PHY682 Special Topics in Solid-State Physics: Quantum Information Science

Lecture time: 2:40-4:00PM Monday & Wednesday

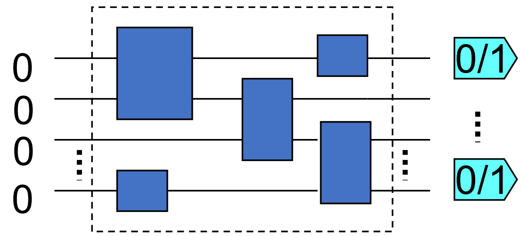
Today 10/21:

1. HW5 due 11:59pm Nov. 1^{st} (selection of presentation topics, and exercises on surface code and Ising anyon gates)
2. Today: Quantum computing by measurement
   (a.k.a. Measurement-based quantum computation)

(Frameworks of) Quantum Computation

✓ Previously covered:

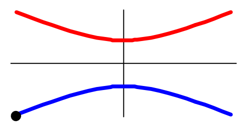
I. Circuit:



✓ Major scheme by most labs: IBM, Intel Rigetti, IonQ, Alibaba

✓ Done with this:

II. Adiabatic:

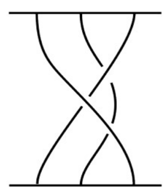


$$H(t) = \left(1 - \frac{t}{T}\right) H_{\text{initial}} + \frac{t}{T} H_{\text{final}}$$

✓ Approach by D-Wave

✓ Previously covered:

III. Topological:

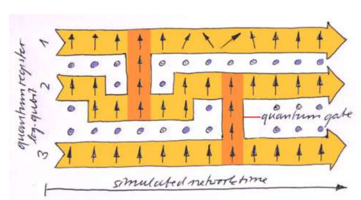


quantum gates = braiding anyons

✓ Approach by Microsoft, Google uses a hybrid of III and I (circuit version of IV)

Today:

IV. Measurement -based:



local measurement is the only operation needed

✓ Used in photonic systems, such as PsiQuantum

References on Measurement-based QC

My article for Oxford Research Encyclopedia in Physics (posted to Blackboard)

Jozsa, R. (2006). An introduction to measurement based quantum computation. NATO Science Series, III: Computer and Systems Sciences. Quantum Information Processing-From Theory to Experiment, 199, 137–158.

Briegel, H. J. (2009), "Cluster States", In Compendium of Quantum Physics - Concepts, Experiments, History and Philosophy. Springer. pp. 96–105. (eds. D. Greenberger, K. Hentschel, F. Weinert).

Briegel, H. J., Browne, D. E., Dür, W., Raussendorf, R., & Van den Nest, M. (2009). Measurement-based quantum computation. Nature Physics, 5(1), 19–26.

Raussendorf, R., & **Wei, T.-C.** (2012). Quantum computation by local measurement. Annu. Rev. Condens. Matter Phys., 3(1), 239–261.

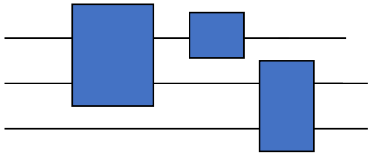
Kwek, L. C., Wei, Z., & Zeng, B. (2012). Measurement-based quantum computing with valence-bondsolids. International Journal of Modern Physics B, 26(02), 1230002.

Wei, T.-C. (2018). Quantum spin models for measurement-based quantum computation. Advances in Physics: X, 3(1), 1461026.

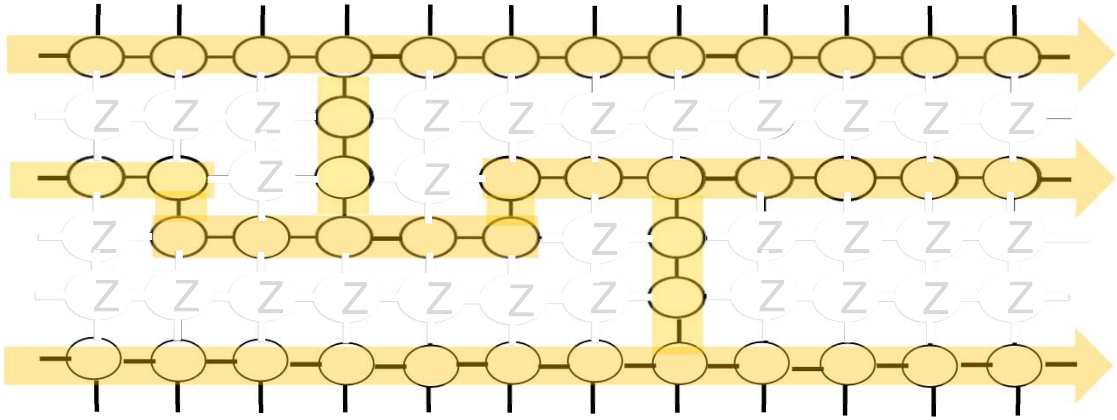
Browne, D. E. & Briegel, H. J. (2019). One-Way Quantum Computation. In Quantum Information (eds D. Bruß and G. Leuchs), Wiles and Sons Ltd.

QC by Local Measurement---an overview picture

[Raussendorf & Brigel '01]



- There is a highly entangled state on a 2D array of qubits. First carve out entanglement structure on cluster state by local Pauli Z measurement



- Then:

  (1) Measurement along each wire simulates one-qubit evolution (gates)

  (2) Measurement near & on each bridge simulates two-qubit gate (CNOT)

 2D or higher dimensions are needed for universal QC

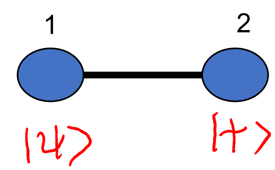
Unitary operation by measurement?

- Intuition: entanglement as resource!

  - Controlled-Z (CZ) gate from Ising interaction

$11 \rightarrow -11$

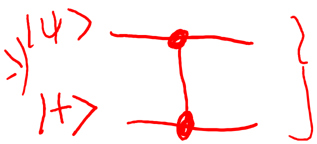
$$CZ_{12} = e^{-i\frac{\pi}{4}(1-\sigma_Z^{(1)})(1-\sigma_Z^{(2)})} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$



  - Entanglement is generated:

$|\pm\rangle = \frac{1}{\sqrt{2}}(|0\rangle \pm |1\rangle)$

$Z|1\rangle = -|1\rangle$



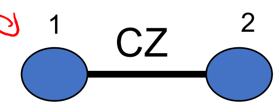
$$(a|0\rangle + b|1\rangle)\,|+\rangle \xrightarrow{CZ} |\psi\rangle = a|0\rangle|+\rangle + b|1\rangle|-\rangle$$

$a|0\rangle|+\rangle + b|1\rangle|+\rangle \rightarrow a|0\rangle|+\rangle + b|1\rangle Z|+\rangle$

Unitary operation by measurement?

