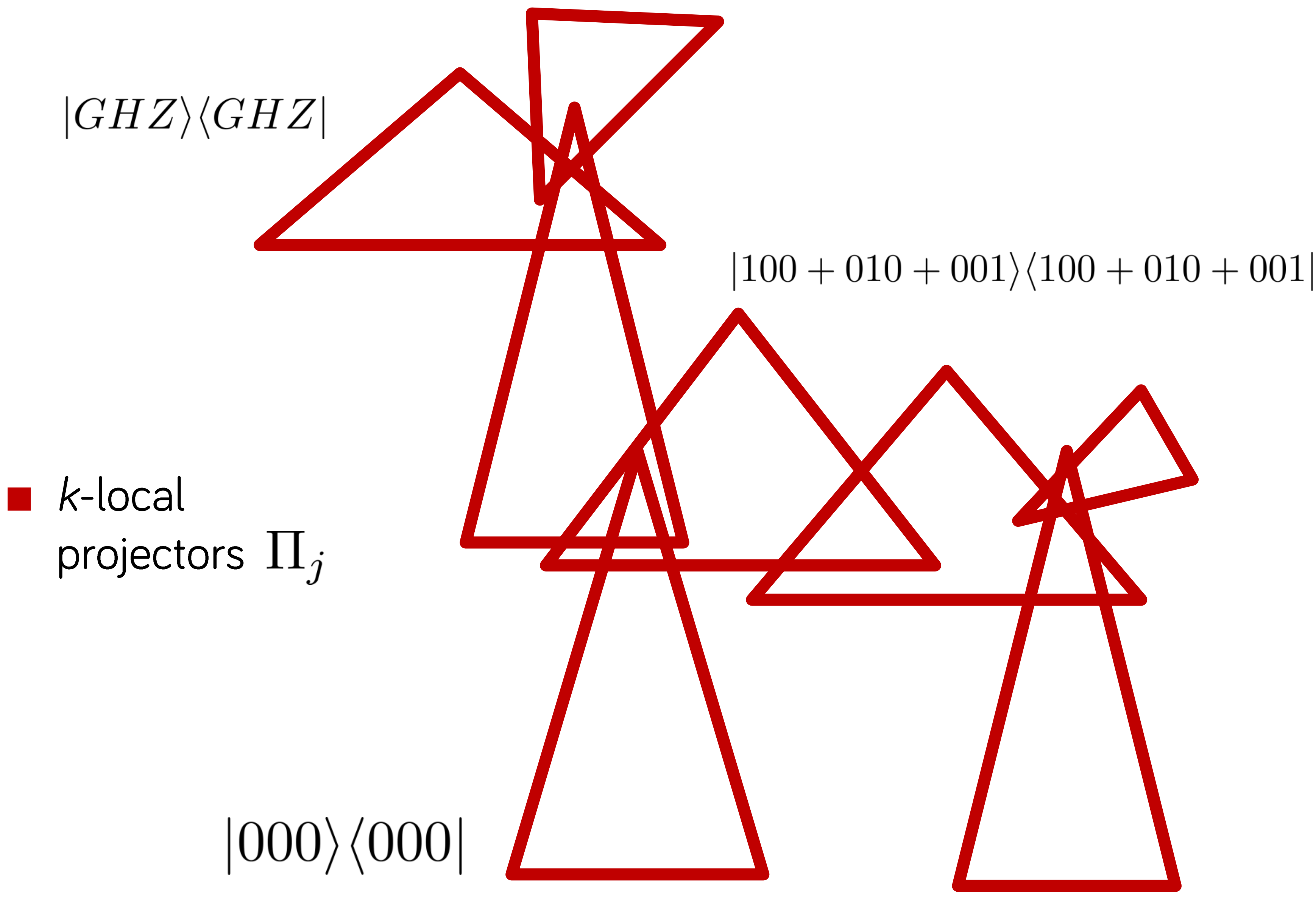


a global
ground state

HARD?

find & describe it?
is it entangled?

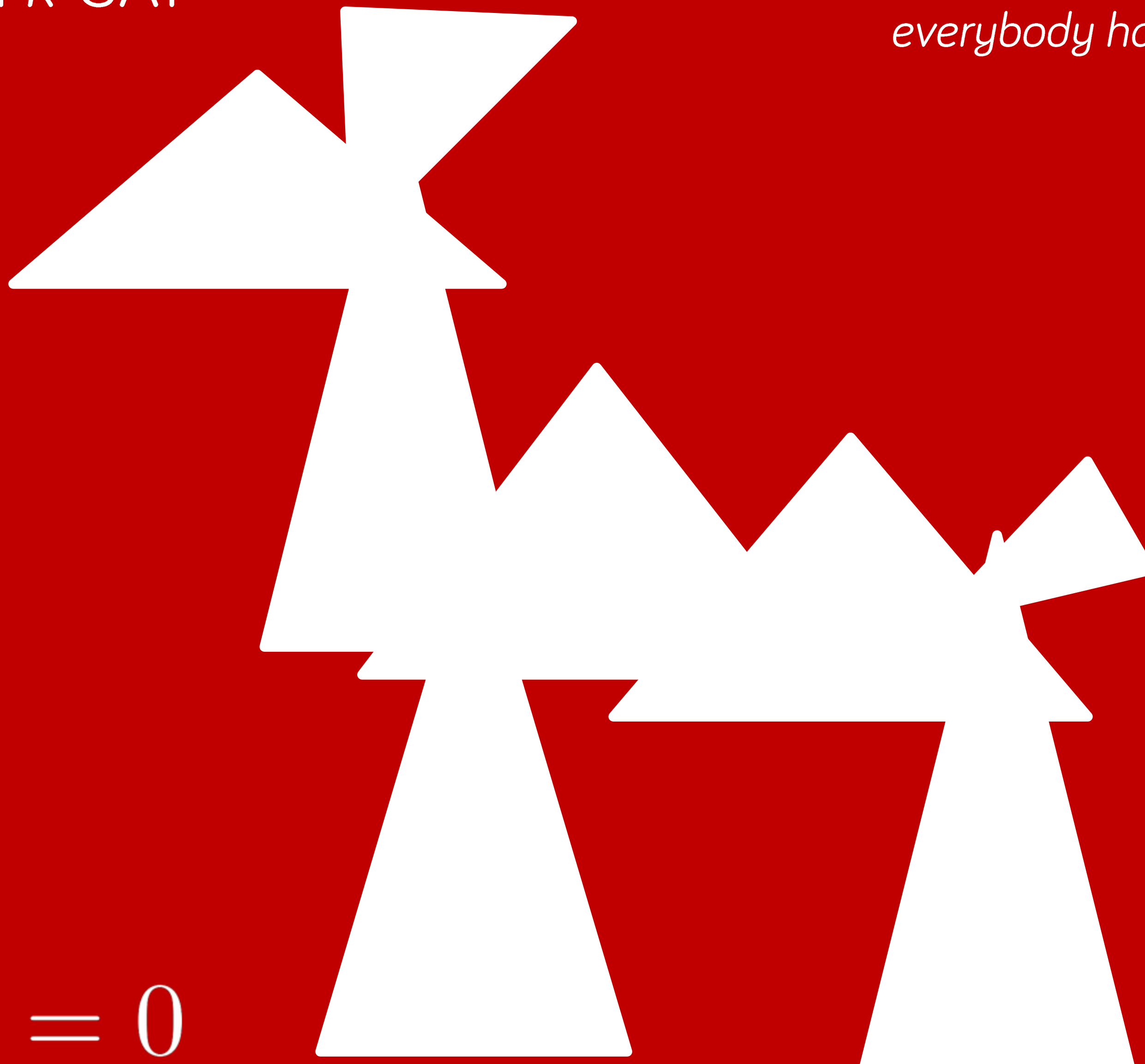

frustrated
FRUST
RATED



$|GHZ\rangle\langle GHZ|$
$|100+010+001\rangle\langle 100+010+001|$
k-local projectors Π_j
$|000\rangle\langle 000|$

Quantum *k*-SAT

Can we make everybody happy?



$$\Pi^j |\psi\rangle = 0$$

1 Local (k-body) Hamiltonians

- optimization

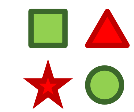
  QMA-completeness

$$H(t) = \sum_j H_j(t)$$

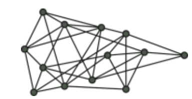
- dynamics

  BQP universality

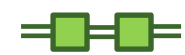
- local particle dimension



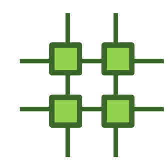
- interaction geometry



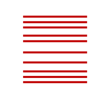
- time independence



- translational invariance



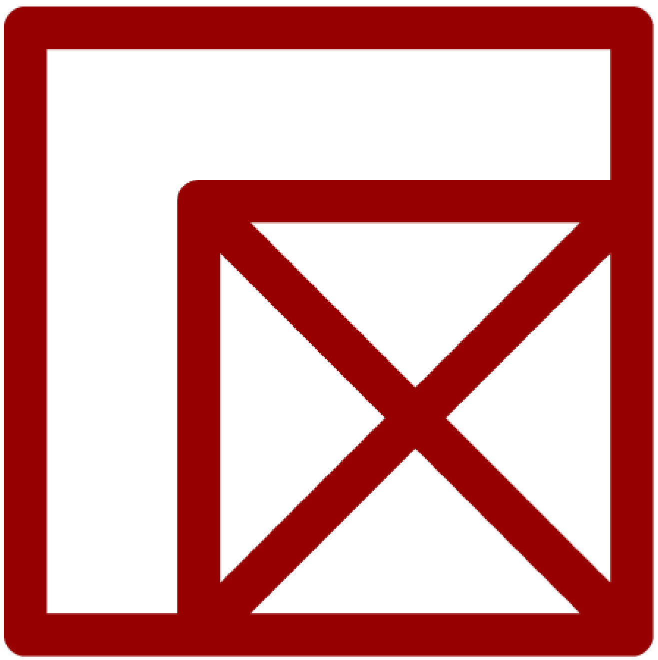
- promise gap, eigenvalue gap, energy × time cost

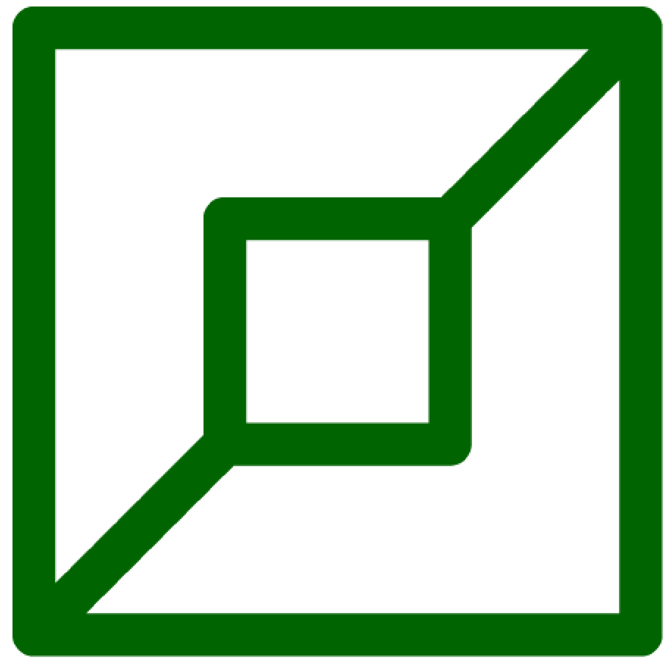


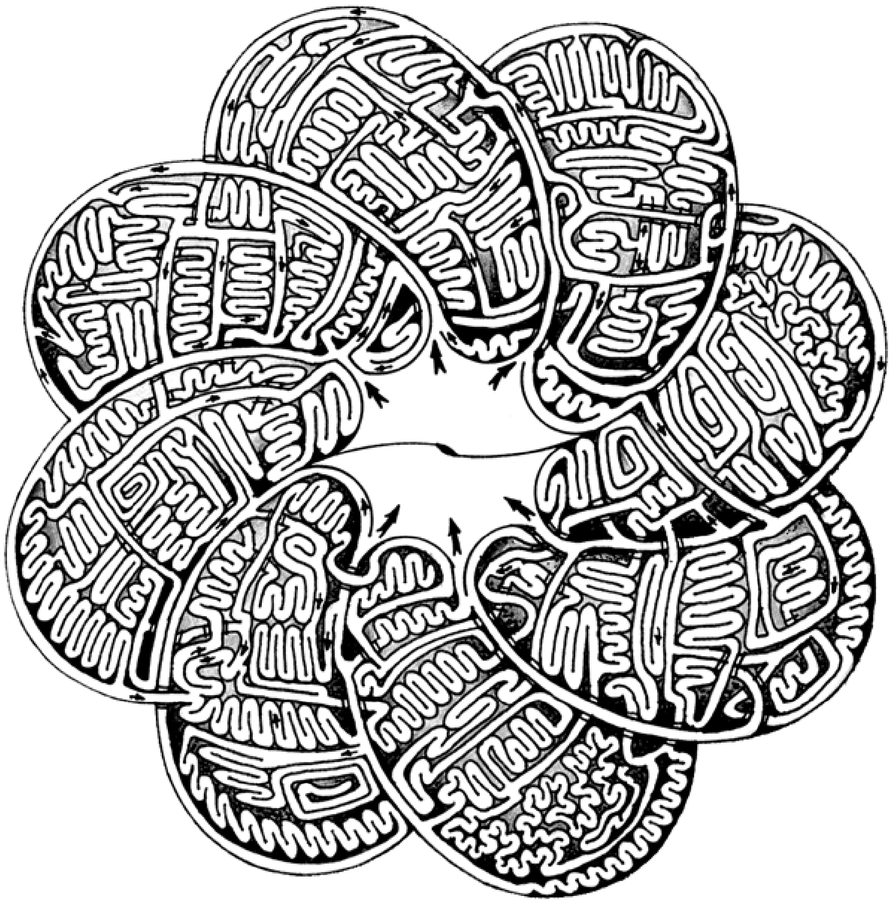
how hard
is this
question

[J. Howard Miller]

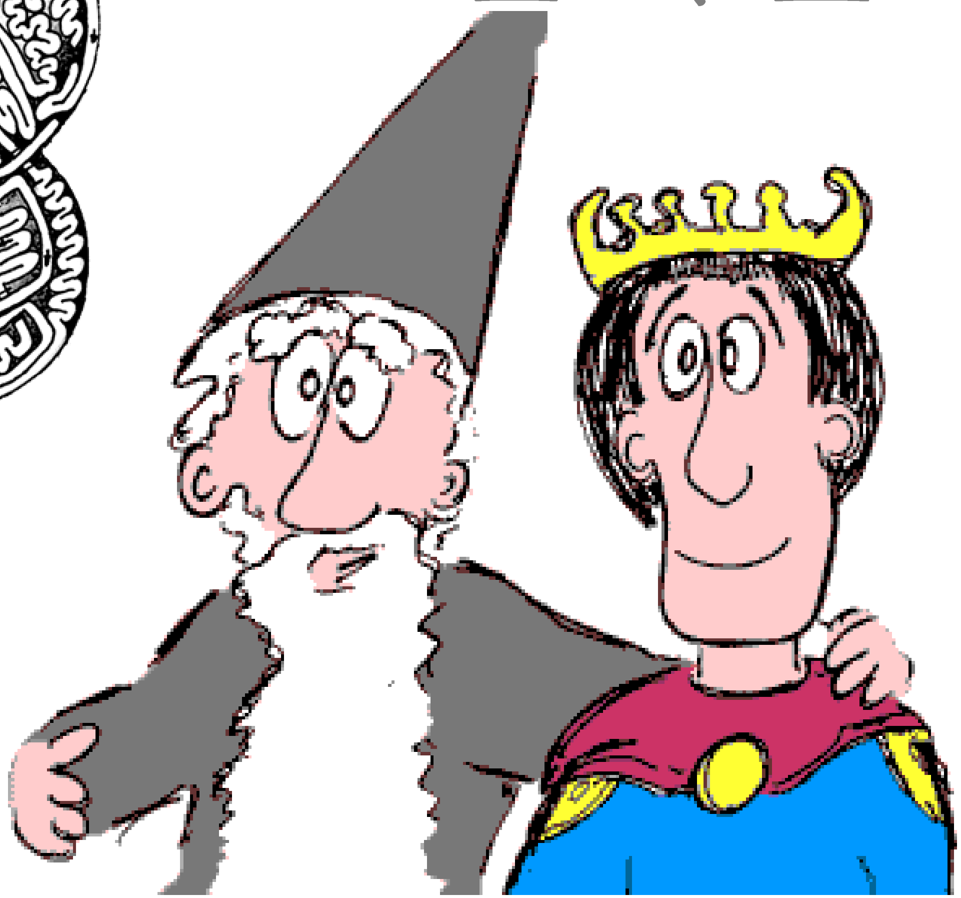
P





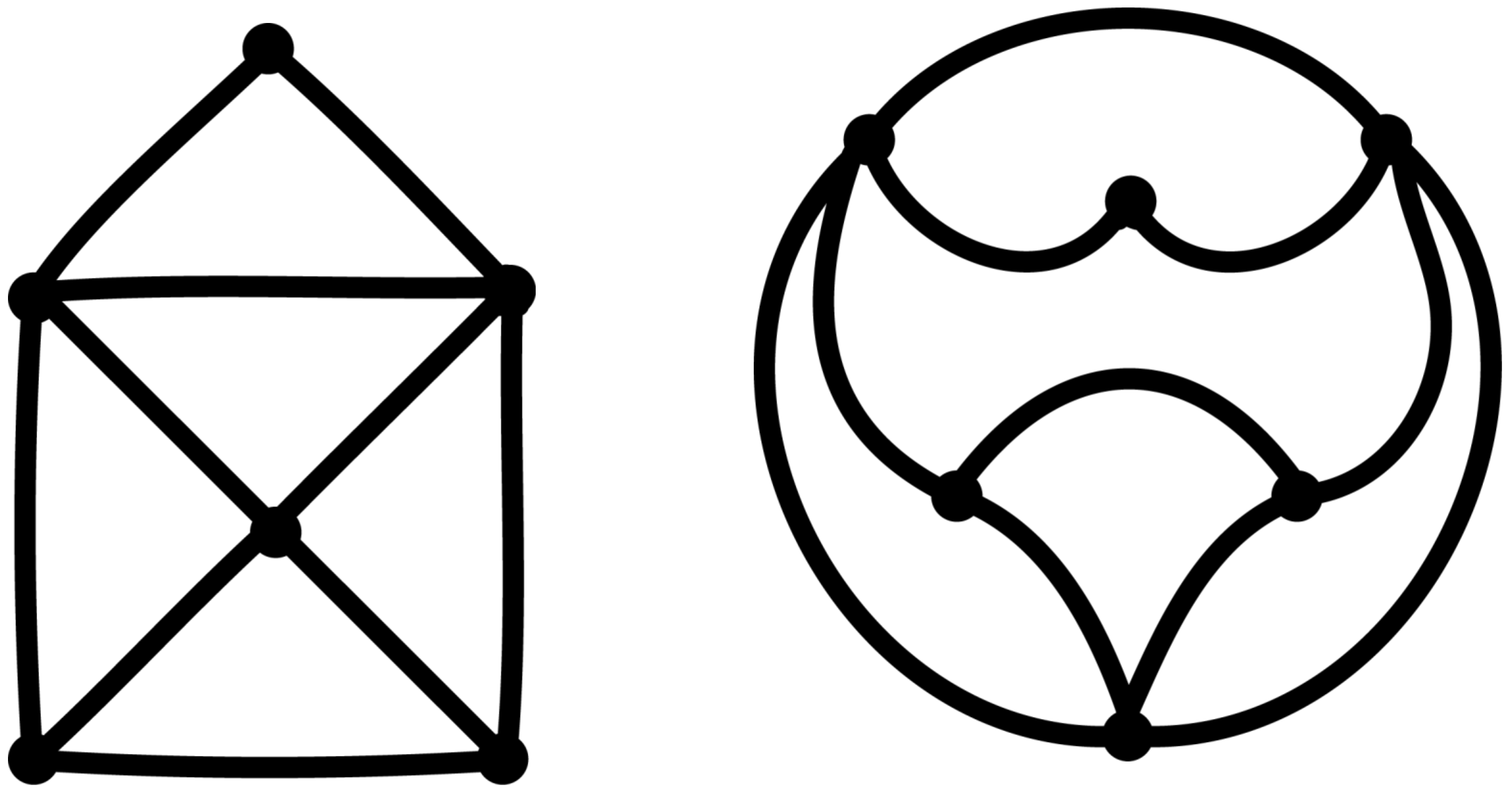


NP

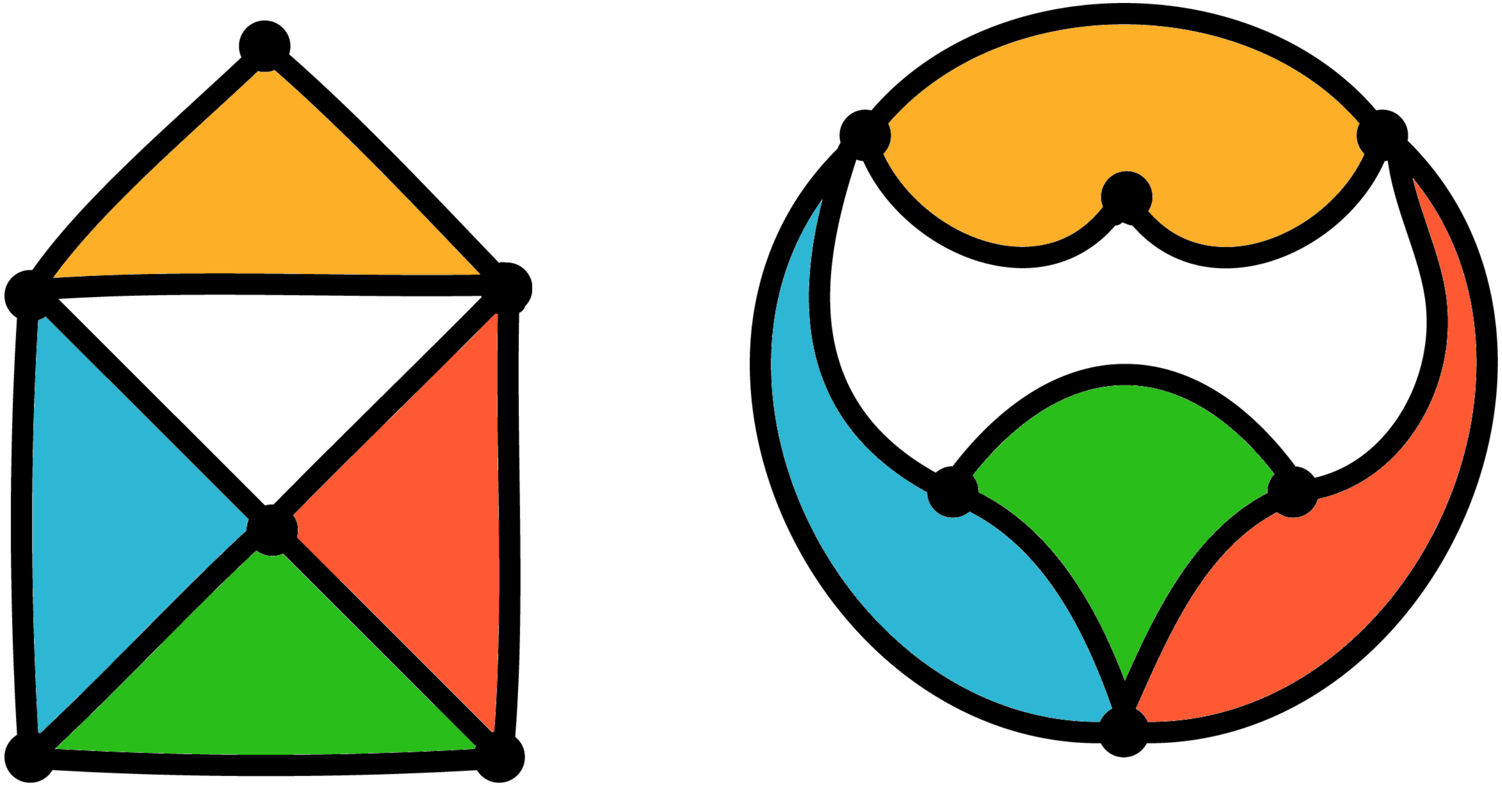


[maze: Andrew Bernhardt]
[A+M: primaryresources.co.uk]

2 A graph isomorphism puzzle



2 A graph isomorphism puzzle



2 A cryptarithmetic puzzle

```
    DID
+ DINOS
-------
  CROAK
```

?

[www.iread.it/cryptarithms.php]

2 A cryptarithmetic puzzle

$$\begin{array}{r} 595 \\ +\ 59842 \\ \hline 60437 \end{array}$$

!

Did dinosaurs exist?

?

a proof

a witness

a verification circuit

from a uniform family

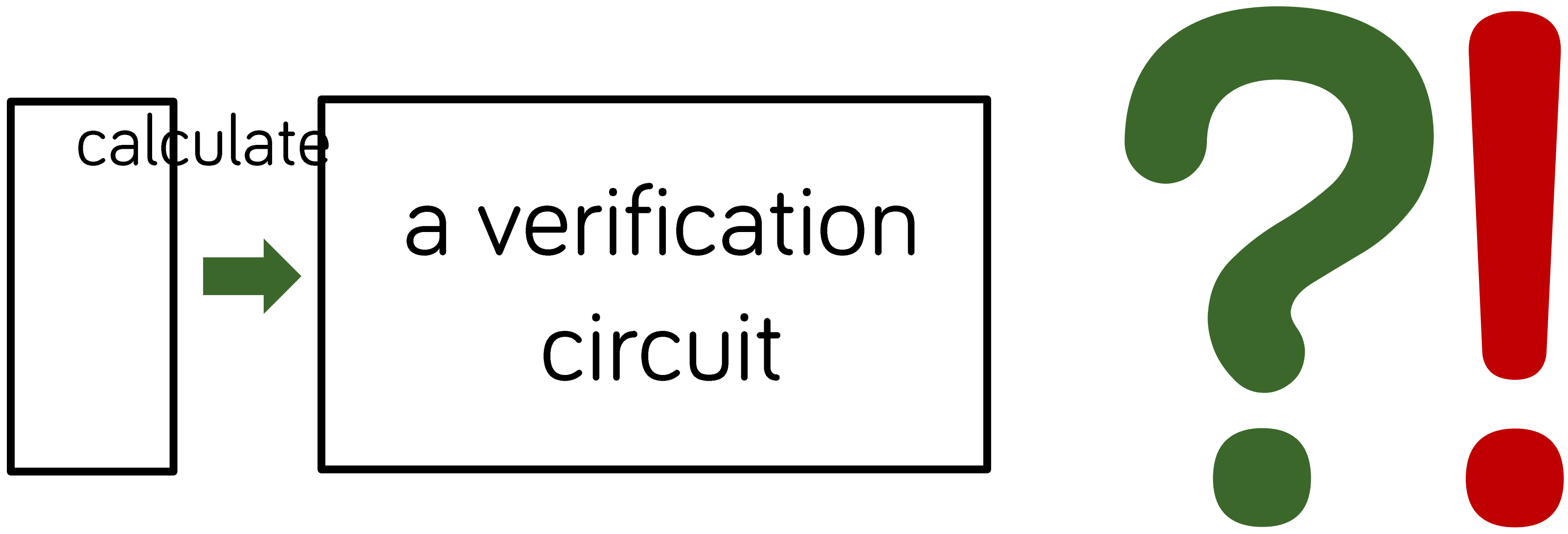
?!

YES? Accept a good proof.

NO? Reject forgeries.

2 The class P

Yes/no questions that we can answer.



YES? Figure it out by yourself.

NO? Figure it out by yourself.

2 The class NP

Yes/no questions, easy to verify solutions.

a verification circuit

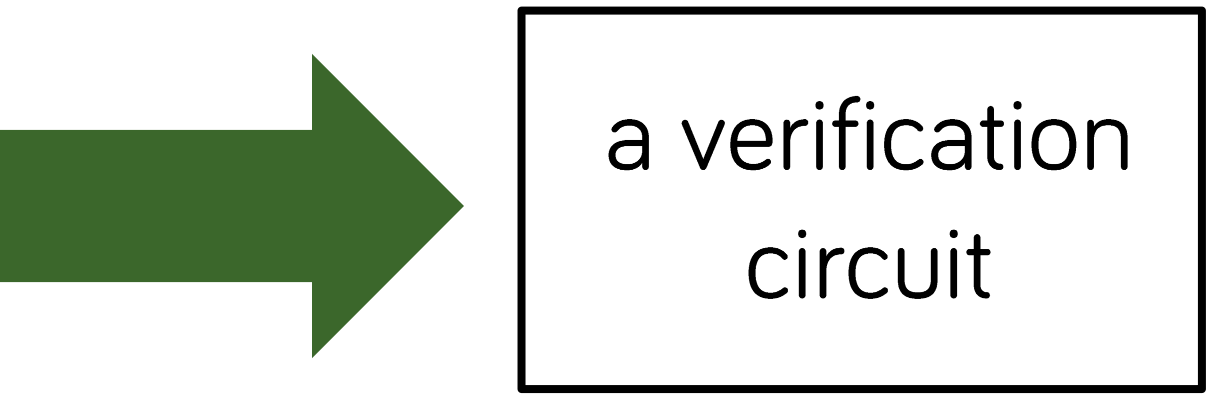
from a uniform family

?!

YES? Accept a good proof.

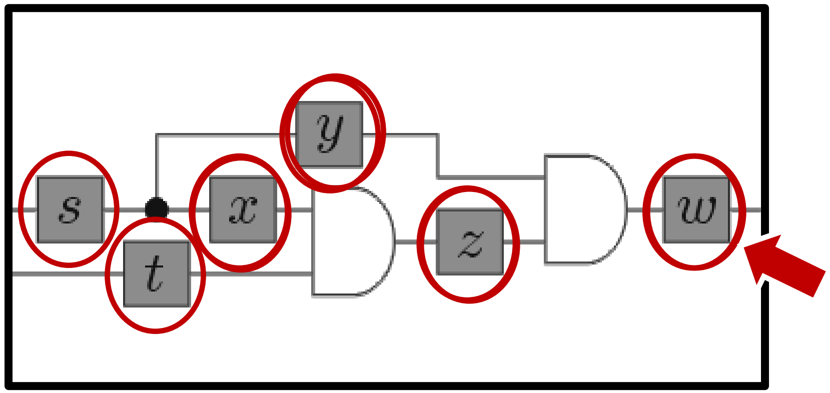
NO? Reject any witness.

- Can you solve this problem? You just solved all of NP.



Could this circuit ever output 1?

- Can you solve this problem? You just solved all of NP.



Could this circuit ever output 1?

3-local conditions

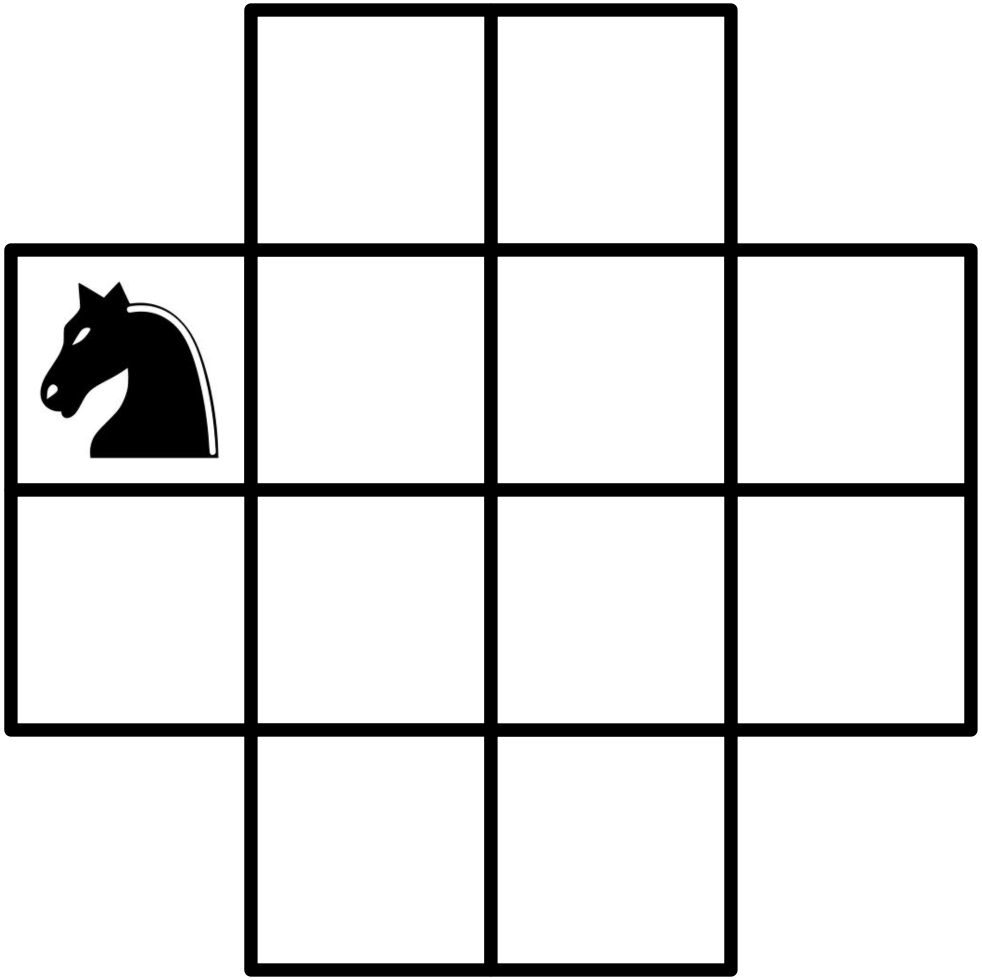
$(\cdots \vee \cdots \vee \cdots) \wedge (\cdots \vee \cdots \vee \cdots) \wedge \cdots$

- 3-SAT is NP-hard.

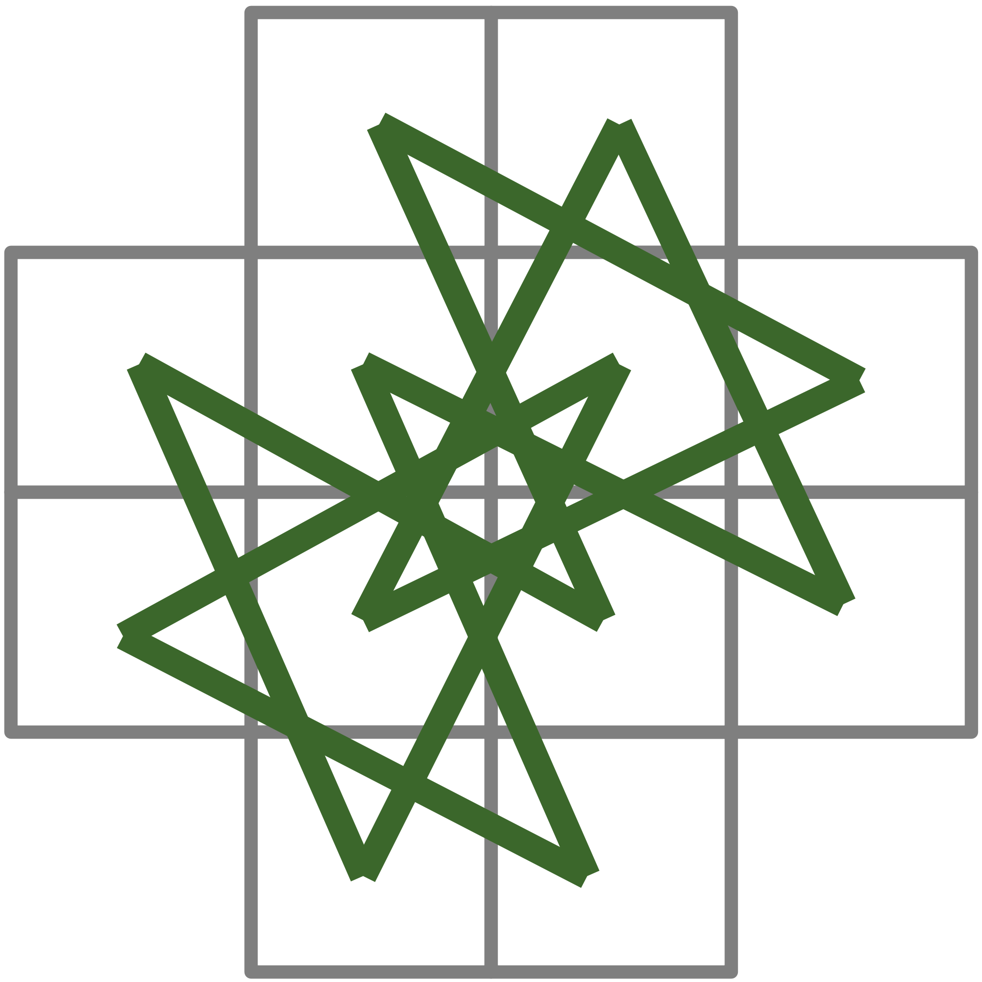
  in NP.

  NP-complete. [Cook, Levin]

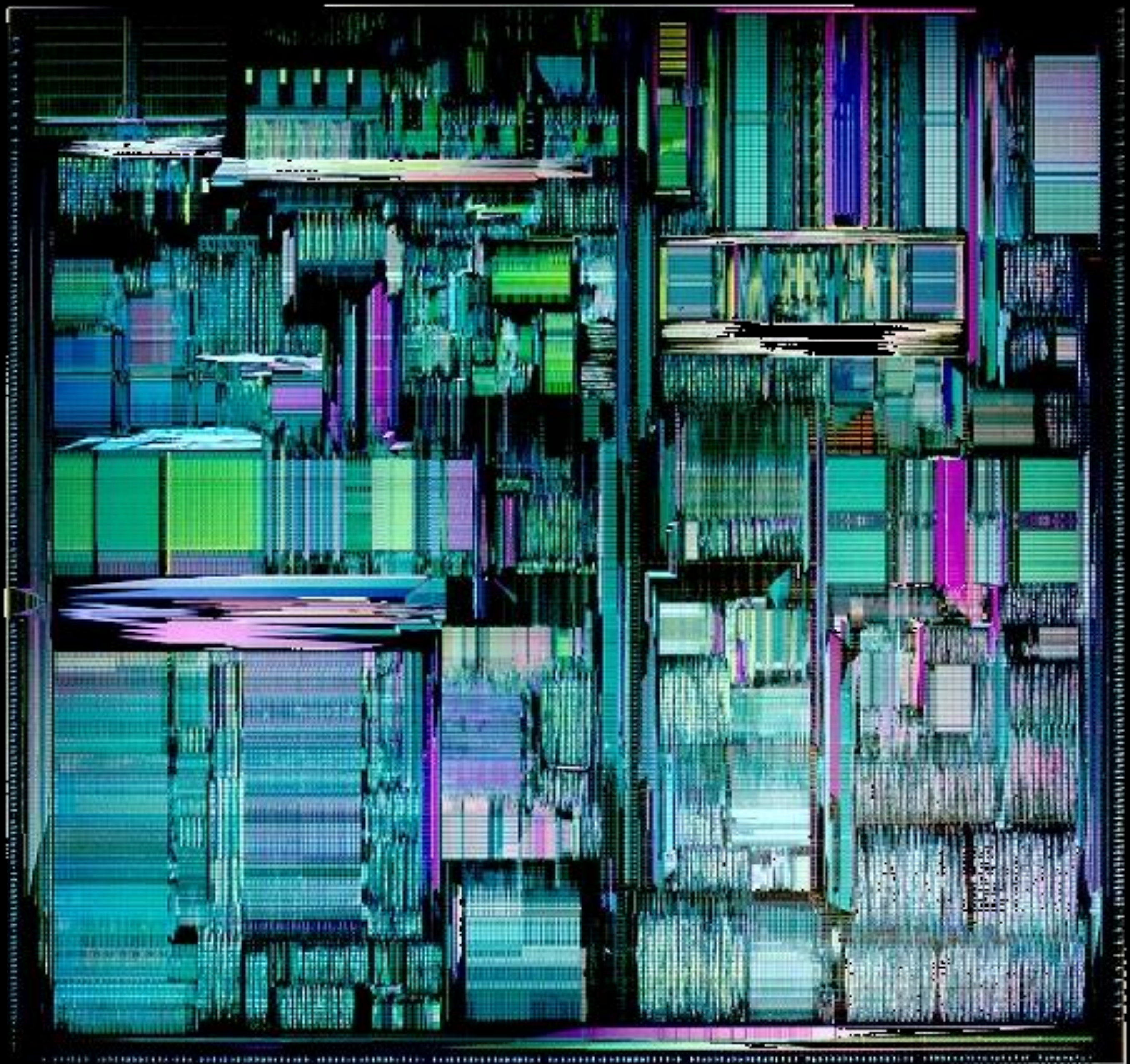
2 Hamiltonian cycle (also NP-c)