- Intuition: entanglement as resource!

measure this qubit first



$$(a|0\rangle + b|1\rangle)\,|+\rangle \xrightarrow{\text{CZ}} |\psi\rangle = a|0\rangle|+\rangle + b|1\rangle|-\rangle$$

$|\text{in}\rangle_1 \Rightarrow U_1|\text{in}\rangle_2$

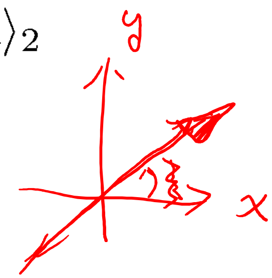
measurement

- Measurement on 1st qubit in basis

$$|\pm\xi\rangle = \left(e^{-i\xi/2}|0\rangle \pm e^{i\xi/2}|1\rangle\right)/\sqrt{2}$$

$$\hat{O}(\xi) \equiv \cos(\xi)\sigma_x + \sin(\xi)\sigma_y$$

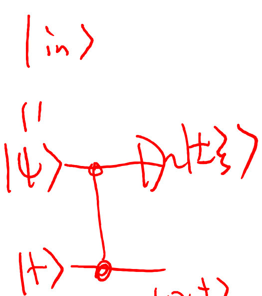
$\sigma_x \equiv X$, $\sigma_y \equiv Y$



with outcome denoted by $\pm = (-1)^s$ $\quad s = 0, 1$

$\hat{O}(\xi)|\pm\xi\rangle = \pm|\pm\xi\rangle$

$\text{Prob}(\pm) = |\langle\pm\xi|\psi\rangle|^2$



➔ Second qubit becomes

$$_1\langle\pm\xi|\psi\rangle_{12} \sim a\,e^{i\xi/2}|+\rangle_2 \pm b\,e^{-i\xi/2}|-\rangle_2 = H\,e^{i\xi Z/2}Z^s(a|0\rangle_2 + b|1\rangle_2)$$

$\pm = (-1)^s$

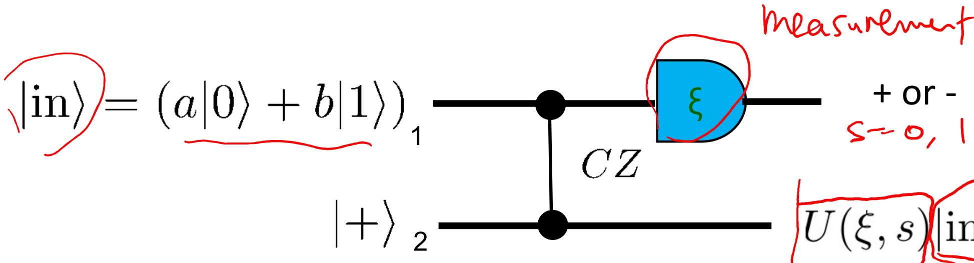
$e^{i\frac{\xi}{2}\begin{pmatrix}1 & 0\\ 0 & -1\end{pmatrix}}$ $\quad \begin{pmatrix}1\\0\end{pmatrix}$ $\quad \sigma_z \begin{pmatrix}0\\1\end{pmatrix}$

➔ A unitary gate is induced: $U(\xi, s) \equiv H\,e^{i\xi Z/2}Z^s$

$$Z = \sigma_z = \begin{pmatrix}1 & 0\\ 0 & -1\end{pmatrix} \quad H = \frac{1}{\sqrt{2}}\begin{pmatrix}1 & 1\\ 1 & -1\end{pmatrix}$$

Saw this before (on 9/2): A variant---gate teleportation*

Controlled-Z gate and single-qubit measurement induces rotation



$U(\xi, s)|\mathrm{in}\rangle_2$

rotation

$U(\xi, s) = H e^{i\xi Z/2} Z^s$

Hadamard

0 or 1

$\mathbb{1}$ Z

$$\mathrm{CZ}_{12} = |0\rangle\langle 0| \otimes I + |1\rangle\langle 1| \otimes Z = \left(\begin{array}{cc|cc} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ \hline 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{array}\right)$$

00 → 00
01 → 01
10 → 10
11 → −11

X $\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$

(3rd rule QM)

The measurement basis ξ is defined via

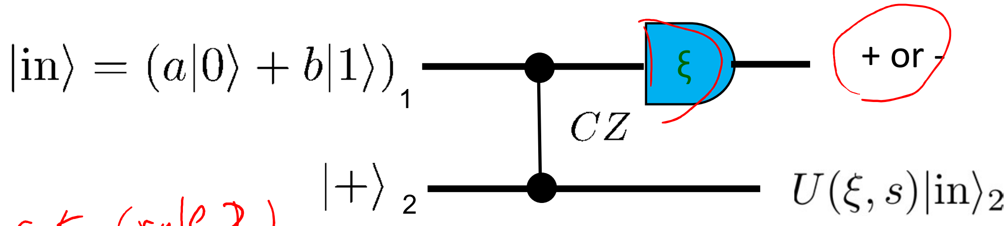
$$|\pm\xi\rangle = (e^{-i\xi/2}|0\rangle \pm e^{i\xi/2}|1\rangle)/\sqrt{2}$$

or the observable:

$$\cos(\xi)\underset{X}{\underset{\equiv}{\sigma_x}} + \sin(\xi)\underset{Y}{\underset{\equiv}{\sigma_y}} = \begin{pmatrix} 0 & e^{-i\xi} \\ e^{i\xi} & 0 \end{pmatrix}$$

$|\pm\xi\rangle = \pm|\pm\xi\rangle$

Saw this before (on 9/2): Derivation*



The measurement basis ξ is defined via

$$|\pm\xi\rangle = \left(e^{-i\xi/2}|0\rangle \pm e^{i\xi/2}|1\rangle\right)/\sqrt{2}$$

$$\mathrm{CZ}_{12} = |0\rangle\langle 0| \otimes I + |1\rangle\langle 1| \otimes Z = \left(\begin{array}{cc|cc} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ \hline 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{array}\right)$$

① $|\Psi\rangle_{12}\ (a|0\rangle + b|1\rangle)\dfrac{(|0\rangle + |1\rangle)}{\sqrt{2}} \longrightarrow a|0\rangle(|0\rangle + |1\rangle) + b|1\rangle(|0\rangle - |1\rangle)$

$= a|0\rangle \otimes |+\rangle + b|1\rangle \otimes |-\rangle \Longrightarrow |\Psi_{12}\rangle$

② measurement : proj to eigenstates $|\pm\xi\rangle = \frac{1}{\sqrt{2}}\left(e^{-i\xi/2}|0\rangle + e^{i\xi/2}|1\rangle\right)$

$\langle \pm\xi|_1 \cdot |\Psi_{12}\rangle = \frac{1}{\sqrt{2}}\left(e^{i\xi/2}\langle 0|_1 \pm e^{-i\xi/2}\langle 1|_1\right)\left(a|0\rangle \otimes |+\rangle + b|1\rangle \otimes |-\rangle\right)$

$= \frac{1}{\sqrt{2}}\left(a\, e^{i\xi/2}|+\rangle_2 \pm b\, e^{-i\xi/2}|-\rangle_2\right) = \frac{1}{\sqrt{2}} H e^{i\frac{\xi}{2}\begin{pmatrix}1 & 0\\ 0 & -1\end{pmatrix}}(a|0\rangle \pm b|1\rangle)$

$|0\rangle \qquad |1\rangle$

$= \frac{1}{\sqrt{\ }}$

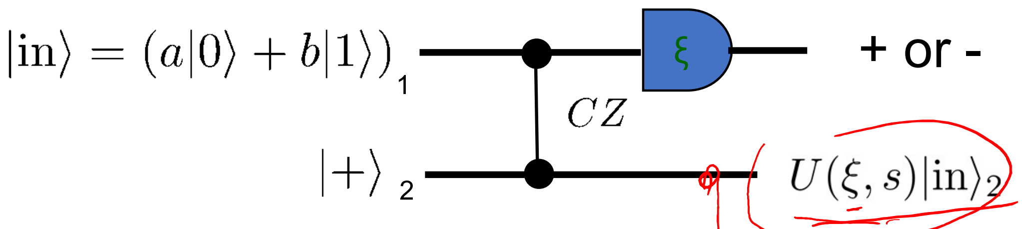
$= \frac{1}{\sqrt{2}} H e^{i\frac{\xi}{2} Z} Z^s (a|0\rangle + b|1\rangle)$

$s = (-1)$ or $(-1)^1$

Simulating arbitrary one-qubit gates

- In terms of circuit:

[*Raussendorf &* ***Wei***, Ann Rev Cond-Mat '12]



$$U(\xi, s) = H\, e^{i\xi Z/2} Z^s$$

basis change

Z-rotation

ξ', s'

D ~

y

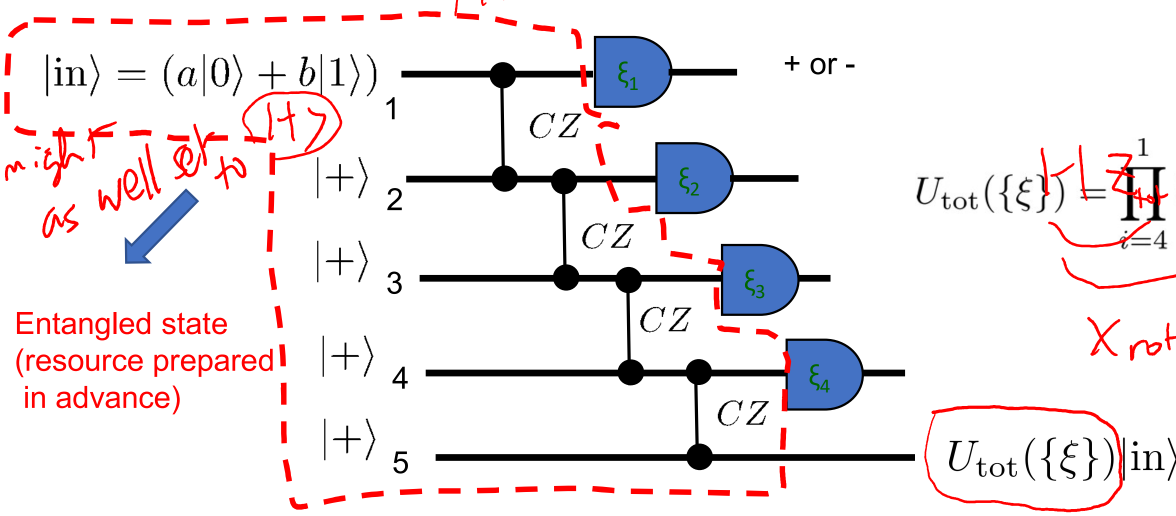
x

ξ

$U(\xi', s')\, U(\xi, s)|\mathrm{in}\rangle$

- Can cascade this a few times:

$|+\rangle$



might as well set to $|+\rangle$

Entangled state (resource prepared in advance)

$$U_{\mathrm{tot}}(\{\xi\}) = \prod_{i=4}^{1} U(\xi_i, s_i)$$

H Zrot H Zrot H Zrot H Zrot

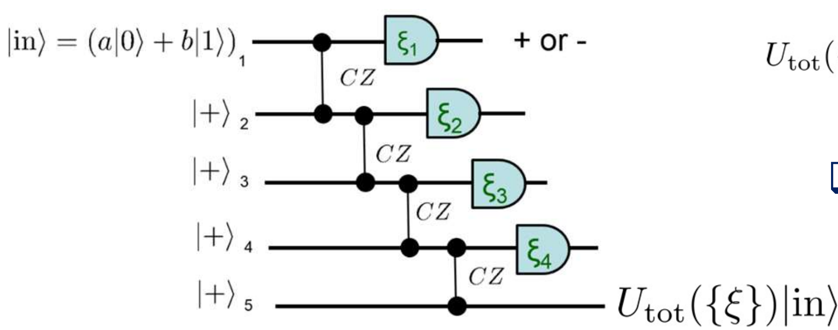
basis change

angle = 0

X rot Zrot Xrot ⇒ Euler rotation

any single-qubit rotation

Arbitrary one-qubit gate



$$U_{\rm tot}(\{\xi\}) = \prod_{i=4}^{1} U(\xi_i, s_i) \quad U(\xi, s) = H\, e^{i\xi Z/2} Z^s$$

- ❑ Consider: $\xi_1=0$ & construct arbitrary rotation

$H Z = X H$

$$U_{\rm tot}(\{\xi\}) = \overset{X^{s_4}}{(}H e^{i\xi_4 Z/2} \cancel{Z^{s_4}})(H e^{i\xi_3 Z/2} Z^{s_3})(H e^{i\xi_2 Z/2} Z^{s_2})(H Z^{s_1})$$

$e^{i\xi_4 Z/2}$ $\boxed{X^{s_3}}$ $e^{i(-1)^{s_3}\xi_4 Z/2}$

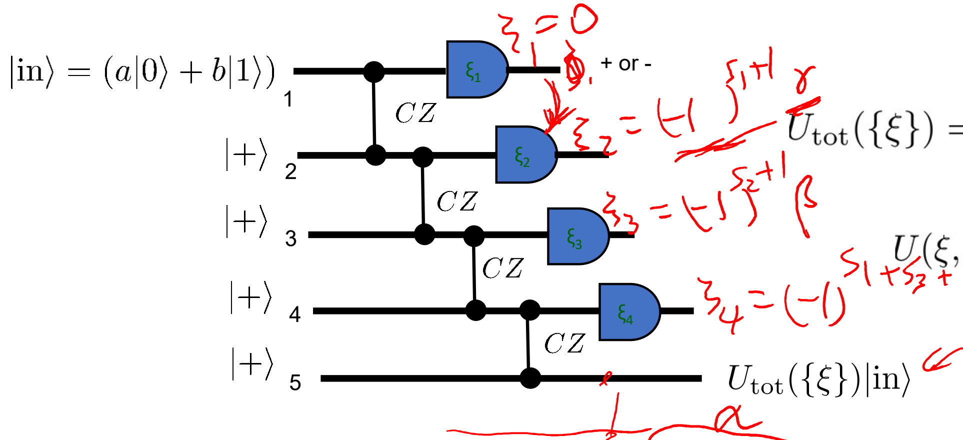
$Z X = (-1) X Z$

- ❑ Propagating Z's to left and use *HZH=X*:

$$U_1(\{\xi\},\{s\}) = Z^{s_1+s_3} X^{s_2+s_4} \underbrace{e^{i(-1)^{s_1+s_3}\xi_4 X/2}\, e^{i(-1)^{s_2}\xi_3 Z/2}\, e^{i(-1)^{s_1}\xi_2 X/2}}$$

Euler rotation (α, β, γ)

Realizing arbitrary rotation



$$U_{\mathrm{tot}}(\{\xi\}) = \prod_{i=4}^{1} U(\xi_i, s_i)$$

$$U(\xi, s) = H\, e^{i\xi Z/2} Z^s$$

$$U_1(\{\xi\},\{s\}) = Z^{s_1+s_3} X^{s_2+s_4}\, e^{i\overbrace{(-1)^{s_1+s_3}\xi_4}^{\alpha} X/2}\ e^{i\overbrace{(-1)^{s_2}\xi_3}^{\beta} Z/2}\ e^{i\overbrace{(-1)^{s_1}\xi_2}^{\gamma} X/2}$$

future angle needs to adapted

❑ Take $\xi_1 = 0,\ \xi_2 = (-1)^{s_1+1}\gamma,\ \xi_3 = (-1)^{s_2+1}\beta,\ \xi_4 = (-1)^{s_1+s_3+1}\alpha$

by product

we realize an Euler rotation:

$$U_1(\{\xi\},\{s\}) = \boxed{Z^{s_1+s_3} X^{s_2+s_4}}\, \overbrace{e^{-i\alpha X/2}\ e^{-i\beta Z/2}\ e^{-i\gamma X/2}}$$

by product

(± 1)