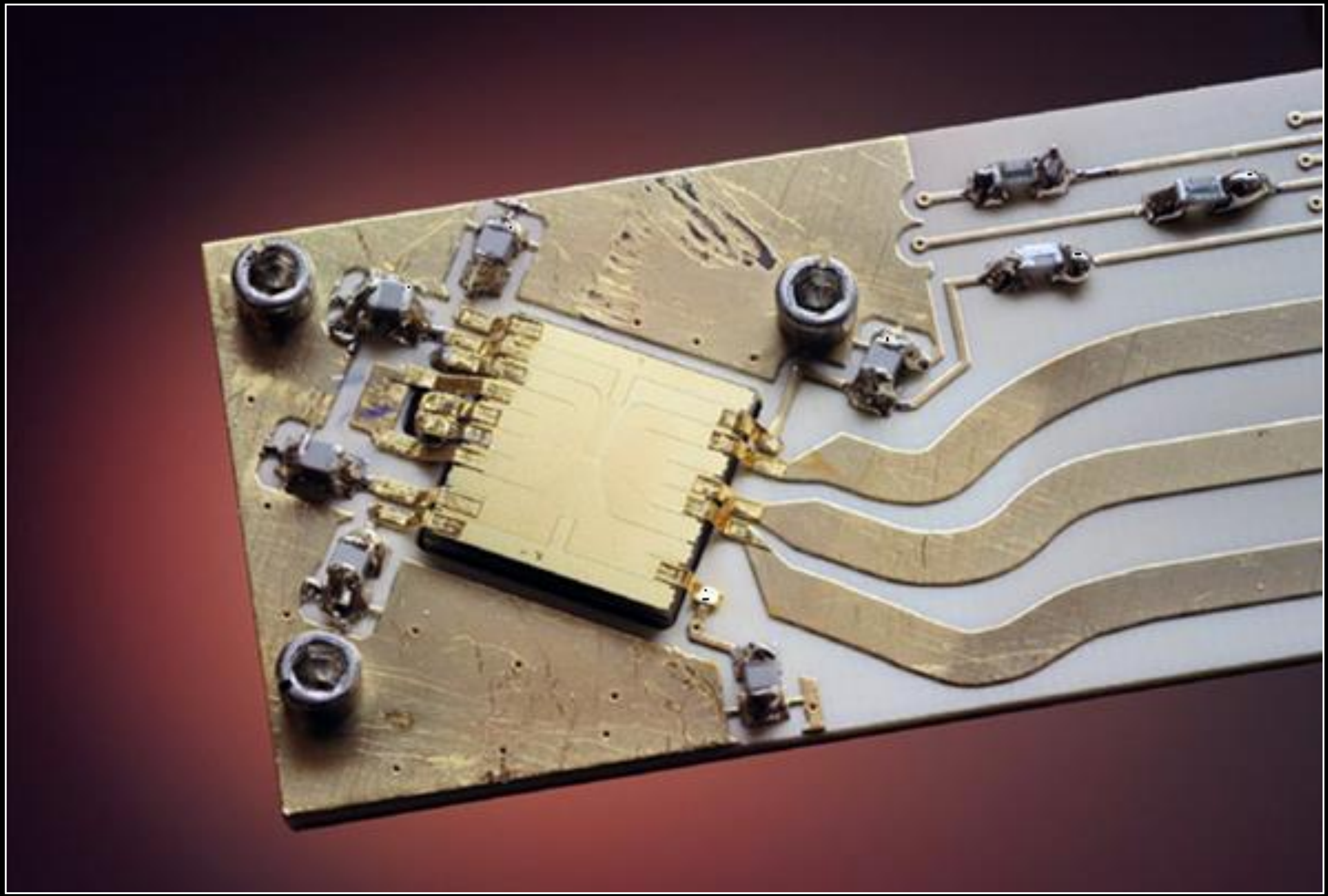
2 Hamiltonian cycle (also NP-c)



the puzzles of QMA



[1995 Pentium Pro



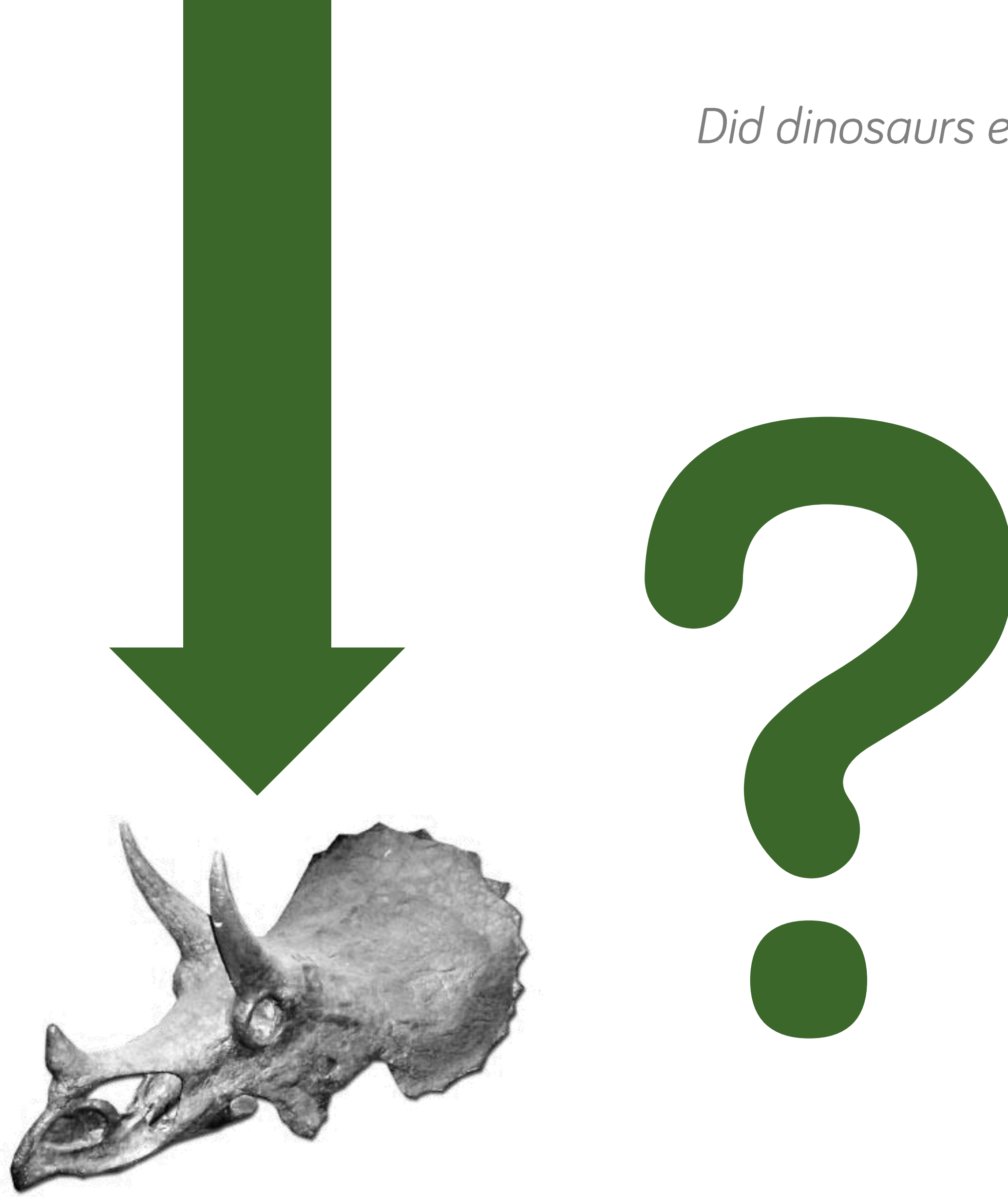
[NIST gold ion trap on aluminum-nitride backing, Y.Colombe/NIST]

[wire

Bounded error Quantum Polynomial time

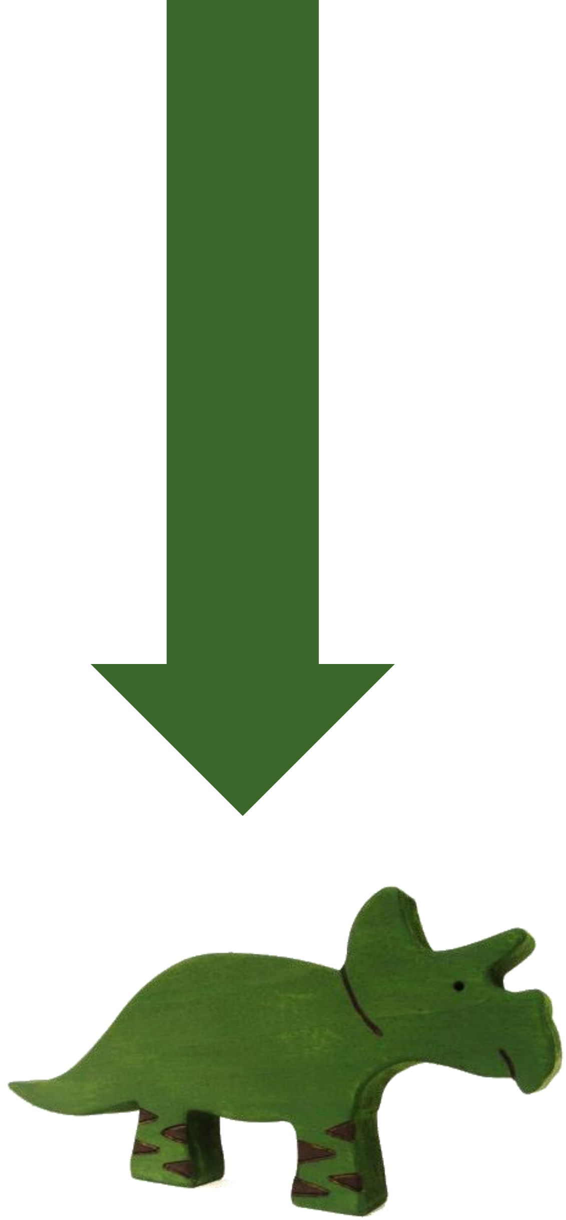
[tha

2 The MA protocol



2 The MA protocol

Did dinosaurs exist?



[wooden animals: Imagination Kids Toys]

2 The MA protocol

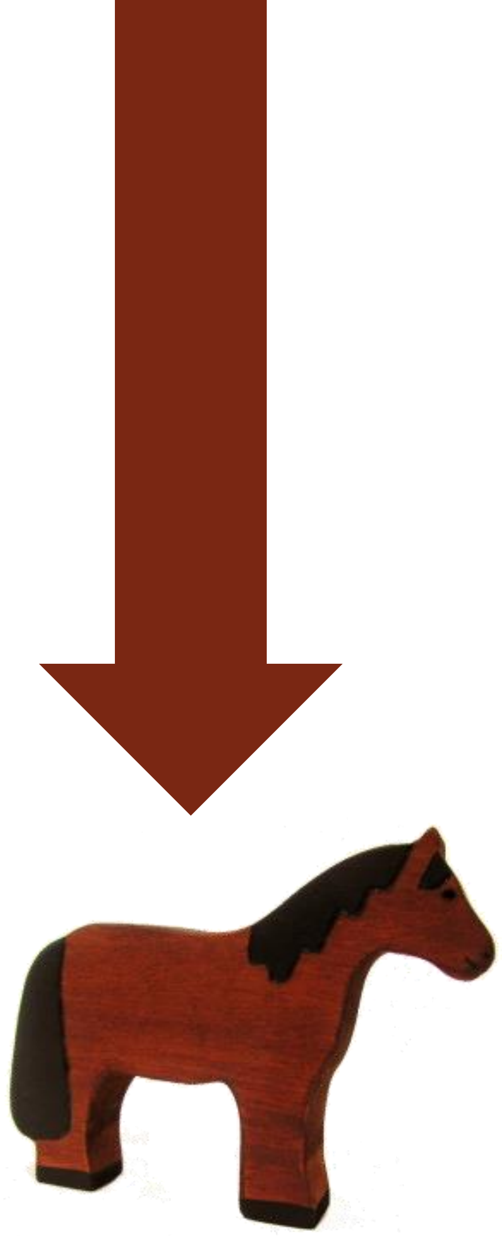
Did dinosaurs exist?

YES?
Eager to be
convinced.

[magnifying glass: hillllall]

2 The MA protocol

Recognizing fakes?



2 The MA protocol

Recognizing fakes?

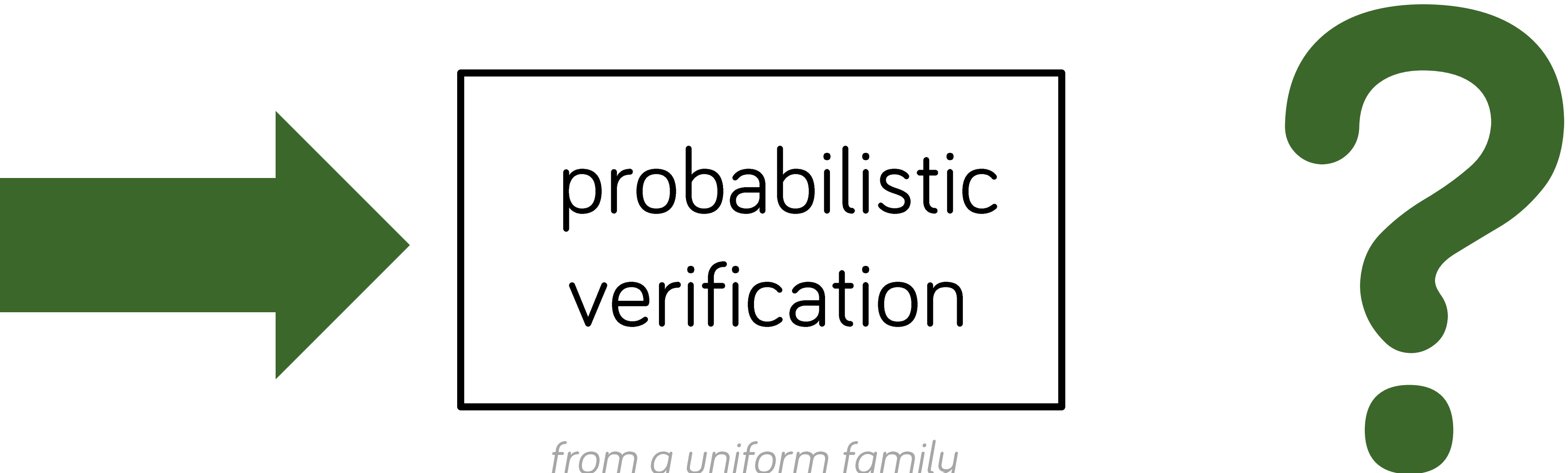
NO?
Don’t be
fooled
easily.

2 Probabilistic checks

Sometimes reject a genuine proof?

Accept a fake?

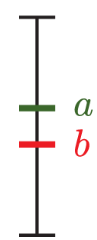
Probabilistic checks.



from a uniform family

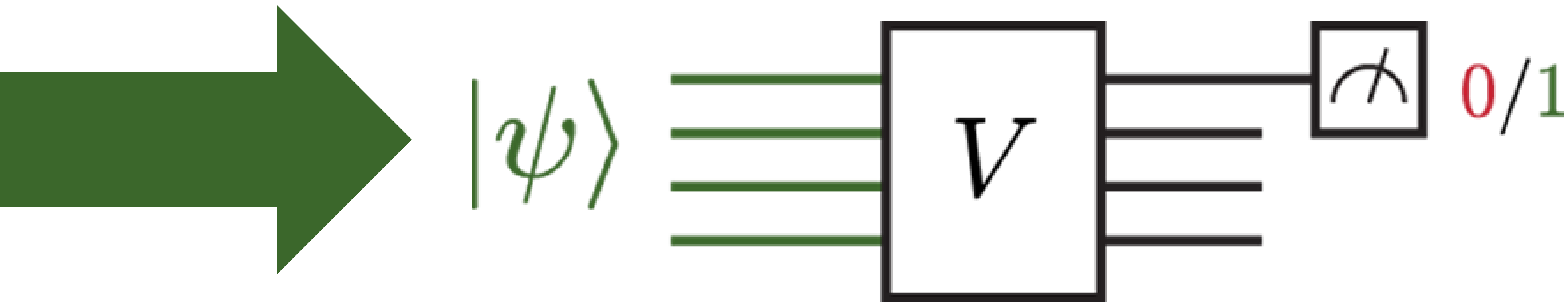
YES? Accept a good proof with p > a.

NO? Probability of accepting p < b.



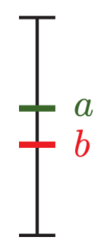
2 The QMA protocol

a quantum verifier



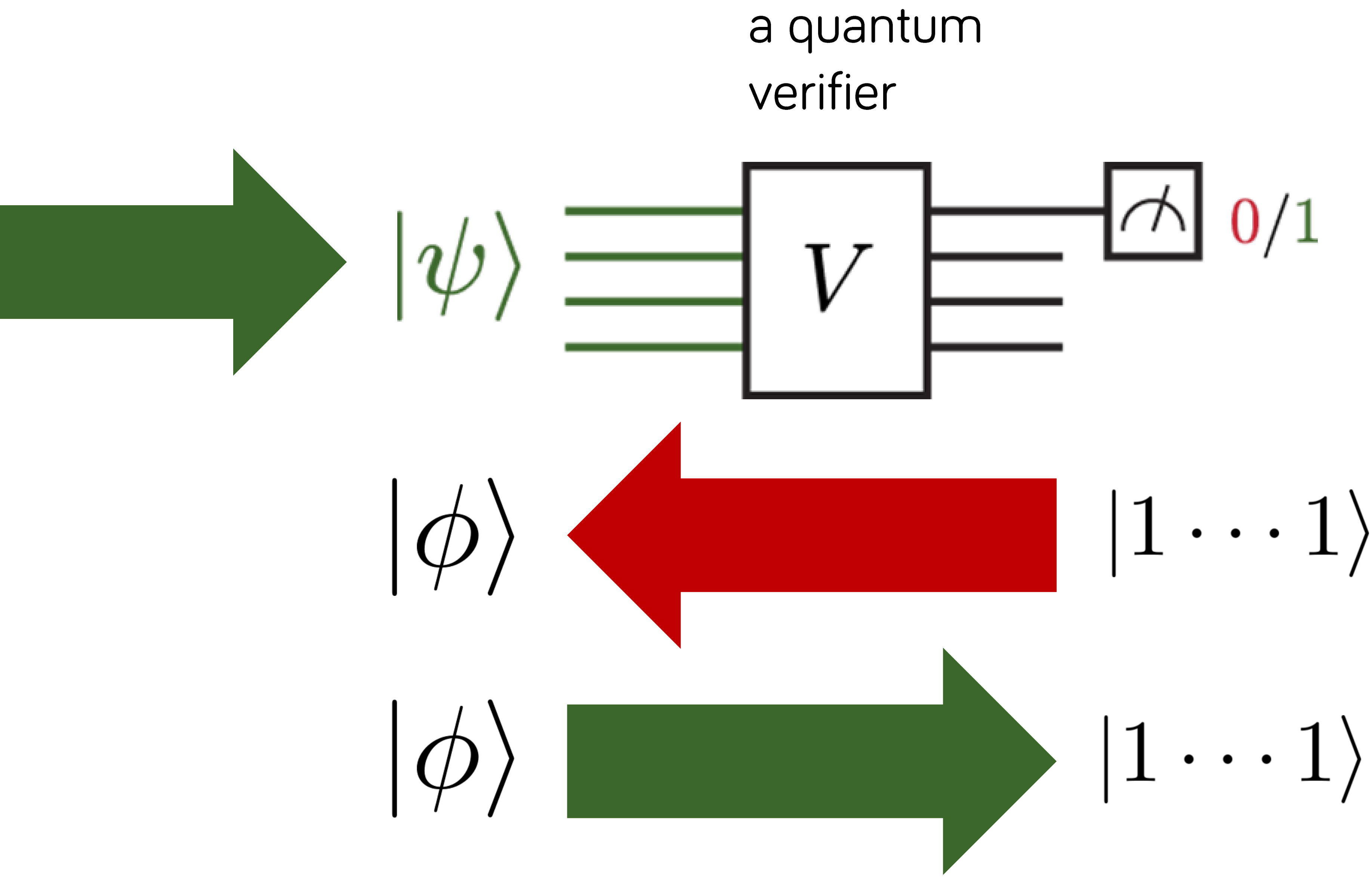
YES? Accept a good proof with $p > a$.

NO? Probability of accepting $p < b$.

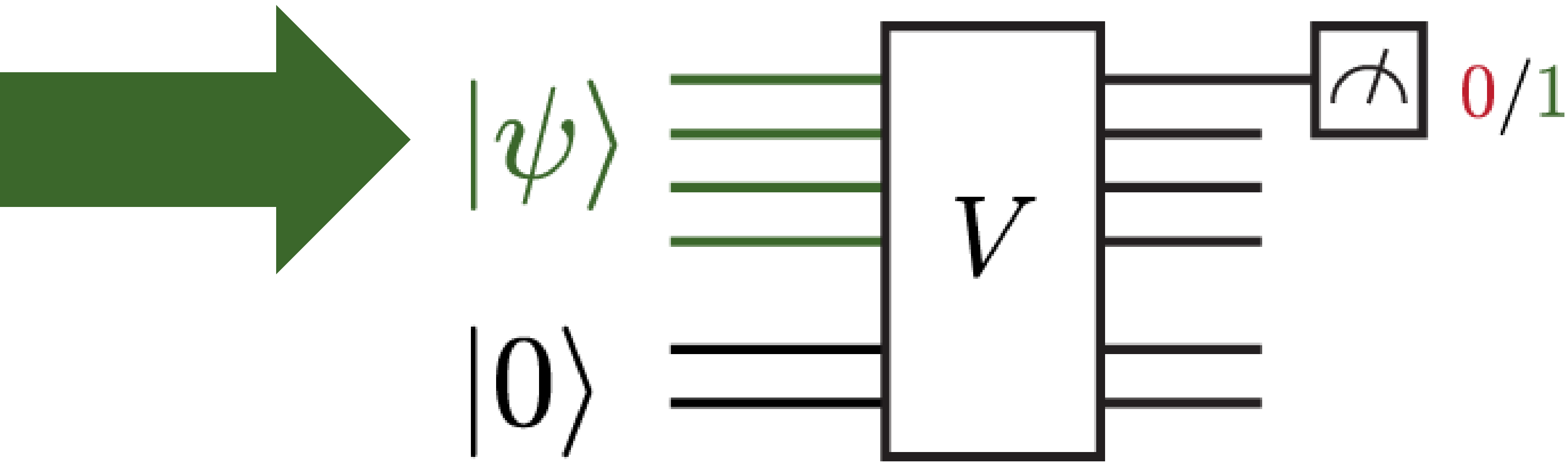


2 The QMA protocol

This is too simple.

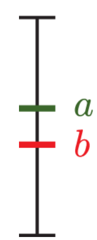


Ancillas are necessary.

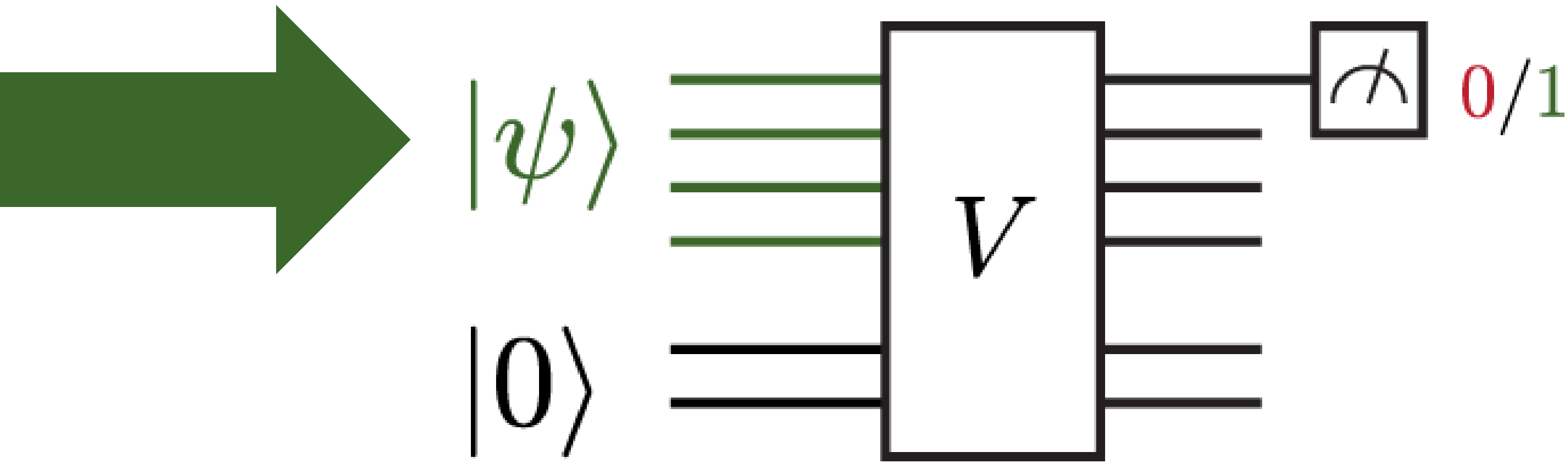


YES? Accept a good proof with $p > a$.

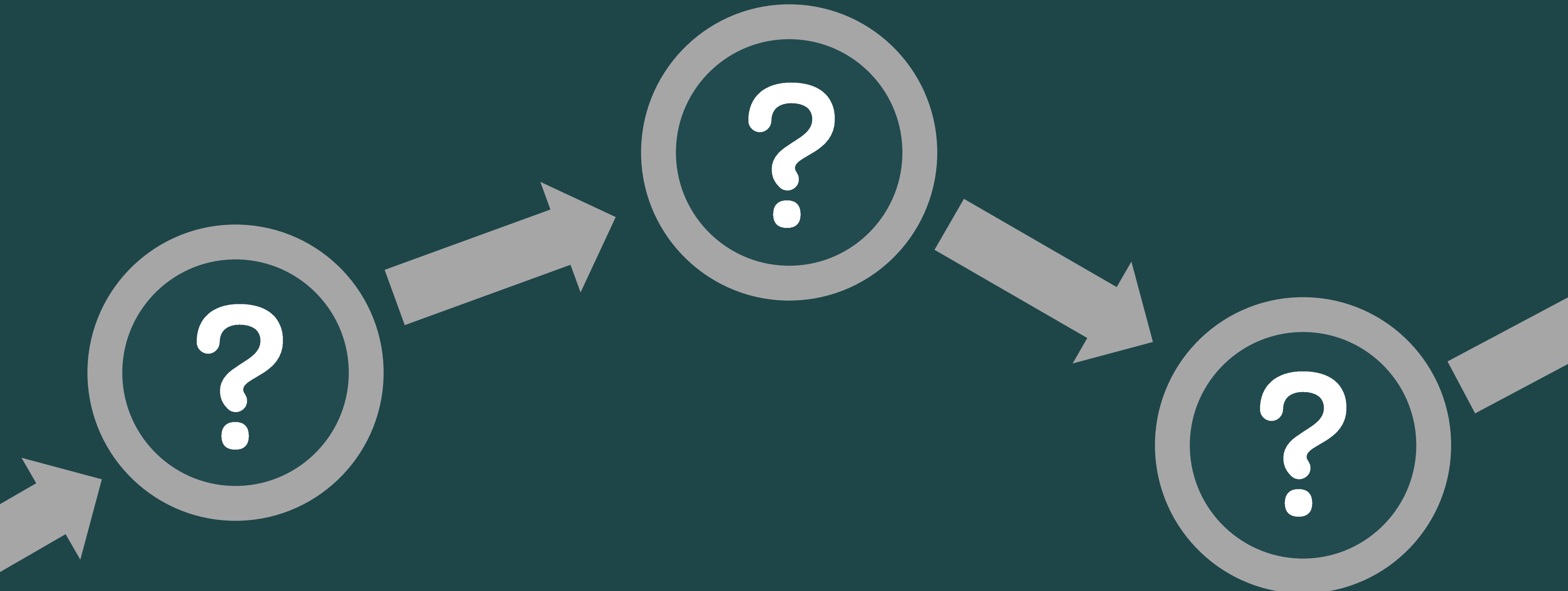
NO? Probability of accepting $p < b$.



2 A QMA-hard question



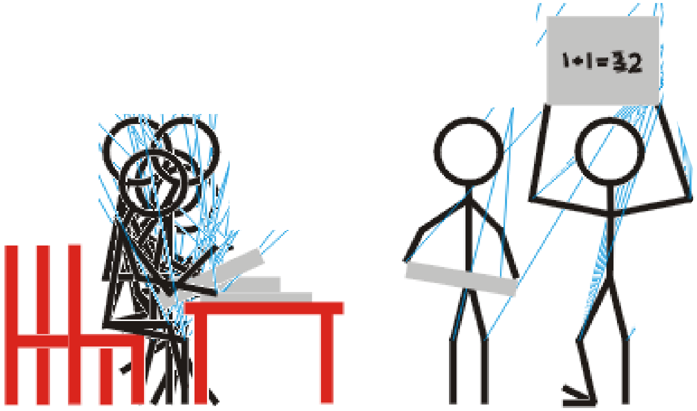
Could we feed this quantum verifier something that likely outputs 1?



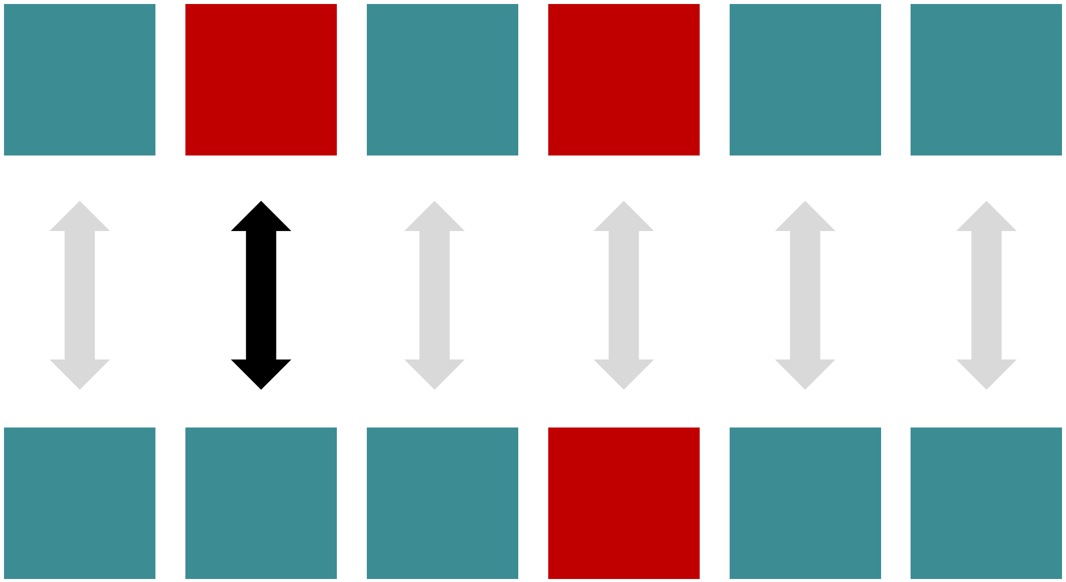
the history state

the ground state

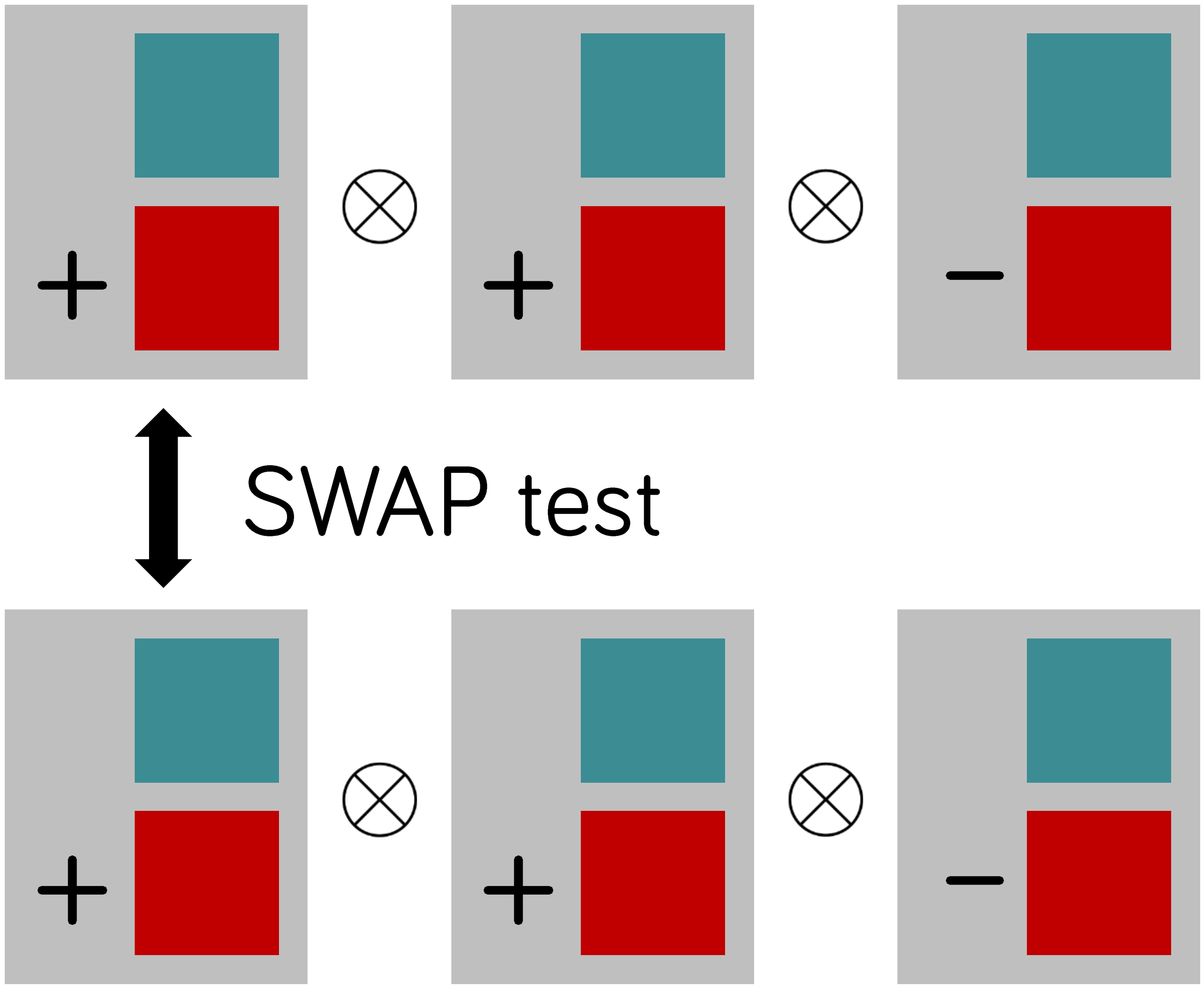
2 Snapshots of a computation



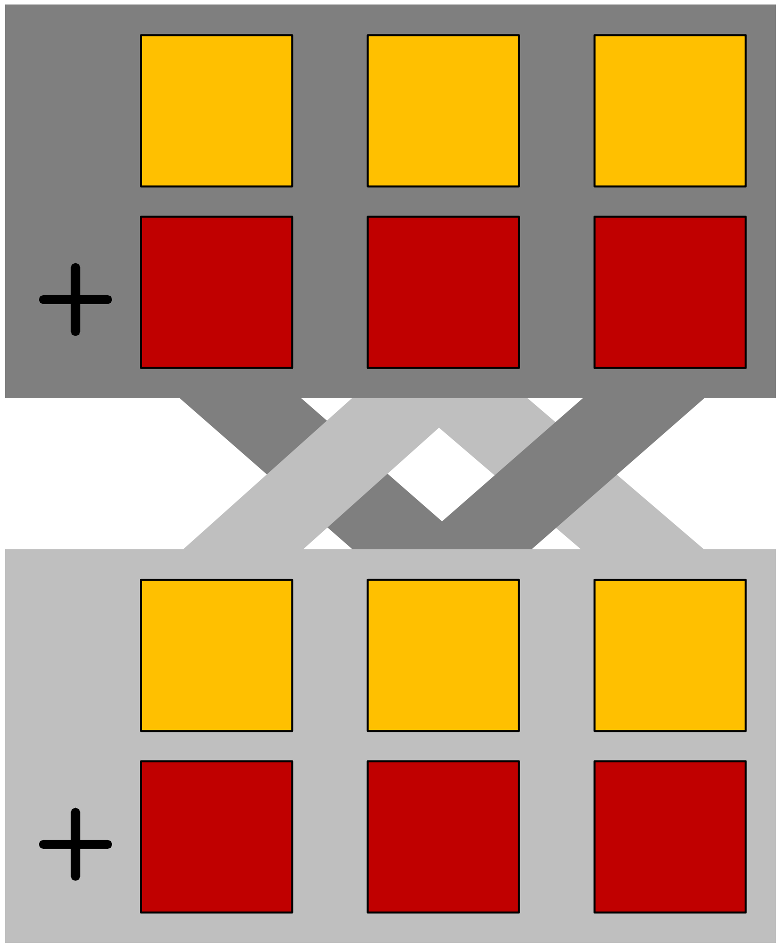
Locally comparing strings.



Locally comparing product states.



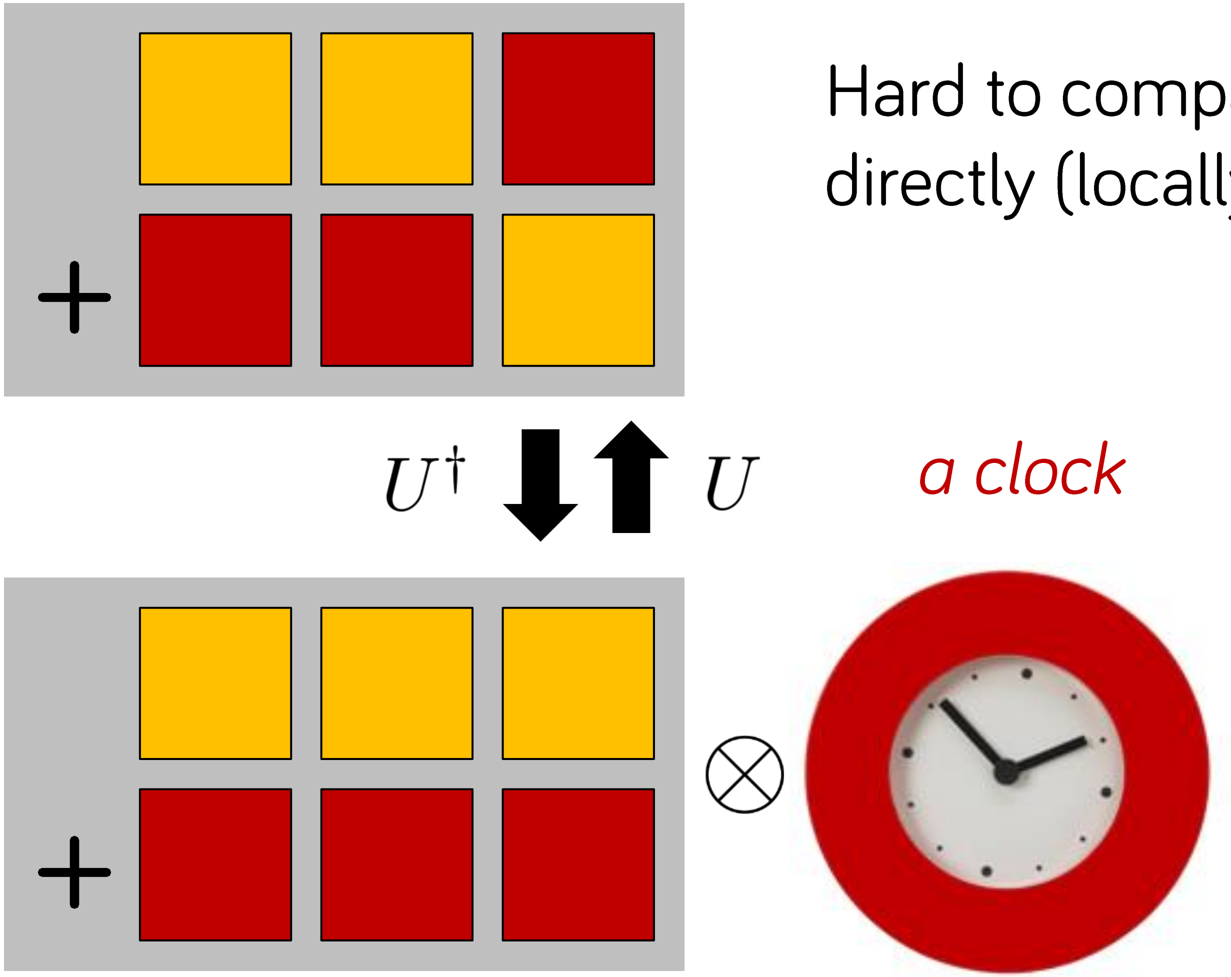
Locally comparing entangled states?