$\alpha|0\rangle + \beta|1\rangle$

final measurement is always 0/1

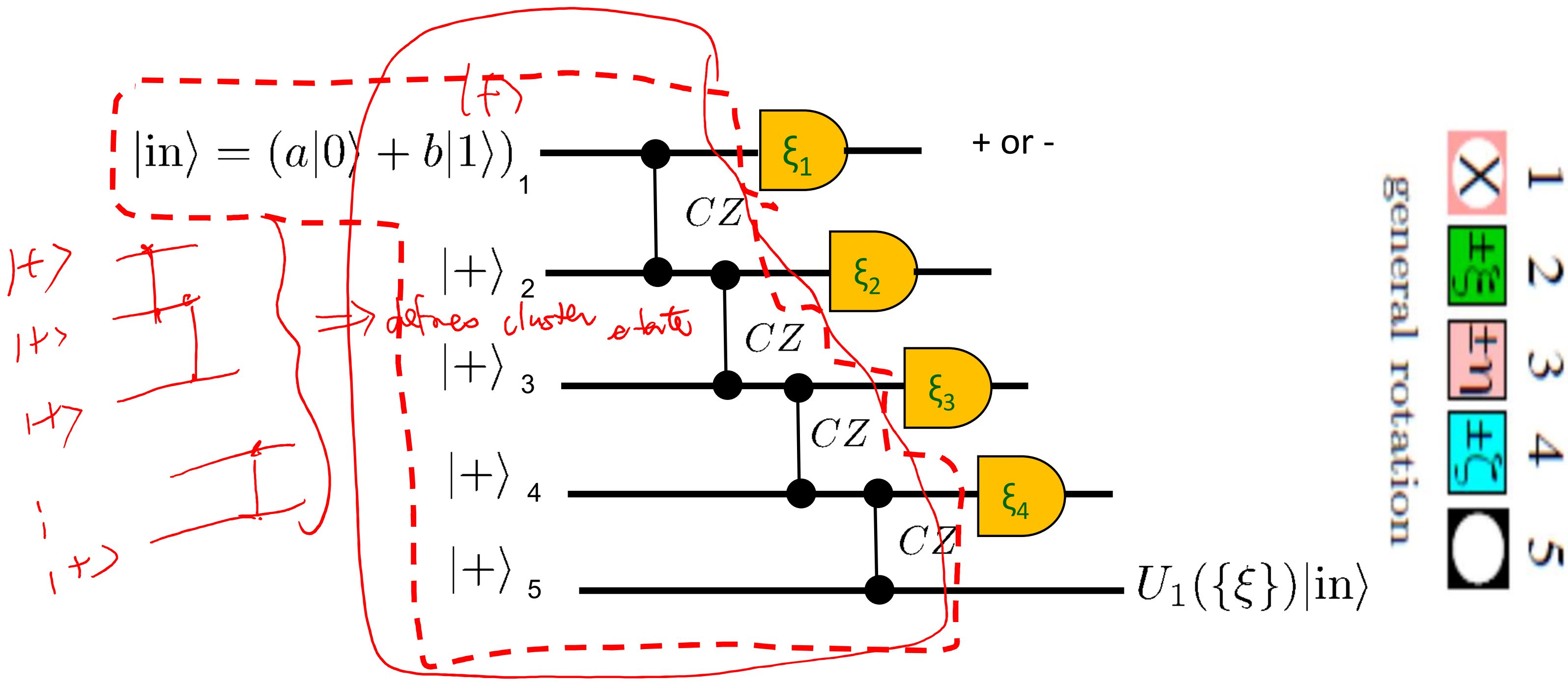
➔ Note: measurement basis can depend on prior results

➔ $Z^{s_1+s_3} X^{s_2+s_4}$ can be absorbed by modifying later measurement basis

has no effect

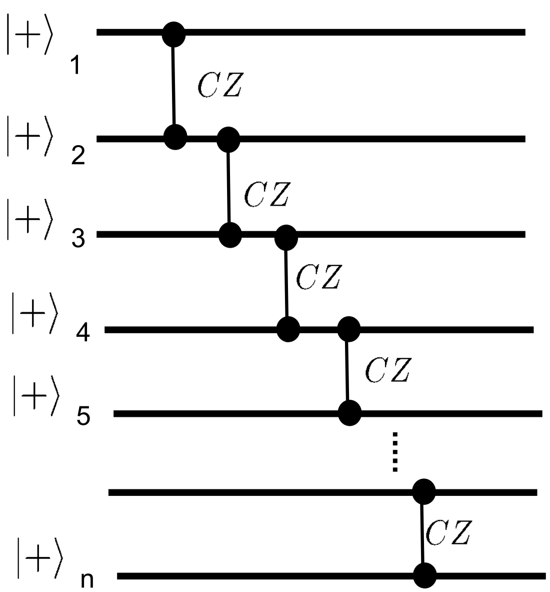
know s_2+s_4 → correct X flip by hand

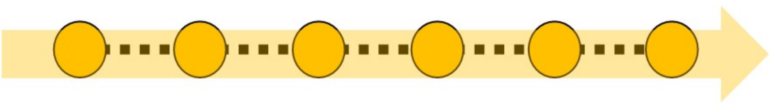
Linear cluster state: resource for simulating arbitrary one-qubit gates



- May as well take |in>=|+>; the whole state before measurement ξ's is a highly entangled state ➔ 1D cluster state

1D Cluster state: simulate 1-qubit gate

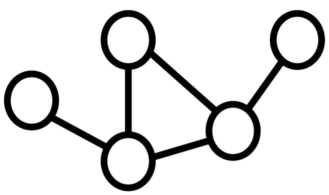




- Local measurement induces discrete evolution of quantum state (one qubit)

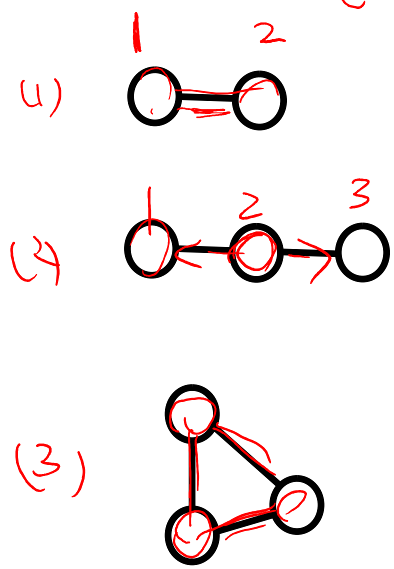
- Cluster/graph states: on any graph:

$$|G\rangle = \bigotimes_{\langle i,j\rangle \in \mathrm{Edge}} CZ_{ij} \left(|+\rangle|+\rangle\cdots|+\rangle\right)$$



Working out cluster states

cluster state (graph) $\equiv \prod_{\langle ij\rangle} CZ_{\langle ij\rangle} |+\rangle \cdots |+\rangle$