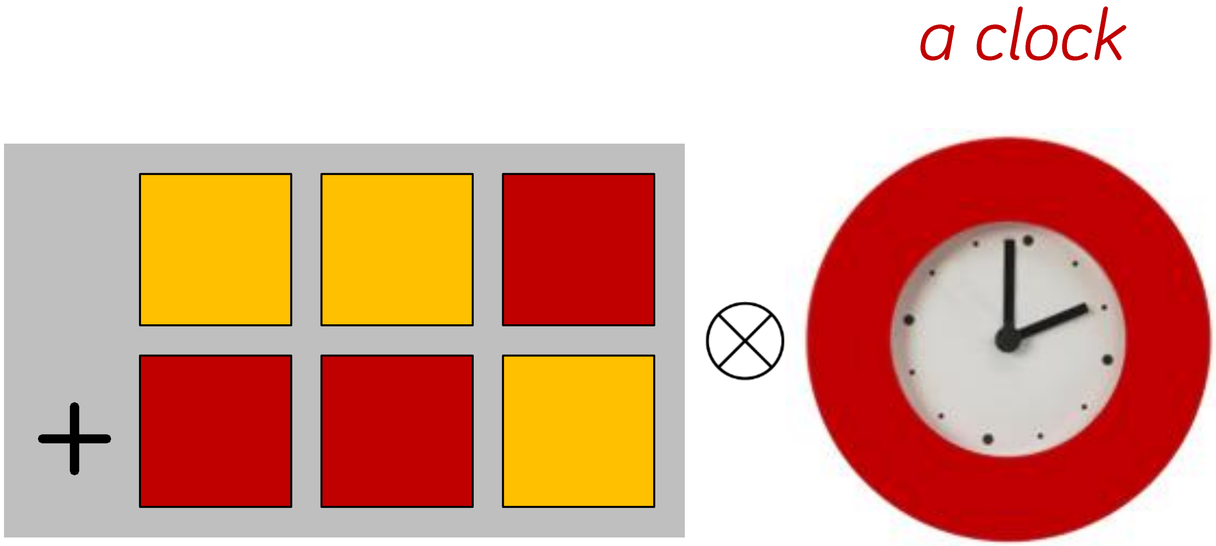
UGH!

2 Labeling the data

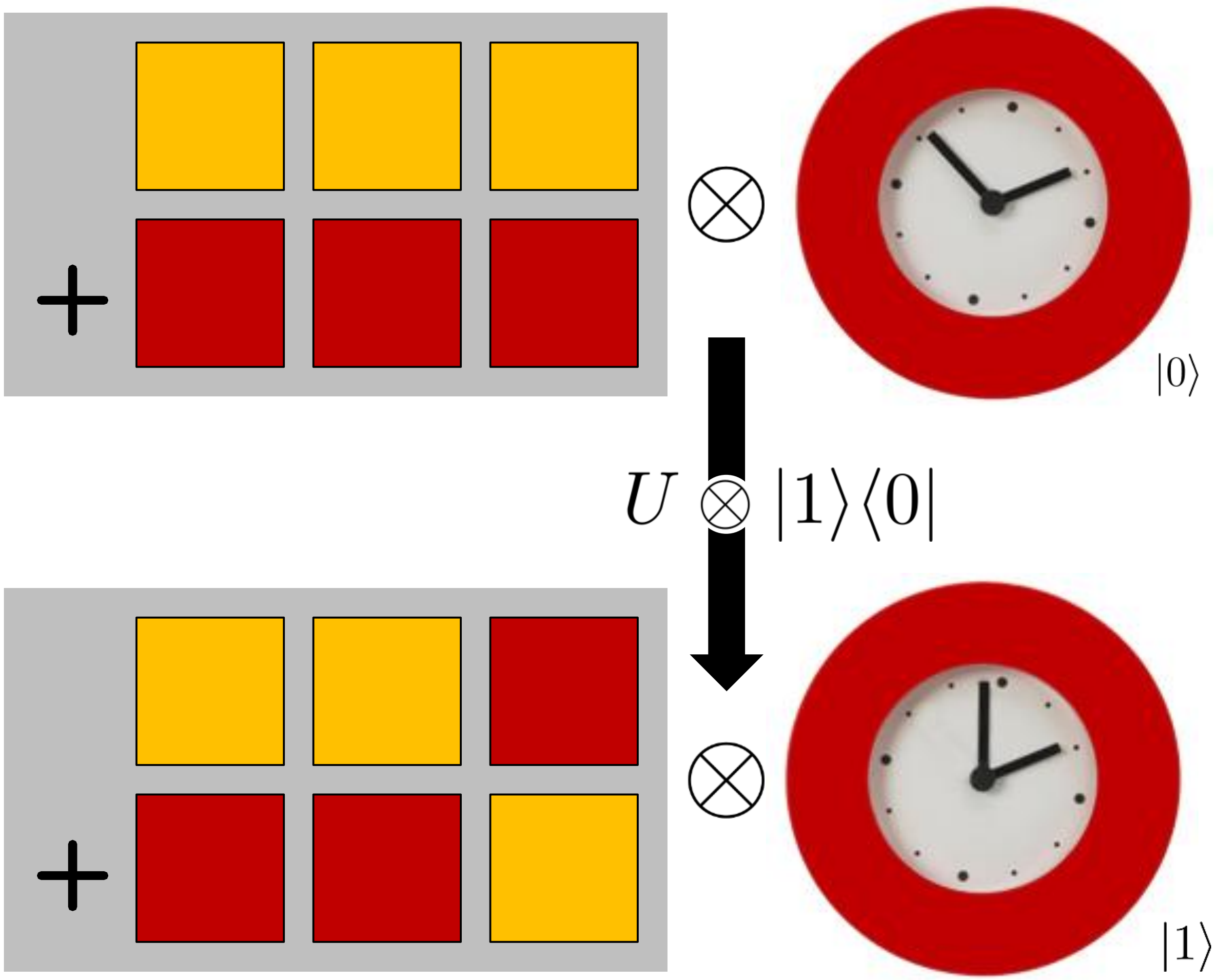
Hard to compare directly (locally).



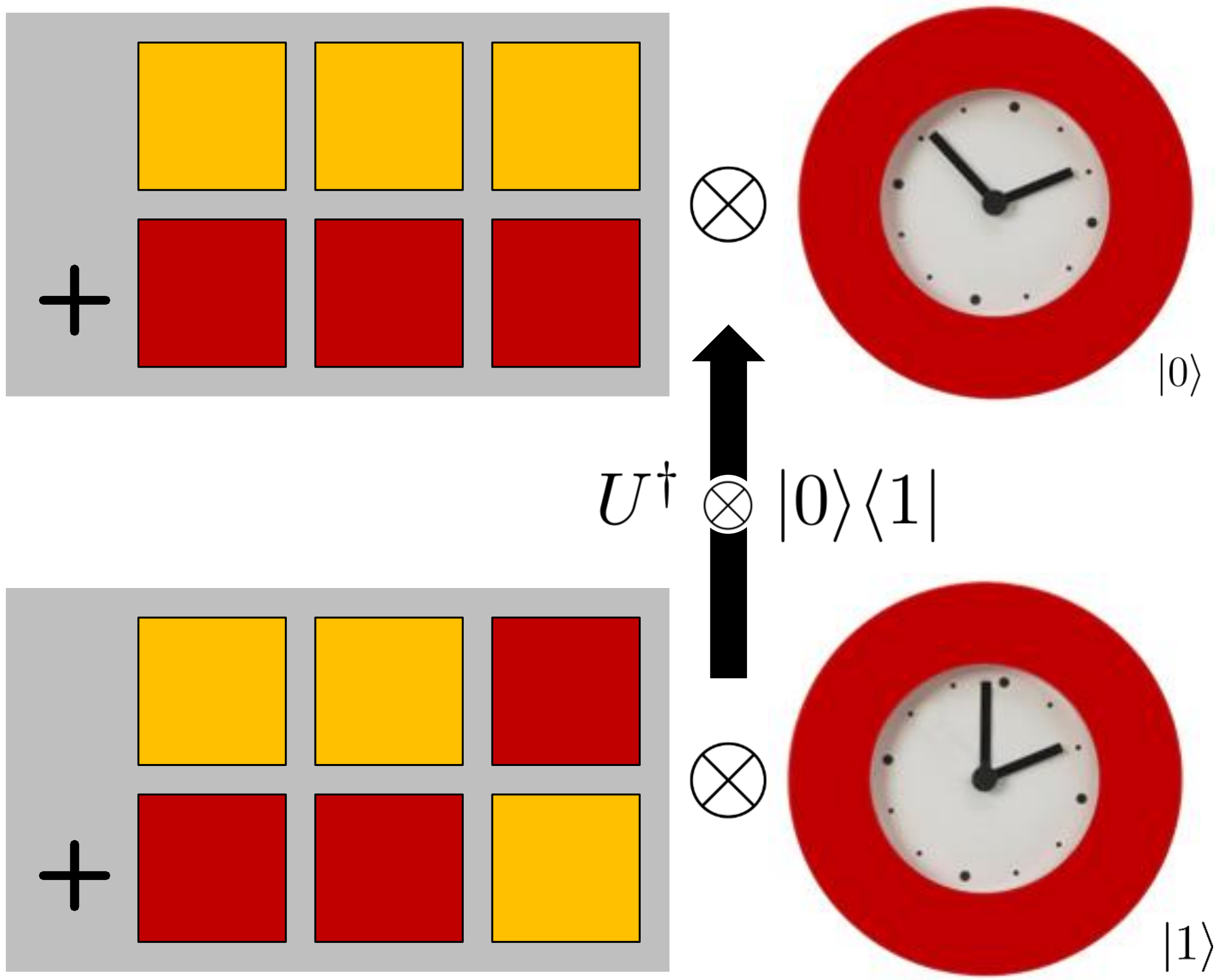
2 Labeling the data



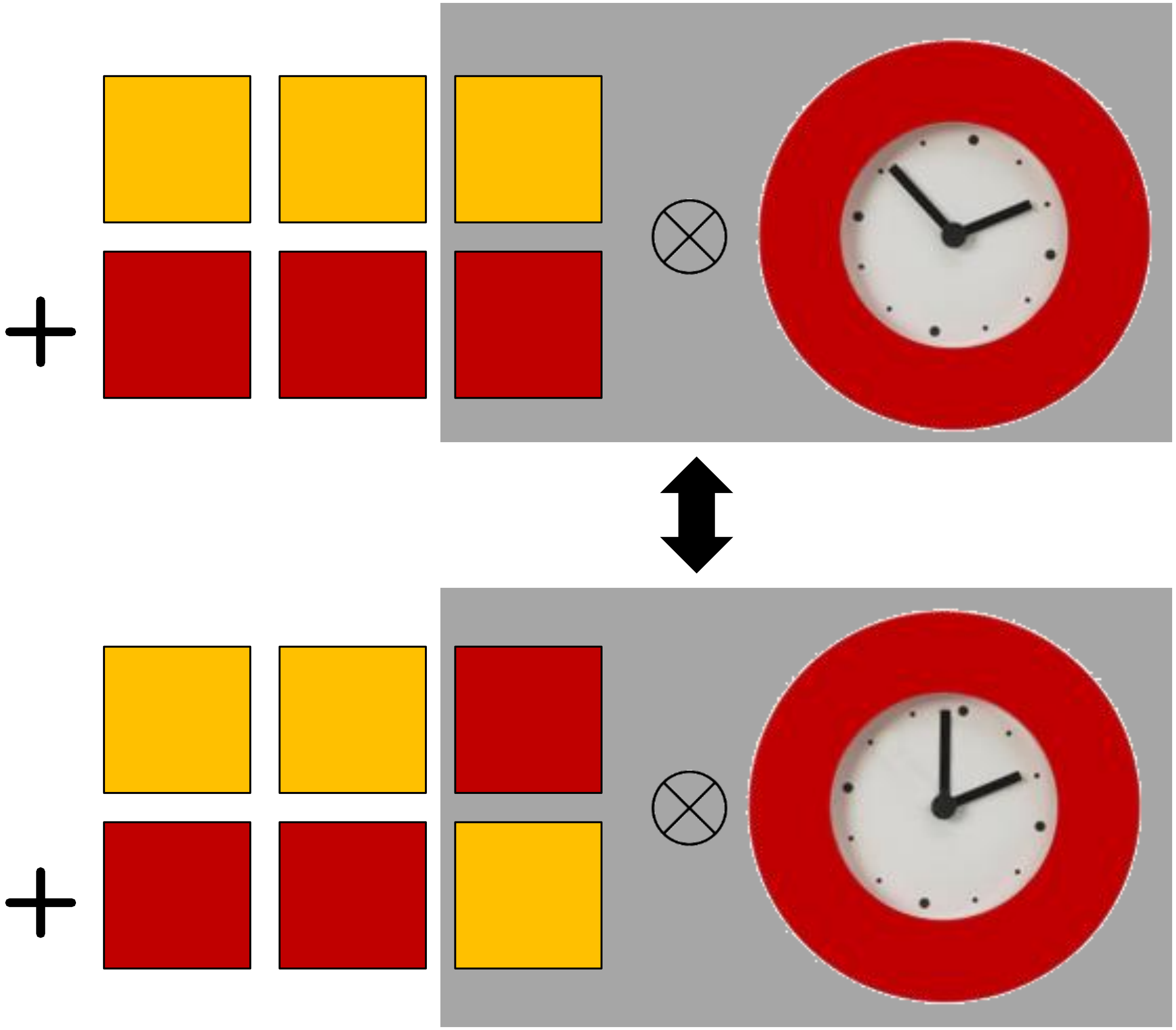
2 The data & the clock



2 The data & the clock

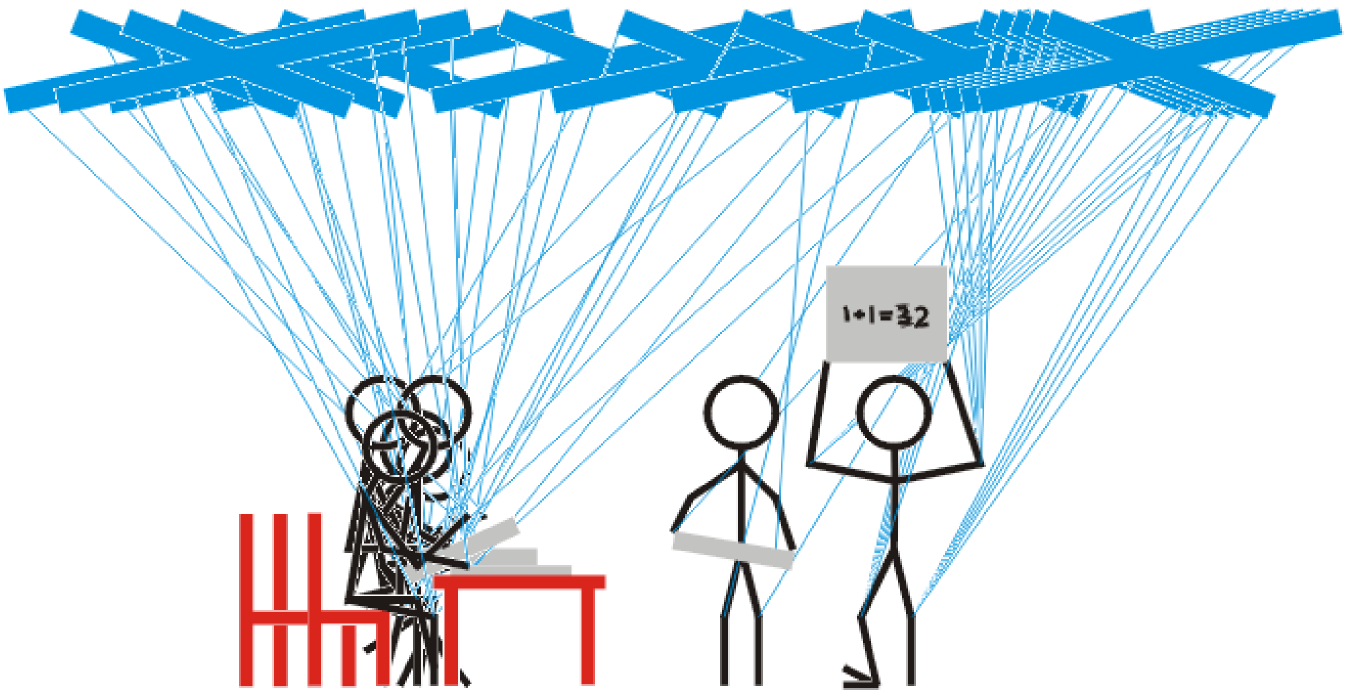


2 The data & the clock: locally comparing related states

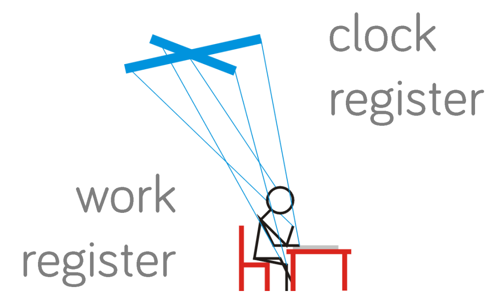


2 Feynman's computer

The data & a pointer.



2 Feynman's (Hamiltonian) computer

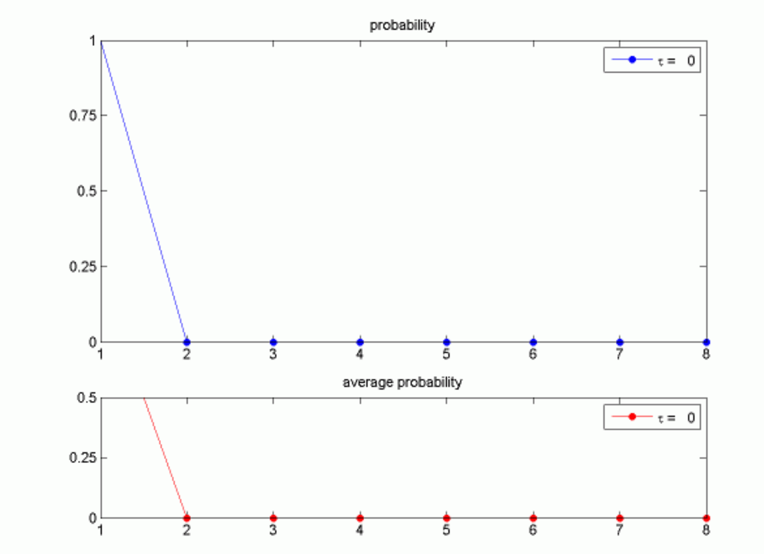


- The Hamiltonian

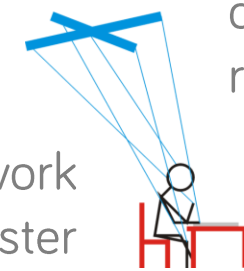
$$H_F = -\sum_{t=1}^{L} \left(U_t \otimes |t\rangle \langle t-1| + U_t^\dagger \otimes |t-1\rangle \langle t| \right)$$

- A quantum walk on a "line"

$$|\varphi_0\rangle \otimes |0\rangle_c$$
$$U_1 |\varphi_0\rangle \otimes |1\rangle_c$$
$$U_2 U_1 |\varphi_0\rangle \otimes |2\rangle_c$$
$$U_3 U_2 U_1 |\varphi_0\rangle \otimes |3\rangle_c$$



2 Feynman's (Hamiltonian) computer

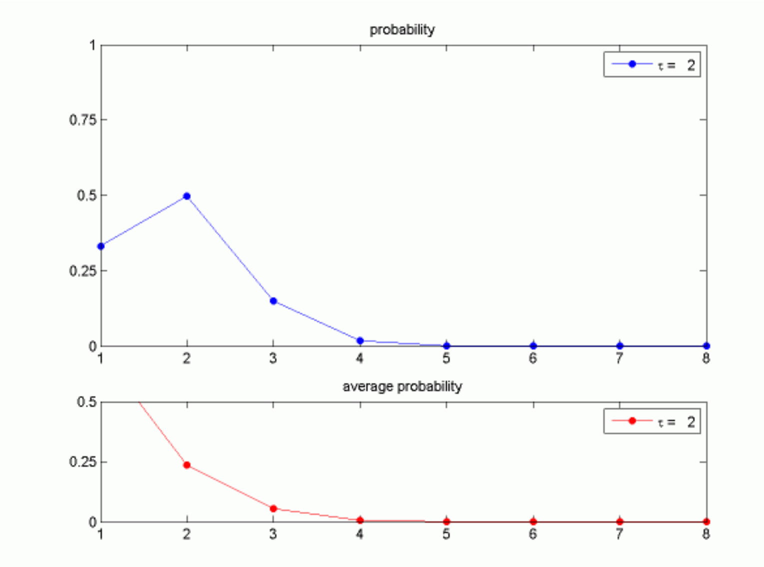


- The Hamiltonian

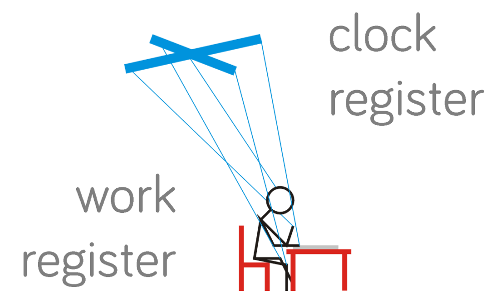
$$H_F = -\sum_{t=1}^{L} \left(U_t \otimes |t\rangle \langle t-1| + U_t^\dagger \otimes |t-1\rangle \langle t| \right)$$