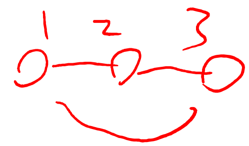
$|\psi_{(1)}\rangle = CZ\,|++\rangle = |0\rangle|+\rangle + |1\rangle|-\rangle = |+\rangle|0\rangle + |-\rangle|1\rangle$

(ignoring $\frac{1}{\sqrt{2}}$ factor)

$(|0\rangle + |1\rangle)|+\rangle \Rightarrow |0\rangle|+\rangle + |1\rangle|-\rangle = |00\rangle + |01\rangle + |10\rangle - |11\rangle$

$|\psi_{(2)}\rangle = CZ_{21}CZ_{23}|+++\rangle = \left(|+\rangle_1|0\rangle_2|+\rangle_3 + |-\rangle_1|1\rangle_2|-\rangle_3\right)/\sqrt{2}$

$(|0\rangle + |1\rangle)$

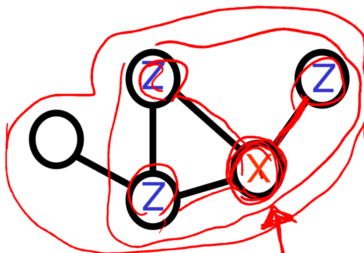


$|\psi_{(3)}\rangle = CZ_{13}|\psi_{(2)}\rangle$

$= \big(000 + 001 + 010 + (-1)\,011 + 100 + (-1)\,101 + (-1)\,110 + (-1)\,111\big)/\sqrt{8}$

Graph states and the stabilizer group

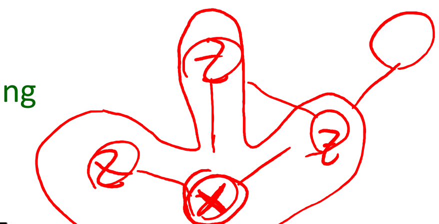
- Cluster state: special case of general "graph" states



$$K_v|G\rangle = |G\rangle, \ \forall \,\text{vertex}\, v$$

$$K_v = X_v \bigotimes_{u\in \mathrm{Nb}(v)} Z_u$$

(can show this, using above def. of G)



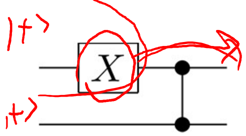
➔ Uniquely define the state G, also via Hamiltonian $H = -\sum K_v$

for each vertex there is one stabilizer K_v operator

⇒ The set (group) uniquely determines the state

$n - n = 0$

Recall:



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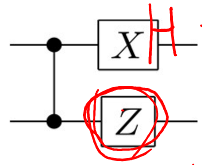
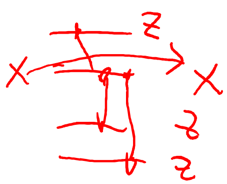


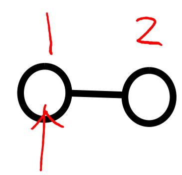
$H = -\sum_v K_v$

cf. $H_{Toric} = -\sum_s A_s - \sum_p B_p$

$$|\psi\rangle = CZ\, \underbrace{X_1|+\rangle}_{=|+\rangle}|+\rangle = X_1 Z_2\, CZ|+\rangle|+\rangle = X_1 Z_2 |\psi\rangle$$



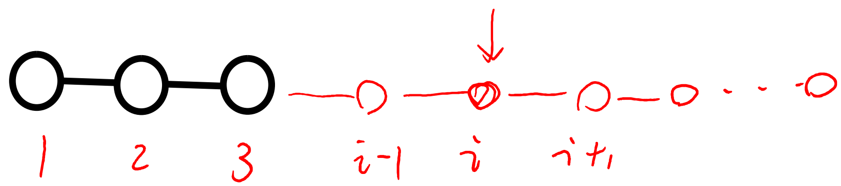
Example of graph Hamiltonians



2 stabilizer elements: $X_1 Z_2 \quad - \quad X_2 Z_1$ $\qquad \Big(S = \langle \underbrace{X_1 Z_2, X_2 Z_1}_{2} \rangle \Big)$

$H = - X_1 Z_2 - X_2 Z_1$

boundary term



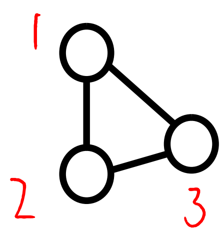
$$\begin{array}{cccccc} & i-1 & i & i+1 & & \\ & \underbrace{Z \quad X \quad Z} & & & & \\ X & 1 & X & 1 & X & \cdots \\ 1 & X & 1 & X & 1 & X \end{array}$$

except boundary

$$H = -\underbrace{\sum Z_{i-1} X_i Z_{i+1}}_{i \notin \text{boundary}} - X_1 Z_2 - X_L Z_{L-1}$$

$\Downarrow$ symmetry protected topological phase

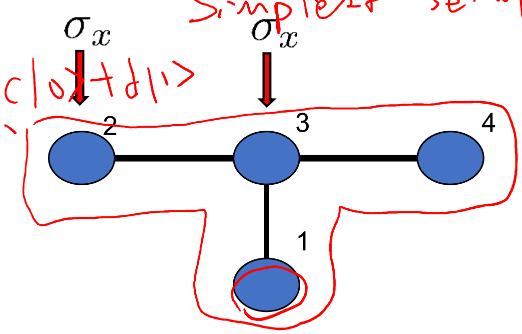
$Z_2 \times Z_2$



$\rightarrow$ $H = -(X_1 Z_2 Z_3 + X_2 Z_3 Z_1 + X_3 Z_1 Z_2)$

Simulating CNOT by measurement

Simplest setup for CNOT



- Consider initial state

$$(a|0\rangle + b|1\rangle)_1\,(c|0\rangle + d|1\rangle)_2\,|+\rangle_3\,|+\rangle_4 \xrightarrow{CZ_{23}\,CZ_{13}\,CZ_{34}} |\psi\rangle_{1234}$$

$$|\psi\rangle_{1234} = |0\rangle_3\big(a|0\rangle_1 + b|1\rangle_1\big)\big(c|0\rangle_2 + d|1\rangle_2\big)|+\rangle_4$$
$$+|1\rangle_3\big(a|0\rangle_1 - b|1\rangle_1\big)\big(c|0\rangle_2 - d|1\rangle_2\big)|-\rangle_4$$

a|0>+b|1>

$$|\psi_{\rm in}\rangle_{12} \longrightarrow \mathrm{CNOT}|\psi_{\rm in}\rangle_{14}$$

- Measurement on 2nd and 3rd qubits in basis $|\pm\rangle \equiv (|0\rangle \pm |1\rangle)/\sqrt{2}$

If outcome=++: an effective CNOT applied: (could be an exercise)

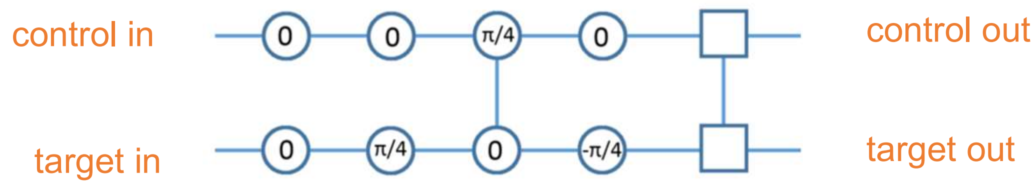
$$|\psi\rangle_{14} = {}_{23}\langle + + |\psi\rangle_{1234} \sim \mathrm{CNOT}_{14}(a|0\rangle_1 + b|1\rangle_1)(c|0\rangle_4 + d|1\rangle_4)$$

Can show: $|\psi_{\rm out}\rangle \sim Z_1^{s_2}\,X_4^{s_3}\,Z_4^{s_2}\,\mathrm{CNOT}_{14}|\mathrm{in}\rangle_{14}$

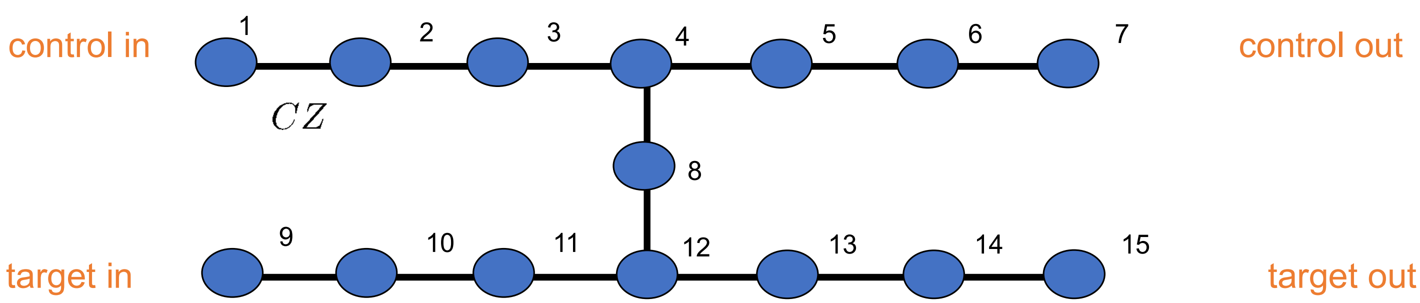
- Note the action of CZ gates can be pushed up front
(a 4-qubit "cluster" state can be used to simulating CNOT)

CNOT: Other implementations

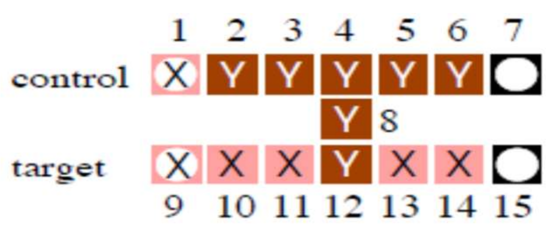
1.



2.



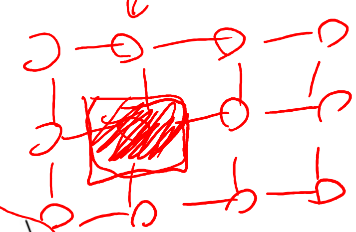
with measurement pattern:



CNOT-gate

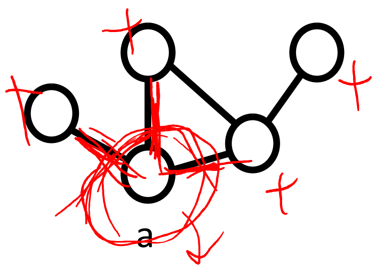
Z measurement on graph state

affects this ??



- The effect is just to remove the measured qubit, keeping the remaining entanglement structure

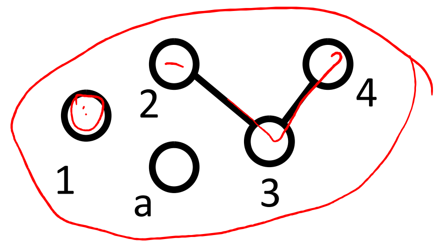
Think in terms of "construction stage" when we grow the graph



$$|\Psi_G\rangle = |0\rangle_a |\Psi_{G\setminus a}\rangle + |1\rangle_a \left(\prod_{b \in NB(a)} Z_b \right) |\Psi_{G\setminus a}\rangle$$

up to Z correction

➔ Graph after Z measurement on qubit ***a***:



$|0\rangle_a |\Psi_{G\setminus a}\rangle$

✓ If outcome =0: $|0\rangle_a |+\rangle_1 |C\rangle_{234}$ $|C\rangle_{234}$: linear cluster state

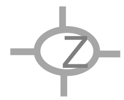
$|1\rangle_a \prod_{b \in Nb(a)} Z_b |\Psi_{G\setminus a}\rangle$

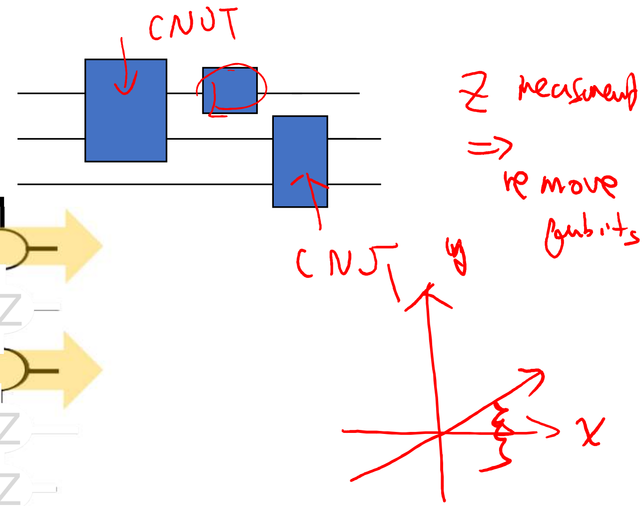
✓ If outcome =1: $|0\rangle_a |-\rangle_1 Z_2 Z_3 |C\rangle_{234}$

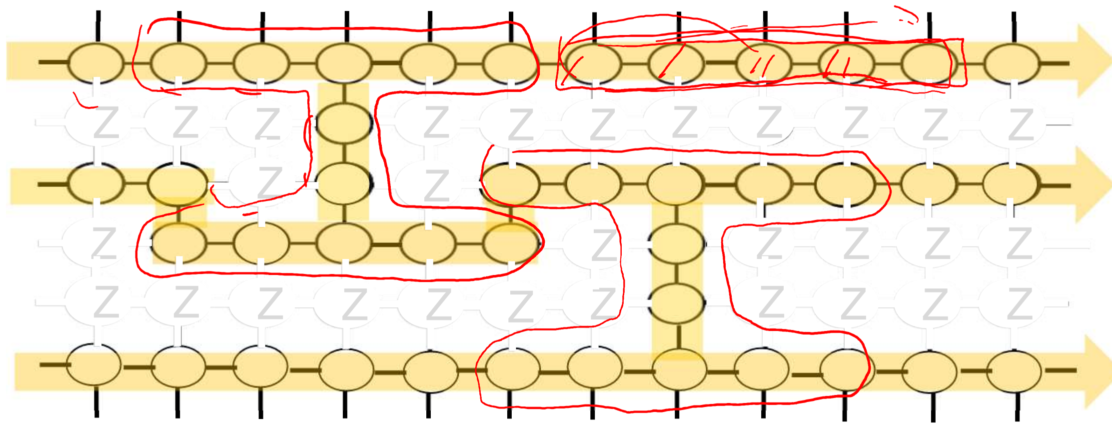
Measurement-based QC: cluster state

[*Raussendorf & Briegel* PRL 01']