- A quantum walk on a "line"

$$|\varphi_0\rangle \otimes |0\rangle_c$$
$$U_1 |\varphi_0\rangle \otimes |1\rangle_c$$
$$U_2 U_1 |\varphi_0\rangle \otimes |2\rangle_c$$
$$U_3 U_2 U_1 |\varphi_0\rangle \otimes |3\rangle_c$$



2 Feynman's (Hamiltonian) computer



- The Hamiltonian

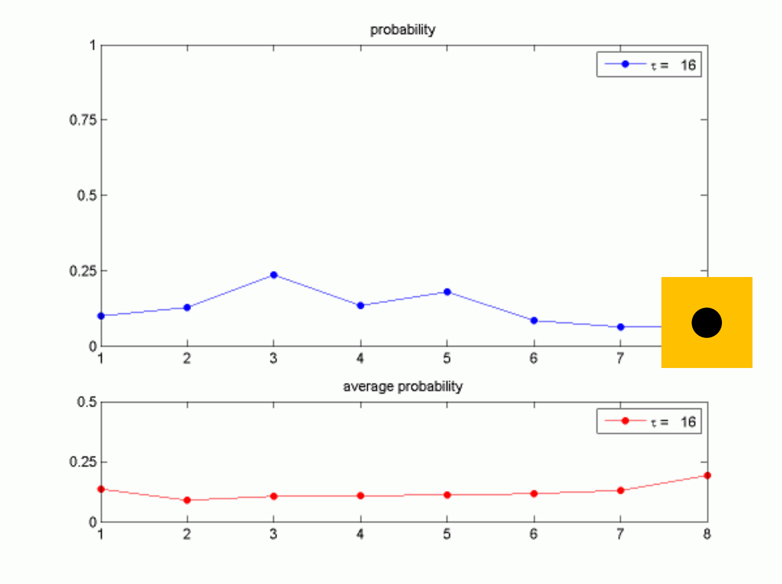
$$H_F = -\sum_{t=1}^{L} \Big(U_t \otimes |t\rangle \langle t-1| + U_t^\dagger \otimes |t-1\rangle \langle t| \Big)$$

- A quantum walk on a "line"

$$|\varphi_0\rangle \otimes |0\rangle_c$$

the output

$$U_L \cdots U_1 |\varphi_0\rangle \otimes |L\rangle$$



- Feynman's Hamiltonian

$$H_F = -\sum_{t=1}^{L} \left(U_t \otimes |t\rangle\langle t-1| + U_t^\dagger \otimes |t-1\rangle\langle t| \right)$$

- The "line" of states

$$\begin{aligned} &|\varphi_0\rangle \otimes |0\rangle_c \\ U_1 &|\varphi_0\rangle \otimes |1\rangle_c \\ U_2 U_1 &|\varphi_0\rangle \otimes |2\rangle_c \\ U_3 U_2 U_1 &|\varphi_0\rangle \otimes |3\rangle_c \\ U_4 U_3 U_2 U_1 &|\varphi_0\rangle \otimes |4\rangle_c \end{aligned}$$

$$H_F = -\begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 \end{bmatrix}$$

- The eigenvectors: combinations of plane waves

2 Hamiltonian QC

It's a walk.

- Feynman's Hamiltonian

$$H_F = -\sum_{t=1}^{L} \left(U_t \otimes |t\rangle\langle t-1| + U_t^\dagger \otimes |t-1\rangle\langle t| \right)$$

- The "line" of states

a possibility: wrap around a circle

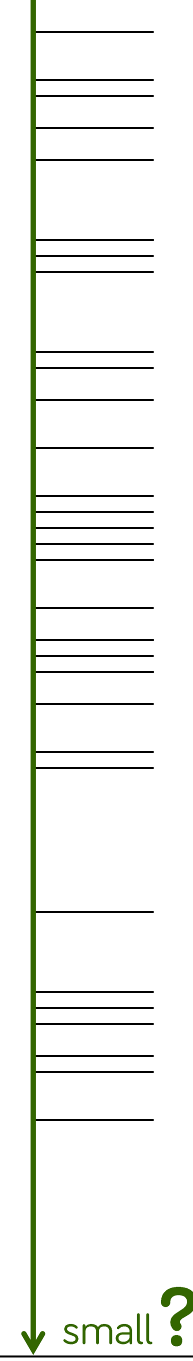
$$\begin{aligned} |\varphi_0\rangle &\otimes |0\rangle_c \\ U_1 |\varphi_0\rangle &\otimes |1\rangle_c \\ U_2 U_1 |\varphi_0\rangle &\otimes |2\rangle_c \\ U_3 U_2 U_1 |\varphi_0\rangle &\otimes |3\rangle_c \\ U_4 U_3 U_2 U_1 |\varphi_0\rangle &\otimes |4\rangle_c \end{aligned}$$

$$H_F = - \begin{bmatrix} 0 & 1 & 0 & 0 & \textcircled{1} \\ 1 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 1 \\ \textcircled{1} & 0 & 0 & 1 & 0 \end{bmatrix}$$

- The eigenvectors: combinations of plane waves

1 Hamiltonians and their ground states

Is the ground state energy of a **LH**

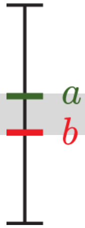


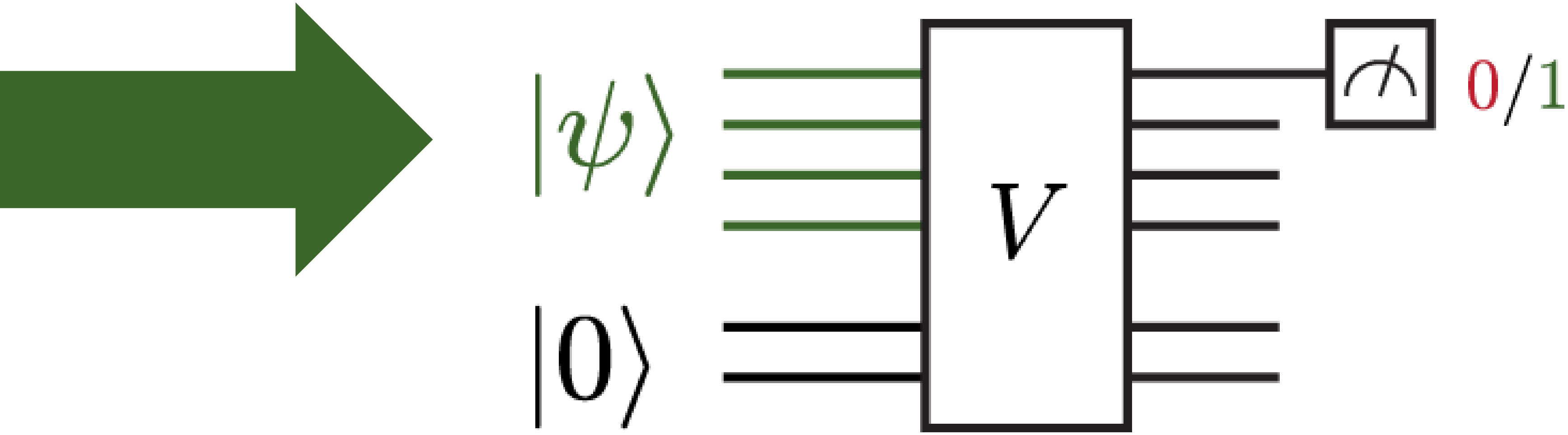
1 The QMA protocol

YES? Accept a good proof with $p > a$.

the promise

NO? Probability of accepting $p < b$.





- Is there an acceptable quantum witness?
- Is some local Hamiltonian (nearly) frustration-free?

1 The QMA protocol

YES? Accept a good proof with $p > a$.

the promise

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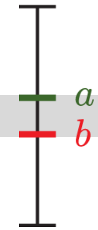
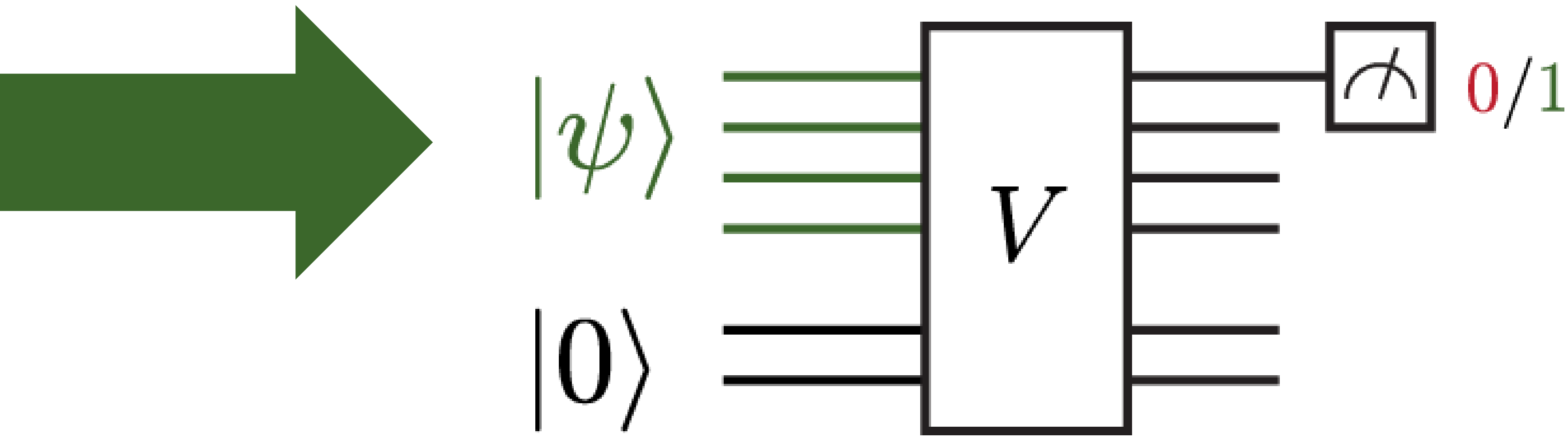
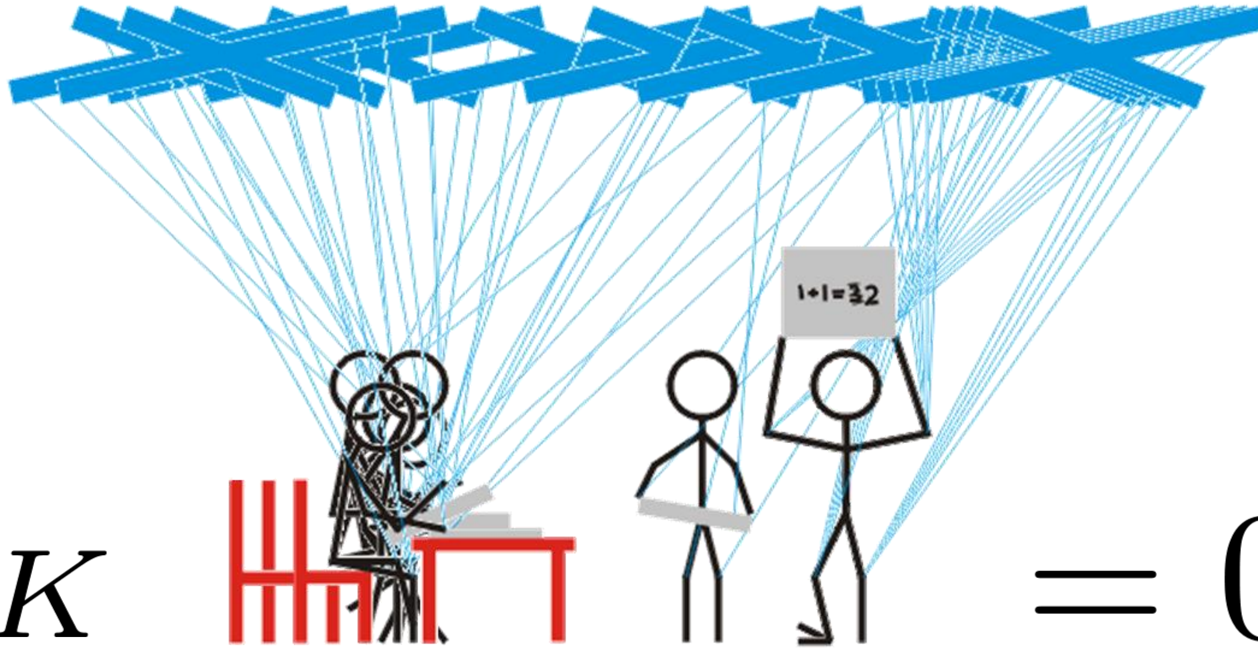




- Is there an acceptable quantum witness?
- Does some local Hamiltonian have a low ground energy?

2 The history state: a ground state

H_K



$= 0$

$$|\psi_{hist}\rangle = \frac{1}{\sqrt{T+1}} \sum_{t=0}^{T} \underbrace{|\varphi_t\rangle}_{U_t \cdots U_1 |\varphi_0\rangle} \otimes |t\rangle$$

2 The history state is a ground state

k-local

c-o-n-d-i-t-i-o-n-s

clock encoding

state progression

initialization

outpu

$$|\cdots 000 \cdots 0\rangle \otimes |0\rangle$$

$$|\varphi_t\rangle \otimes |t\rangle$$

$$|\varphi_{t+1}\rangle \otimes |t+1\rangle$$

$$\langle T| \otimes |1 \cdots|$$

$$|\psi_{hist}\rangle = \frac{1}{\sqrt{T+1}} \sum_{t=0}^{T} |\varphi_t\rangle \otimes |t\rangle$$

2 Checking proper computation

Antisymmetry checks.

- uniform superpositions: zero-energy eigenstates

$$H_t = \tfrac{1}{2}\left(|t+1\rangle\langle t+1| + |t\rangle\langle t|\right) - \tfrac{1}{2}\left(U_{t+1}\otimes|t+1\rangle\langle t| + U_{t+1}^{\dagger}\otimes|t\rangle\langle t+1|\right) = \frac{1}{2}\begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix}$$

Feynman's Hamiltonian

a projector

$$|\varphi_t\rangle \otimes |t\rangle$$

$$|\varphi_{t+1}\rangle \otimes |t+1\rangle$$

a nice basis

$$|\psi_{hist}\rangle = \frac{1}{\sqrt{T+1}}\sum_{t=0}^{T} |\varphi_t\rangle \otimes |t\rangle$$

2 Checking proper computation

Antisymmetry checks.

$$\sum_{t=1}^{L} H_t = \frac{1}{2}\begin{bmatrix} 1 & -1 & 0 & 0 & 0 \\ -1 & 2 & -1 & 0 & 0 \\ 0 & -1 & 2 & -1 & 0 \\ 0 & 0 & -1 & 2 & -1 \\ 0 & 0 & 0 & -1 & 1 \end{bmatrix}$$

positive semidefinite

$$|\varphi_t\rangle \otimes |t\rangle$$

$$|\varphi_{t+1}\rangle \otimes |t+1\rangle$$

a nice basis

$$|\psi_{hist}\rangle = \frac{1}{\sqrt{T+1}} \sum_{t=0}^{T} |\varphi_t\rangle \otimes |t\rangle$$

2 Checking proper computation

Antisymmetry checks.

$$\sum_{t=1}^{L} H_t = \frac{1}{2}\begin{bmatrix} 1 & -1 & 0 & 0 & 0 \\ -1 & 2 & -1 & 0 & 0 \\ 0 & -1 & 2 & -1 & 0 \\ 0 & 0 & -1 & 2 & -1 \\ 0 & 0 & 0 & -1 & 1 \end{bmatrix}$$

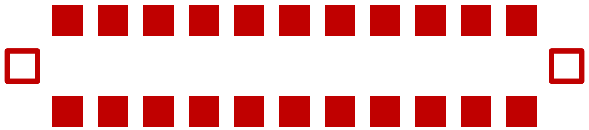
positive semidefinite

local?

$$\sum_t e^{-ipt} |\varphi_t\rangle \otimes |t\rangle$$

eigenvectors: combinations of plane waves

L



2(L+1)

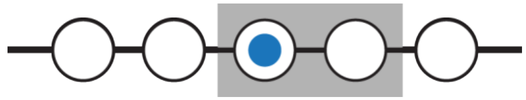
an L^{-2} eigenvalue gap

a clock workshop

3 Constructing local clocks

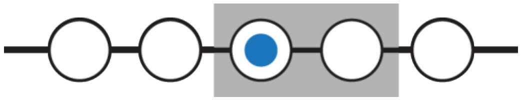
- the pulse

3 Constructing local clocks

- the pulse  transitions: 2-local

- joining the states by projectors

3 Constructing local clocks

- the pulse  transitions: 2-local

00100

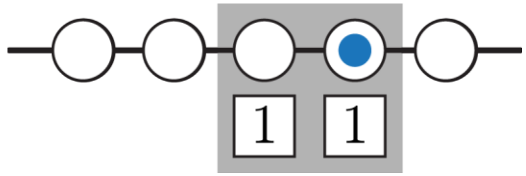
↓

+00010

- joining the states by projectors $|01-10\rangle\langle 01-10|$

3 Constructing local clocks

- the pulse



transitions: 2-local
2-qubit gates: 4-local

interaction
with the data

- joining the states
by projectors $|01-10\rangle\langle 01-10|$

3 Constructing local clocks

- the pulse

transitions: 2-local
2-qubit gates: 4-local

00000 a “dead” state

Initialization!

- joining the states by projectors $|01-10\rangle\langle 01-10|$

3 Constructing local clocks

- the domain wall 

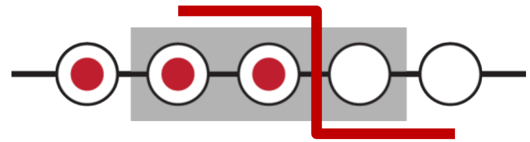
$$|t\rangle = |4\rangle$$
$$= |11110\rangle$$

- 2-local terms “compatible” with **11...1100...00**

?

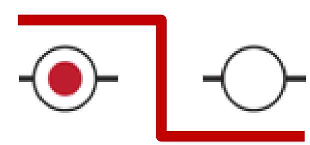
$$|01\rangle\langle 01|$$

3 Constructing local clocks

- the domain wall  transitions: 3-local

$$|t\rangle = |3\rangle$$
$$= |11100\rangle$$

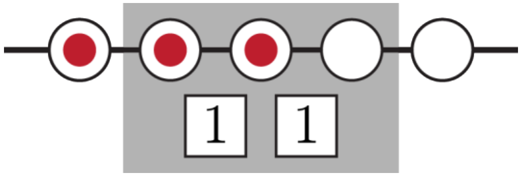
- joining states by transitions? $|100 - 110\rangle\langle 100 - 110|$

- enforce a domain wall: fix the ends 

- the ground state $\cdots + |2\rangle + |3\rangle + \ldots$

3 Constructing local clocks

- the domain wall



transitions: 3-local
2-qubit gates: 5-local

- interacting with work (data) qubits

$$H_t = \tfrac{1}{2}\left(|t+1\rangle\langle t+1| + |t\rangle\langle t|\right) - \tfrac{1}{2}\left(U_{t+1} \otimes |t+1\rangle\langle t| + U_{t+1}^{\dagger} \otimes |t\rangle\langle t+1|\right)$$

5-local

- YES

ground state

• NO

ground state

- NO

lower bound on the ground state energy

good clock states

... 01 ... bad clock states

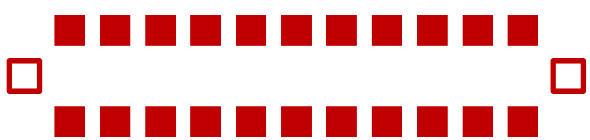
history states

non-uniform
superpositions

history states

a polynomially small gap

$\Delta = O\left(L^{-2}\right)$



history states

well

badly

initialized history states

well

initialized histories

accepted states

well

initialized histories

$H_A + H_B$

$$\lambda_0 \geq \sin^2 \frac{\vartheta}{2} \times \min(\Delta_A, \Delta_B)$$

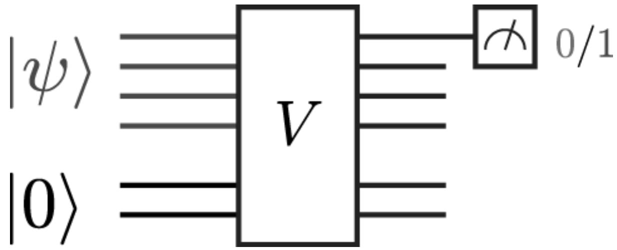
L^{-2}

L^{-1}

accepted states

3-LH and QMA verification

[N., Mozes 07]



LH

NO V is unlikely to accept anything (ϵ)

lowest eigenvalue

$$\geq \frac{c\,(1-\sqrt{\epsilon})}{L^2}$$

promise gap L^{-2} (needs $\epsilon = L^{-1}$)

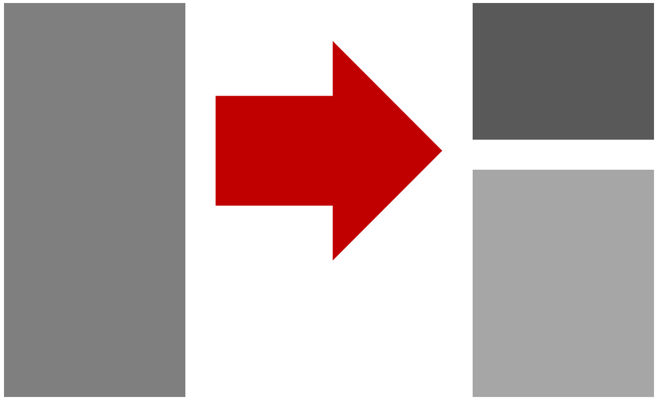
YES a well accepted proof (1-ϵ)

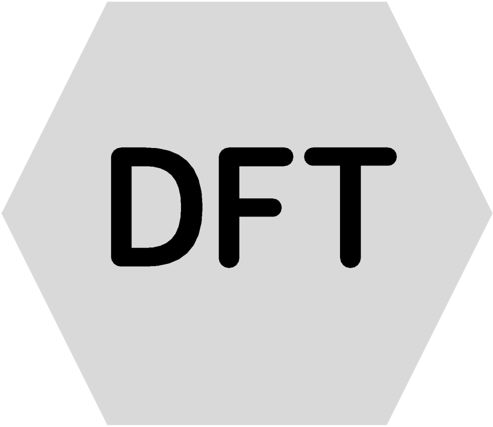
the history state

$$\leq \frac{\epsilon}{L+1}$$

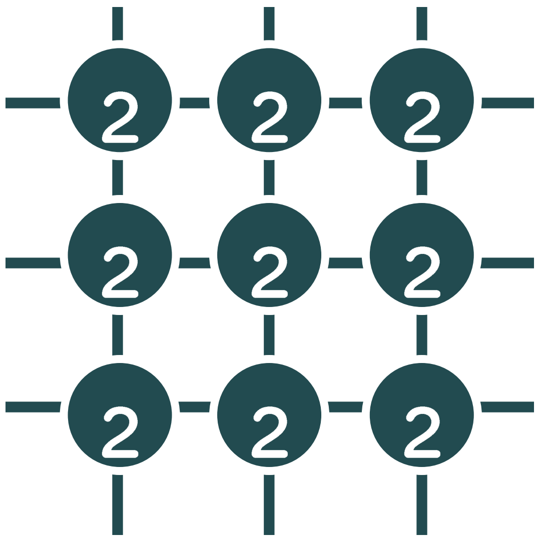
2 Other QMA-complete problems

[Bookatz '13]



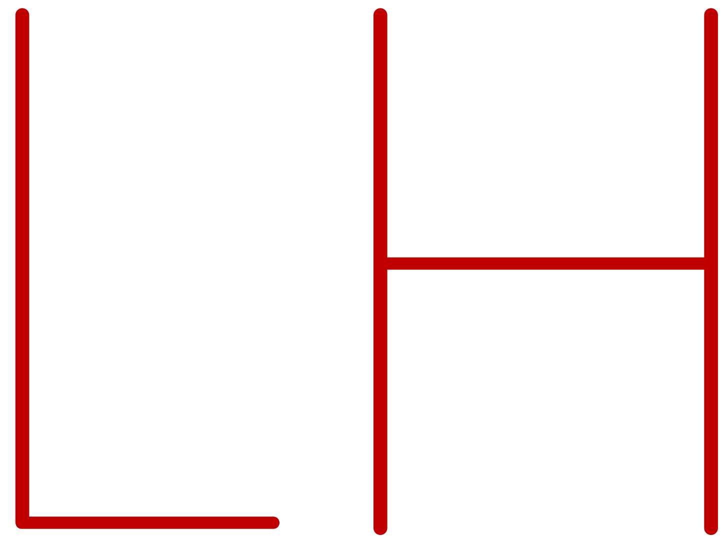


2 2-local Hamiltonian is QMA complete

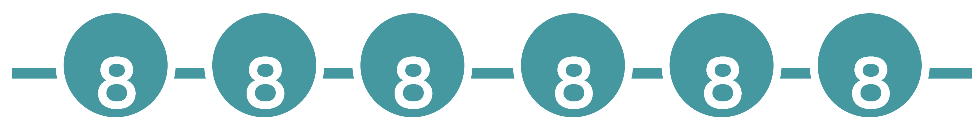


[Oliveira, Terhal '04]

a global minimum

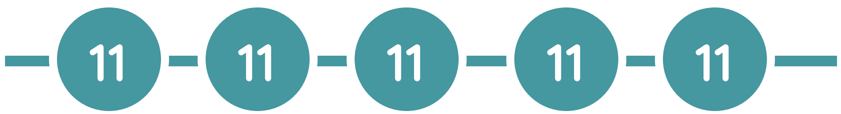


$$\sum H_{jk}$$

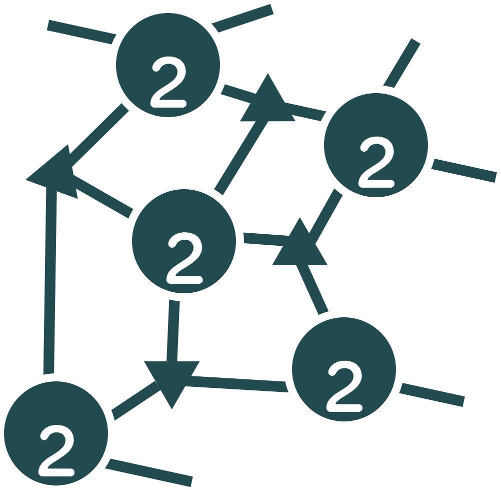


[Hallgren, N., Narayanaswami '13]

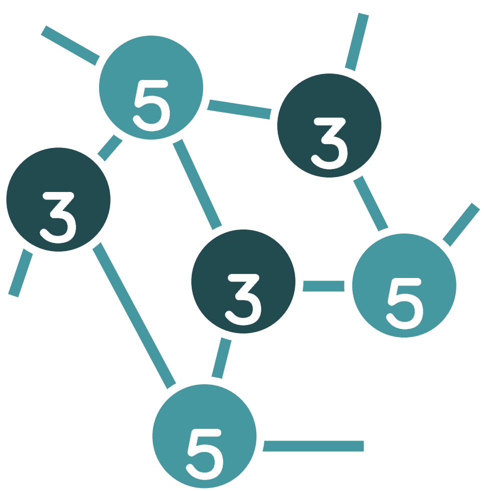
2 QMA_1-complete problems



[N. '08]



[Gosset, N. '13]



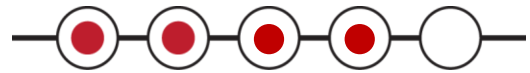
[Eldar, Regev '08]

unfrustrated

qSAT

projections
& gadgets

3 From a 5-local to a 3-local clock [Kempe, Regev]

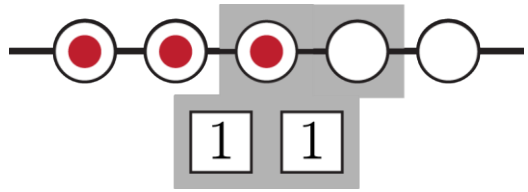
- the domain wall  transitions: 1-local

- transitions $$|1\rangle\langle 0| + |0\rangle\langle 1|$$

- punish mistimed transitions?

$$|01\rangle\langle 01|$$

3 From a 5-local to a 3-local clock [Kempe, Regev]

- the domain wall 

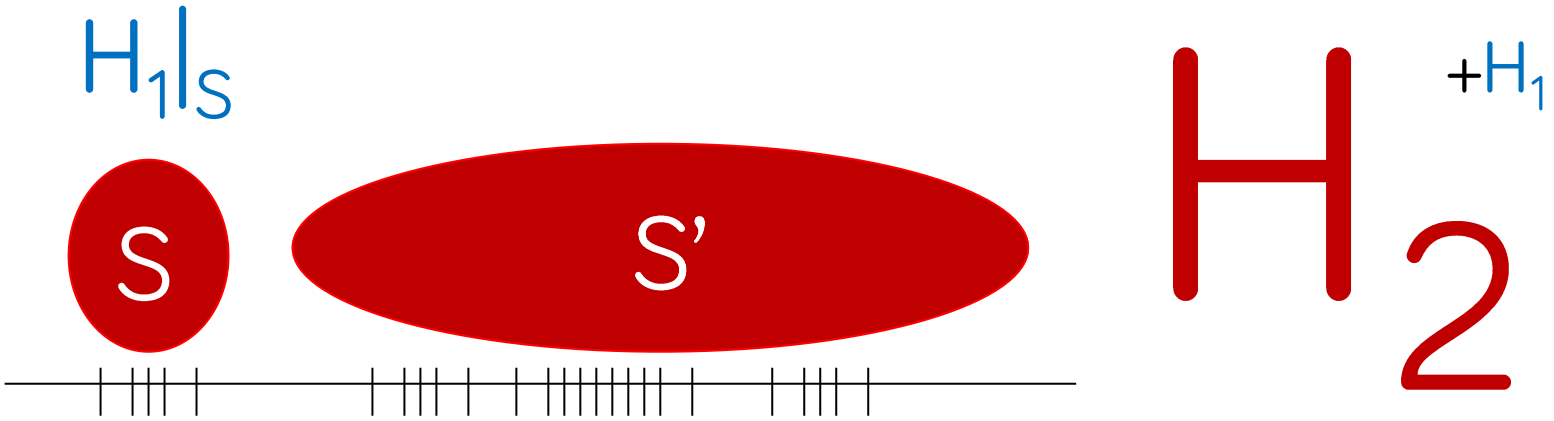
transitions: 1-local
2-qubit gates: 3-local

- transitions $$|10\rangle\langle 10|_{1,2} + |10\rangle\langle 10|_{2,3} - X_2$$

- punish mistimed transitions

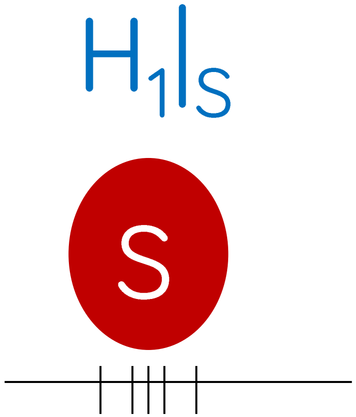
$$|01\rangle\langle 01|$$

4 The projection lemma: a useful tool for proving gaps



- a HIGH energy penalty for "illegal" states?
- the low energy states live near the "legal" subspace

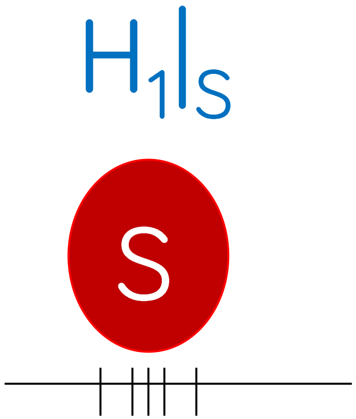
4 The projection lemma in action

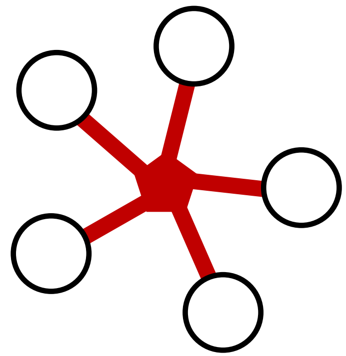


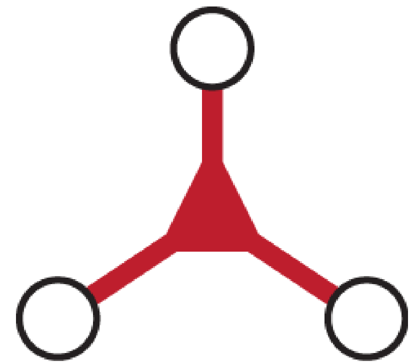
$$|1\rangle\langle 0| + |0\rangle\langle 1|$$

$$|1110000\rangle$$
$$|1111000\rangle$$
$$|1111100\rangle$$

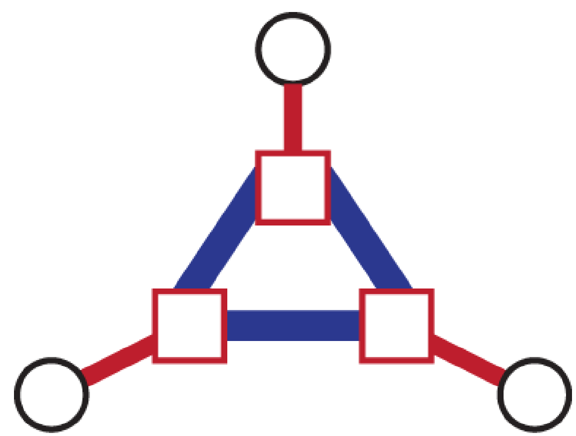
4 The projection lemma: a useful tool for proving gaps





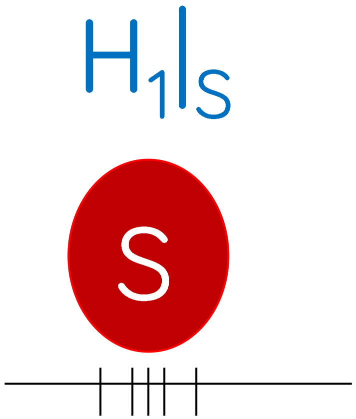


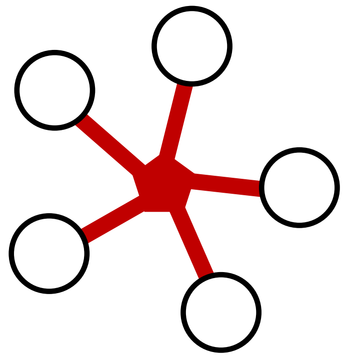
- 3-LH that works well
  in the “good clock subspace”
- 2-LH from
  effective interactions

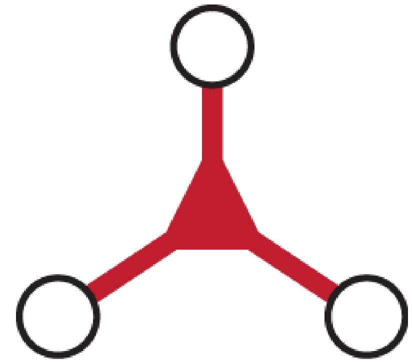


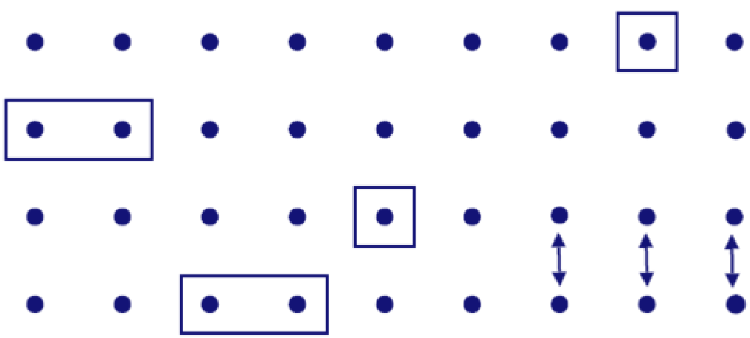
[Kempe, Kitaev, Regev ’03]

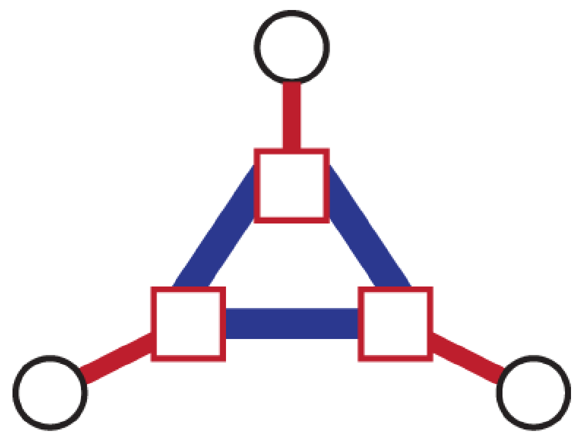
4 The projection lemma: a useful tool for proving gaps





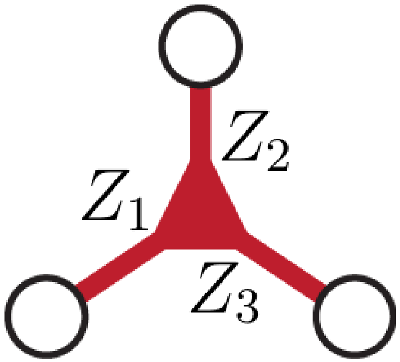


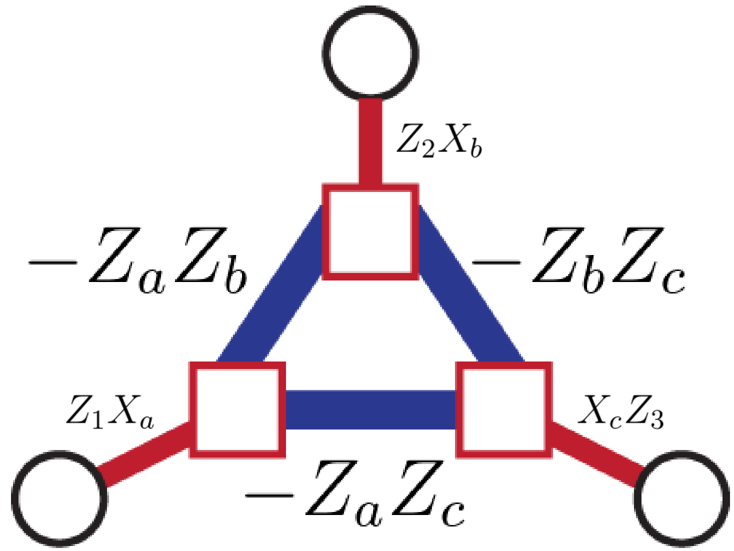




- 2-loc. H. in 2D [Oliveira, Terhal '05]

3 Further decreasing locality: a “3 from 2” gadget





- strongly coupled ancillas (a new energy scale)
- perturbation theory

$$H' = H + V$$

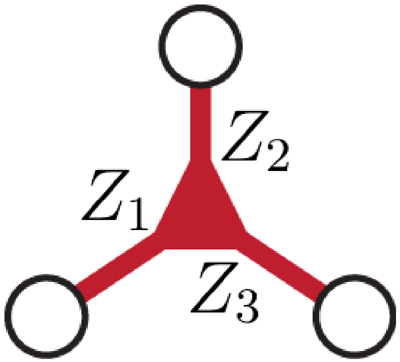
$$||H|| \gg ||V||$$

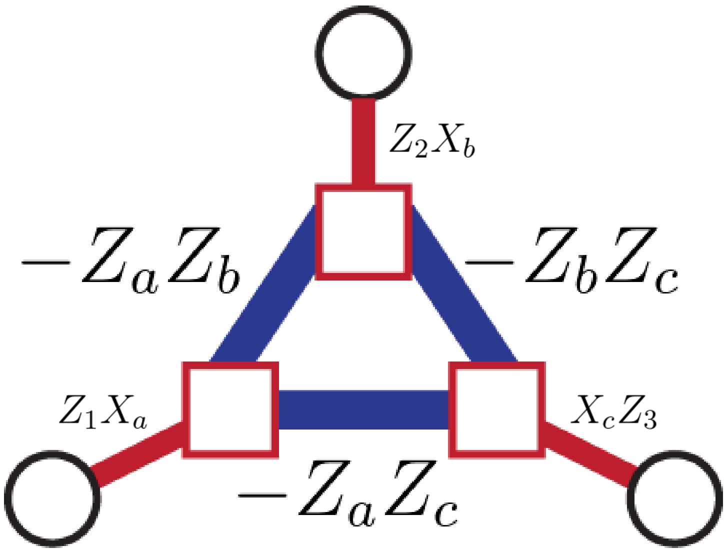
$$G'(z) = \left(z\mathbb{I} - H'\right)^{-1}$$

$$S = \mathrm{span}\left\{|000\rangle, |111\rangle\right\}$$

[Kempe, Kitaev, Regev ’03]