- Carve out entanglement structure by local Z measurement







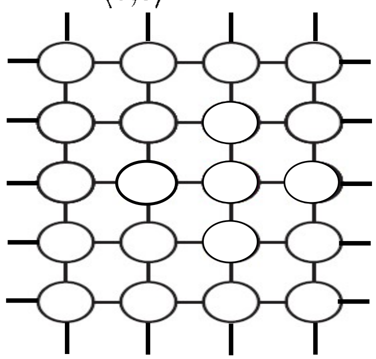
(1) Each wire simulates one-qubit evolution (gates)

(2) Each bridge simulates two-qubit gate (CNOT)

2D or higher dimension is needed for universal QC &
Graph connectivity is essential (percolation)

2D cluster state is a resource for quantum computation

$$|C\rangle = \bigotimes_{\langle i,i\rangle} CZ_{ij}\left(|+\rangle|+\rangle\cdots|+\rangle\right)$$

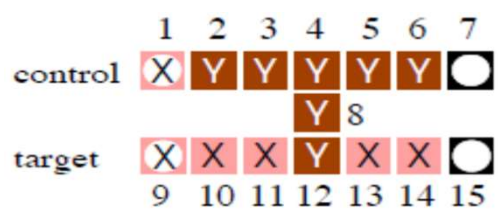


- Whole entangled state is created first (by whatever means)
- Operations needed for *universal* QC are single-qubit measurements only

➔ Pattern of measurement gives computation
(entanglement is being consumed → one-way)

➔ Elementary "Lego pieces" for QC:

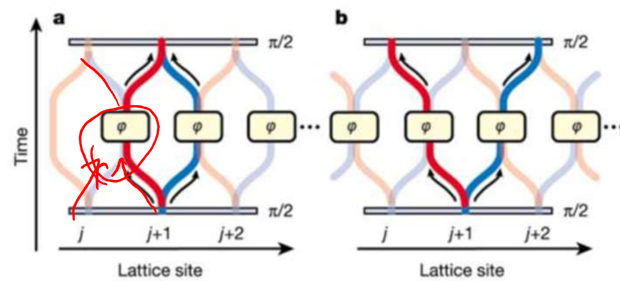
general rotation



CNOT-gate

Realizations of cluster states

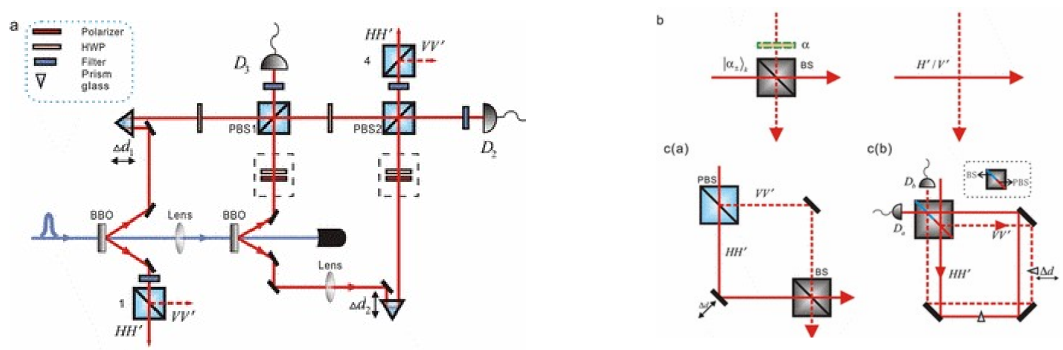
- Bloch's group: controlled collision in cold atoms (Nature 2003)



$(1-\sigma_z)(1-\sigma_z)$

Ising coupling

- J-W Pan's group: 4-photon 6 qubit and CNOT (PRL 2010)



Linear optic QC & cluster state

- Linear optic universal QC possible with single photon source, linear optic elements (beam splitters, mirrors, etc) & photon counting

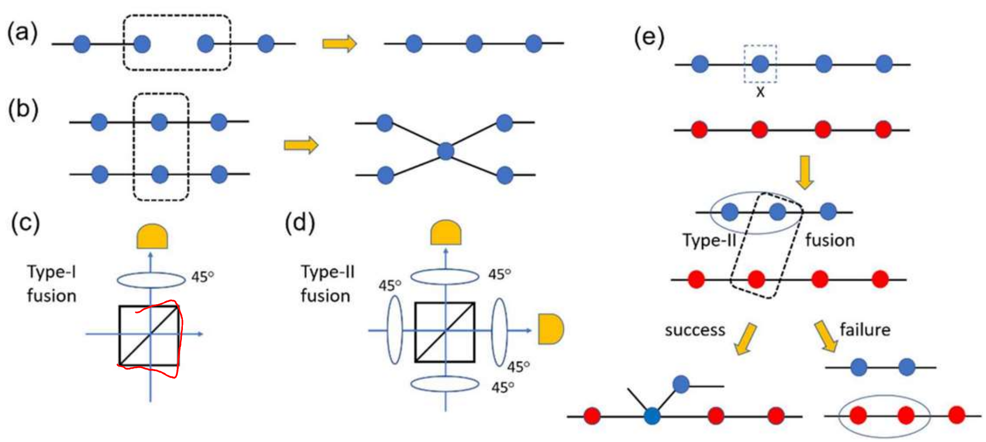
  ➔ High overhead in entangling gates

  [Knill, Laflamme & Milburn '01]

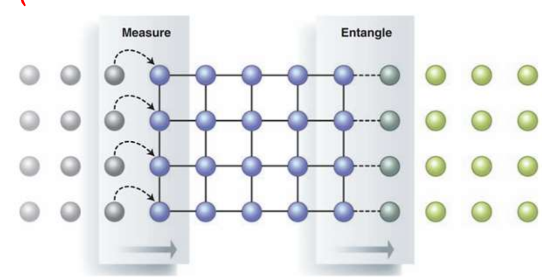
- Cluster state helps reduce this overhead

  ➔ Grow cluster states efficiently

  [Yoran & Reznik '03; Nielsen '04; Browen & Ruldoph '05; Kieling, Rudolph &Eisert '07]



measurement of photon polarization can be very high

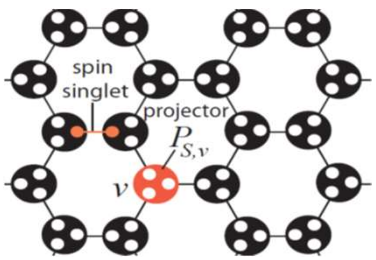


- Experimental prospect: see e.g. [O'Brien, Science '07]

Other universal states*

- So far no complete characterization for resource states
- Can they be unique ground state with 2-body Hamiltonians with a finite gap?

→ If so, create resources by cooling!

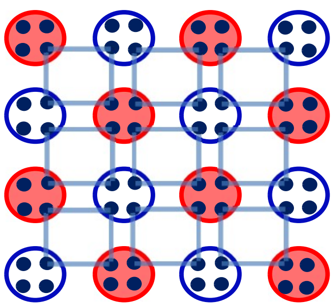


- Affleck-Kennedy-Lieb-Tasaki (AKLT) family of states [*AKLT* '87, '88]

→ Unique ground states of two-body interacting Hamiltonians

1D (not universal): [*Gross et al.* '07, '10] [*Brennen & Miyake* '08?]