3 Further decreasing locality: a "3 from 2" gadget





- strongly coupled ancillas (a new energy scale)
- perturbation theory gives us an effective Hamiltonian

$$H' = H + V$$

$$||H|| \gg ||V||$$

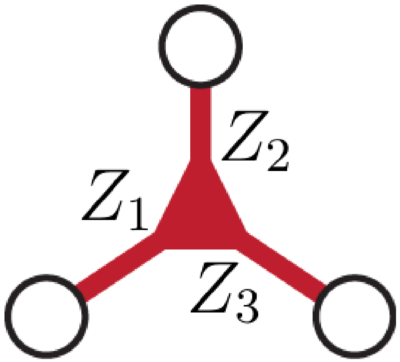
$$S = \text{span}\{|000\rangle, |111\rangle\}$$

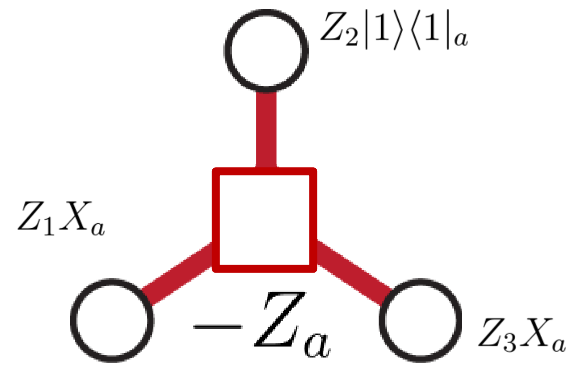
$V\big|_S$	$V^2\big|_S$	$V^3\big|_S$
projection lemma	unwanted (subtract)	the effective 3-local term

[Kempe, Kitaev, Regev '03]

3 STRONG local fields, OK interactions

[Cao et al., 1311.2555]





- strongly bound a single ancilla
  still needs strong interactions

$$S = \{|0\rangle\}$$

- perturbation theory gives us an effective Hamiltonian

$$H' = H + V$$

$$||H|| \gg ||V||$$

$V\big|_S$ projection lemma

$V^2\big|_S$ unwanted (subtract)

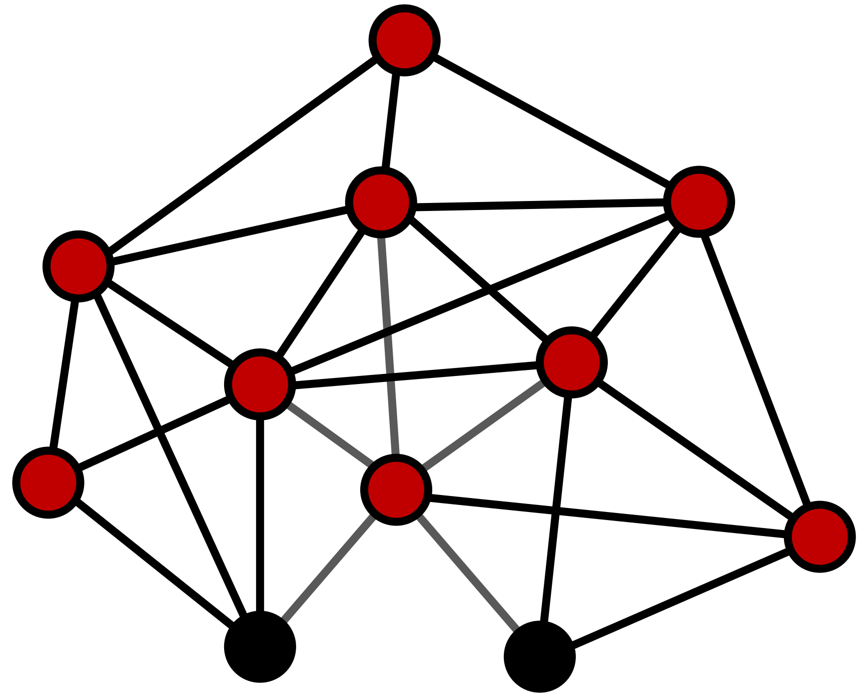
$V^3\big|_S$ the effective 3-local term

special cases (Z-basis) exact gadgets!

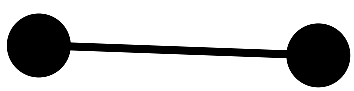
[Biamonte 0801.3800]

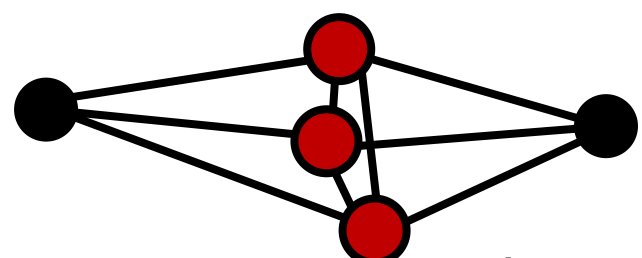
3 “Strengthening”, intermediary gadgets?

- classically easy: copy



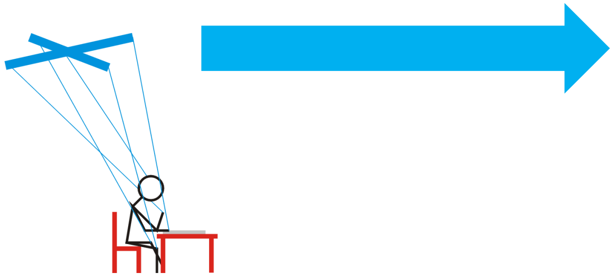
- quantumly?





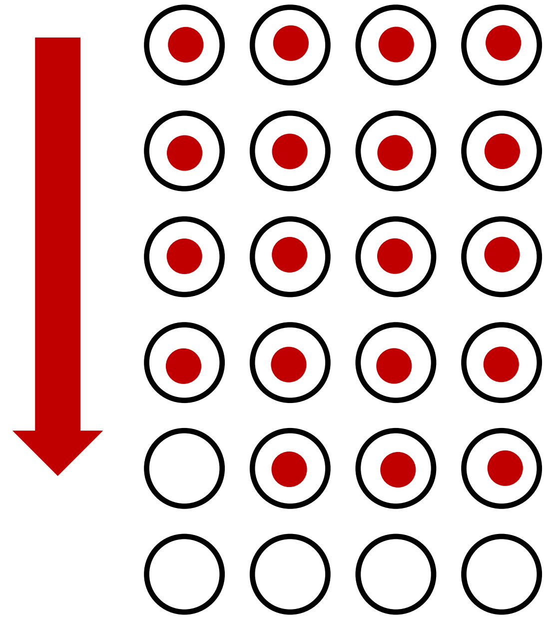
[N., Yudong Cao]

clock/work registers



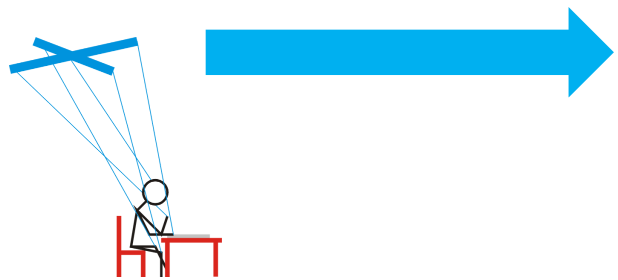
[Kempe, Kitaev, Regev]

a geometric clock

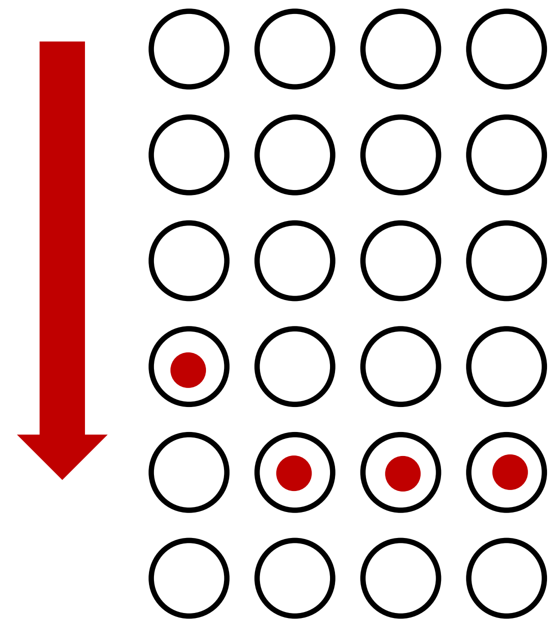


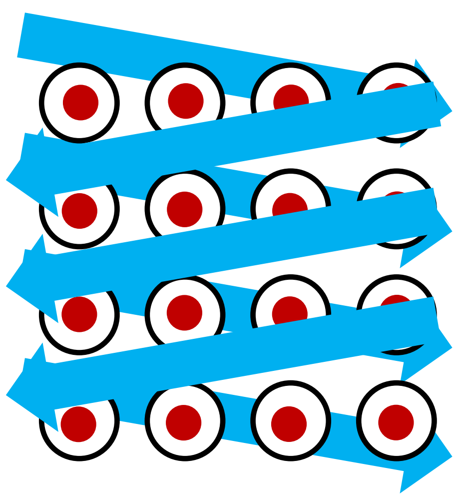
[Mizel] [Aharonov+]

clock/work registers

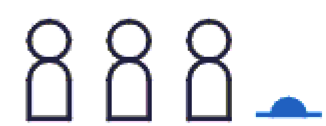


a geometric clock



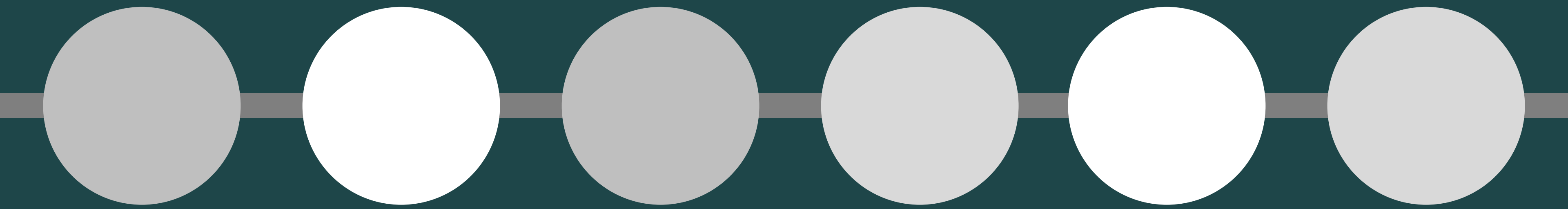


geometric locality

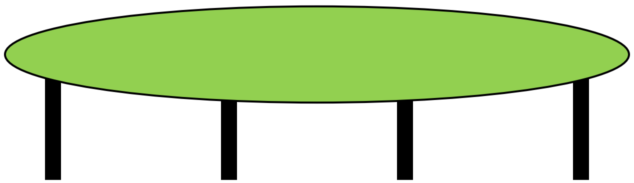


moving data on a line

l-H-a-m-i-l-t-o-n-i-a-n-s-i-n-1-D-L-o-c-a-l-H-a-m-i-l-t-o-n-i-a-n-s-i-n-1-D-L-o-c-a-l-H-a-m

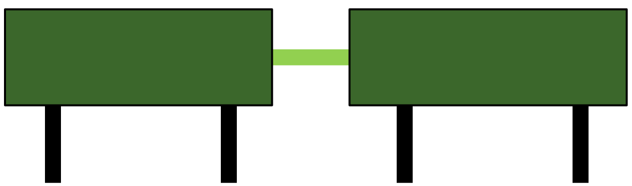


4 Matrix Product States



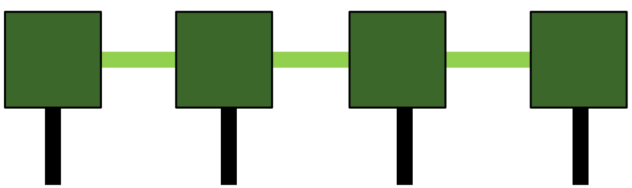
$$\sum_{s,t,u,v=0}^{1} c_{stuv} |stuv\rangle$$

- Schmidt decomposition



$$\sum_{b=1}^{\chi} Q_b^{st} R_b^{uv}$$

- many decompositions → a local description



$$\sum_{b=1}^{\chi} \sum_{a=1}^{\chi} A_a^s B_{ab}^t \sum_{c=1}^{\chi} C_{bc}^u D_c^v$$

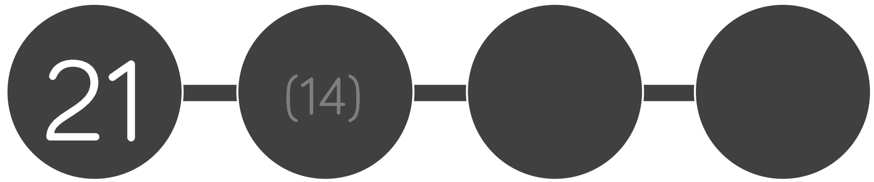
- low entanglement ansatz, local optimization, easy manipulation

4 Ground states in 1D

How hard is it to find/describe them?

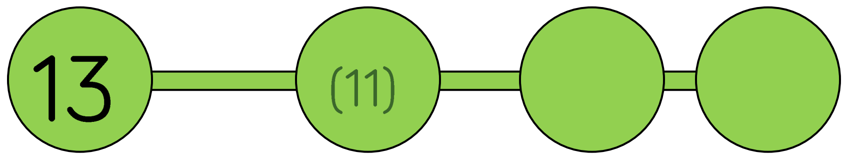
constant gap: OK [Landau+ '13]

entropy ~ L



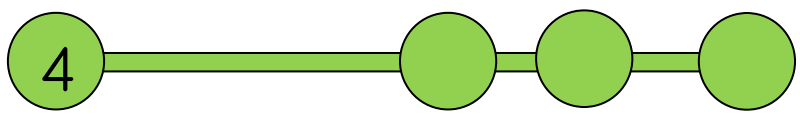
trans. invariant
[Irani]

QMA_1-comp.



history state
[AGIK '06]

very entangled



random projectors
[M+'10]

const. entropy

trans. invariant
AKLT model

product states

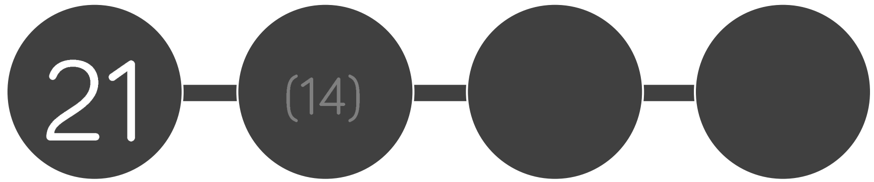
Q 2-SAT in P
[Bravyi, C+]

4 Ground states in 1D

How hard is it to find/describe them?

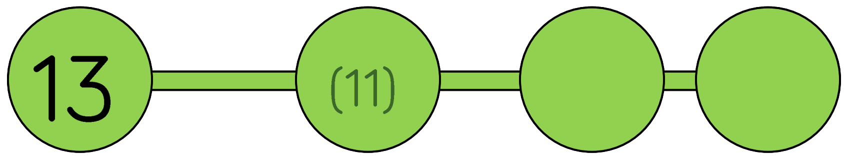
constant gap: OK [Landau+ '13]

entropy ~ L



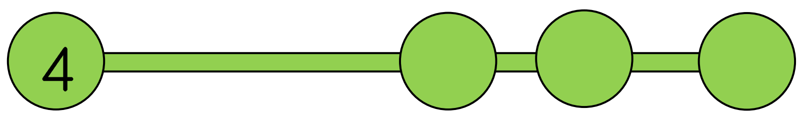
trans. invariant
[Irani]

QMA_1-comp.



history state
[AGIK '06]

very entangled



random projectors
[M+'10]

■ entropy: log L

trans. invariant
[B+'12]

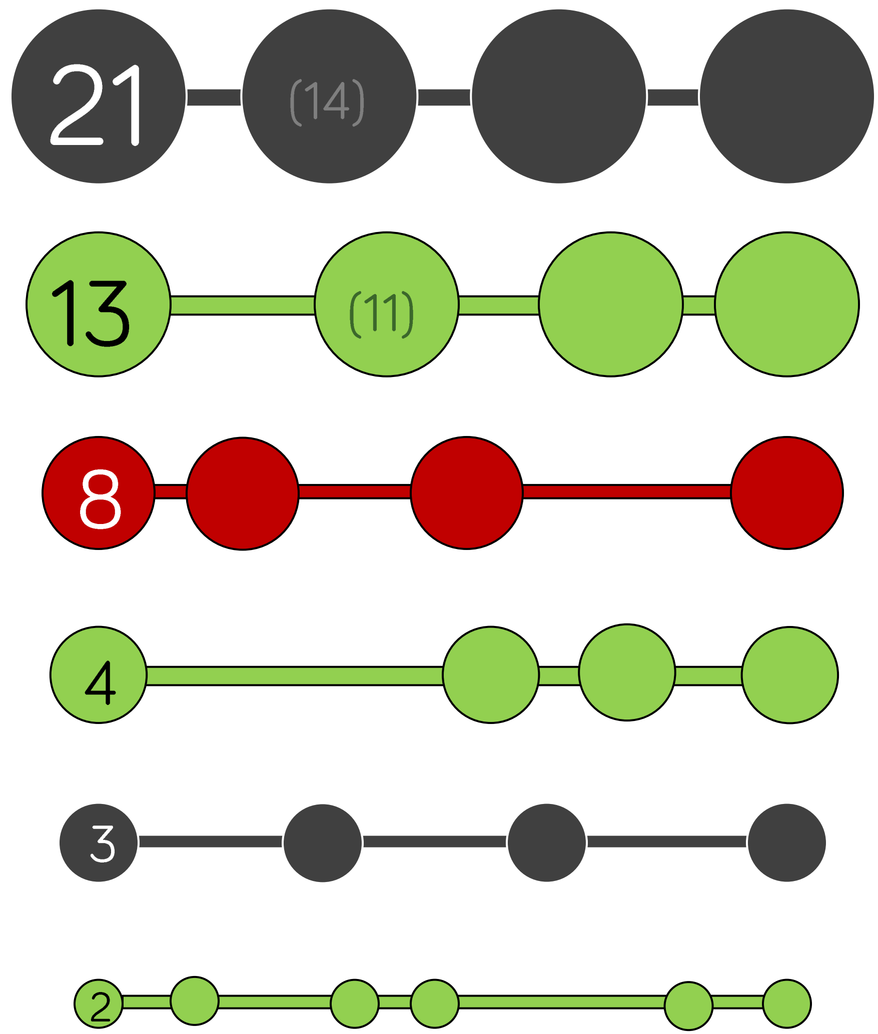
product states

Q 2-SAT in P
[Bravyi, C+]

4 Ground states in 1D

How hard is it to find/describe them?

constant gap: OK [Landau+ '13]



entropy ~ L	trans. invariant [Irani]
QMA_1-comp.	history state [AGIK '06]
■ QMA-comp.	frustrated [Hallgren+'13]
very entangled	random projectors [M+'10]
■ entropy: log L	trans. invariant [B+'12]
product states	Q 2-SAT in P [Bravyi, C+]

1 Hamiltonians?

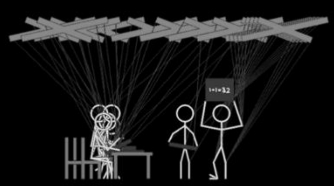
optimization & dynamics

2 complexity

checking (quantum) proofs

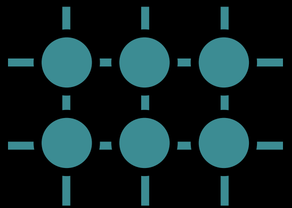
3 ground states?

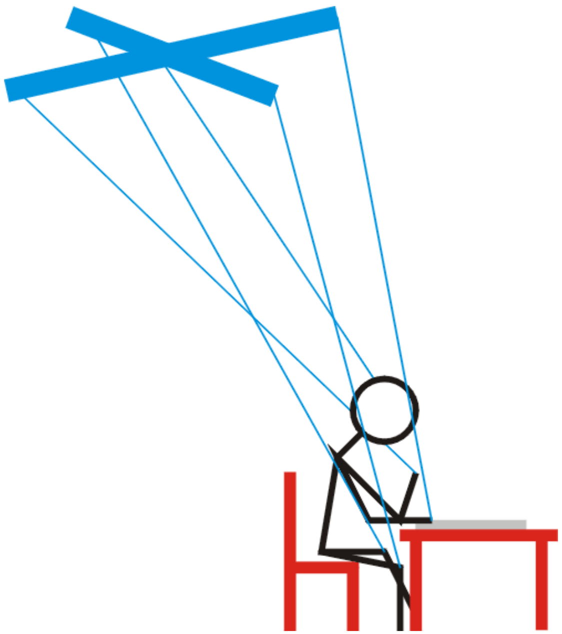
how hard is it to find them: QMA



4 tensor networks

heuristics based on low entanglement





Local Hamiltonians & Quantum Complexity

Daniel Nagaj
universität wien

2014 | 4 | 11
CS lunch @ USC