2D (universal): [*Wei, Affleck & Raussendorf* '11] [*Miyake* '11] [*Wei et al*. '13-'15]



- Symmetry-protected topological states

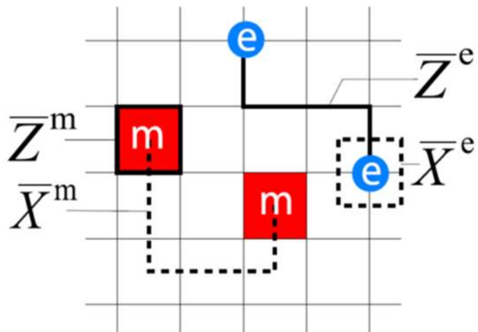
1D (not universal): [*Else, Doherty & Bartlett '12*] [*Miller & Miyake* '15] [*Prakash & Wei* '15] [*Stephen et al.* '17]

2D (universal, *not much explored*): [*Poulsen Nautrup & Wei* '15, *Miller & Miyake* '15, *Chen, Prakash & Wei* '18, Raussendorf et al. '18]

How do we make MBQC fault tolerant?

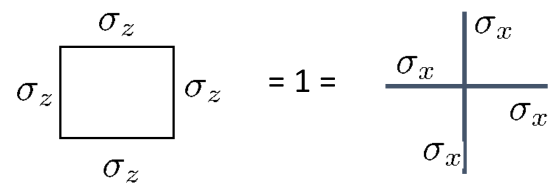
- Key idea: use 3-dimensional cluster state and measurement pattern simulates braiding

- 2d Surface code:



1. Physical qubit on edge

2. Most plaquettes and vertices (stars)



is enforced in code space

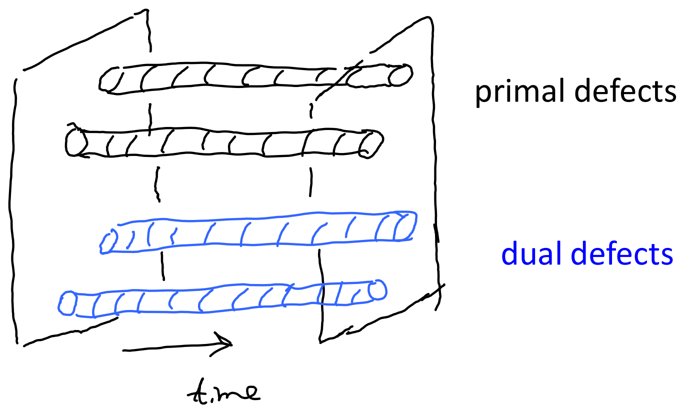
3. When a pair of plaquettes (or stars) not enforced,
   it gives rise to a logical qubit (see above and logical X and Z operators)

- Braiding gives topologically protected logical operations

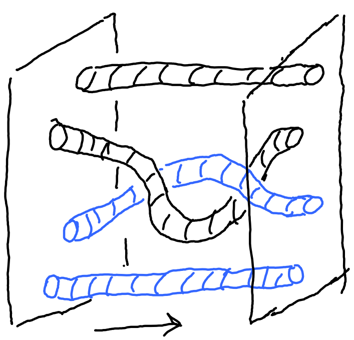
  ☹ But not universal, requires magic state injection to logical qubit (see above and logical X and Z operators)

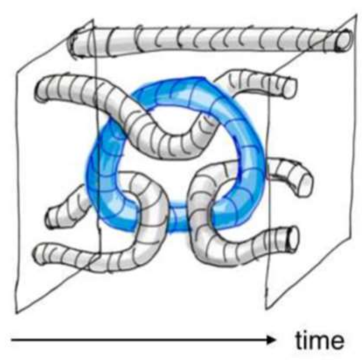
Surface code QC

- Example: 2 logical qubits (one primal and one dual)



- CNOT gates (between primal and dual; between two primal logical qubits)
  ➔ simplest to implement



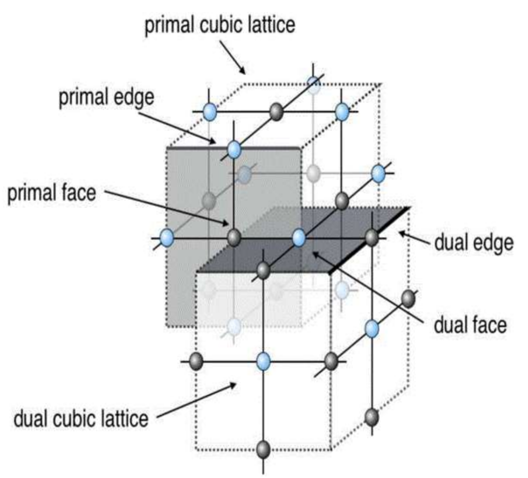


Fault-tolerant MBQC

- Key idea: use 3-dimensional cluster state and measurement pattern simulates braiding

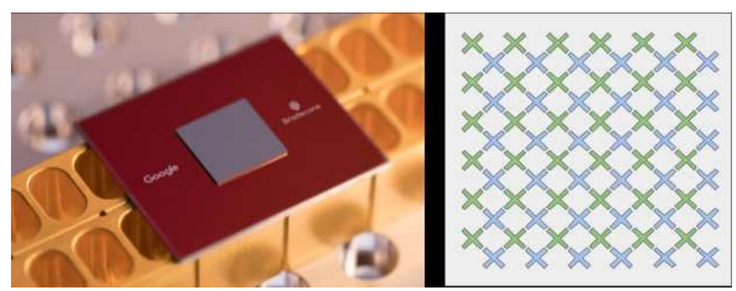
- The diagrams literally translate to measurement pattern (replace time direction by the third dimension)

- The 3d cluster state is given by a lattice with the following unit cell:



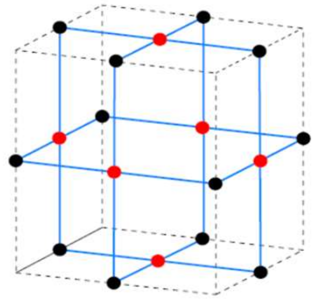
- Gives a high error threshold: 0.75%

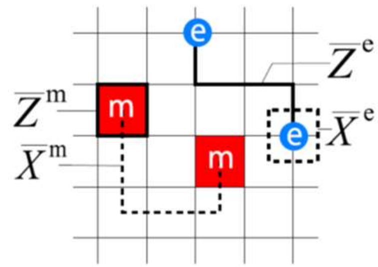
- 2d circuit version is what Google plans to use



Fault tolerant cluster-state QC

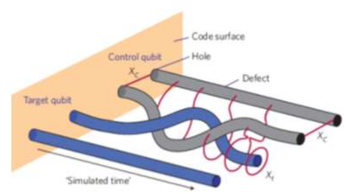
- ❑ Uses a 3d cluster state and implements surface codes in each 2d layer

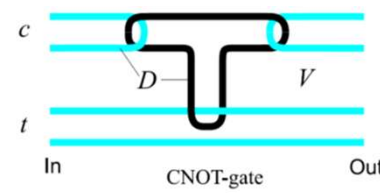




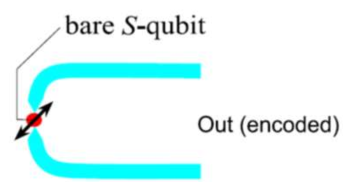
[Raussendorf, Harrington & Goyal '07]

- ❑ CNOT is achievable by measurement





- ❑ Uses magic-state distillation to achieve non-Clifford gate (by measurement)



➔ Error threshold 0.75%, qubit loss threshold 24.9%

[Barrett & Stace '10]

One application of measurement-based QC

Suppose we have a cloud quantum computer server.

Q: Is it possible to run on this cloud quantum computer without the server figuring out what the client is actually running?

A: Blind quantum computation