Quantum Computing

with physics and for physics

Yanzhu Chen
Department of Physics and Astronomy
C.N. Yang Institute for Theoretical Physics

Advisor: Tzu-Chieh Wei

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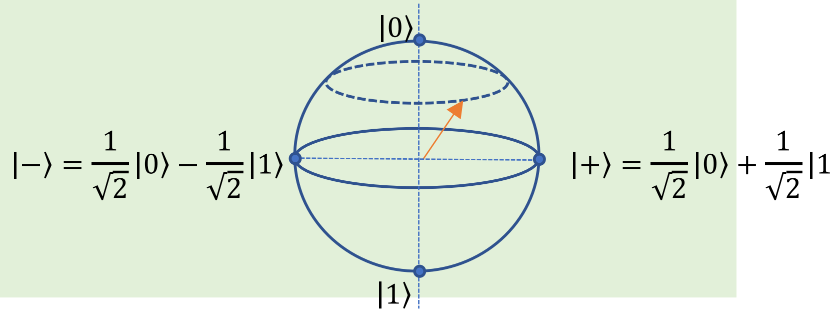
Stony Brook University

Quantum computing



$$|\psi\rangle = \cos\frac{\theta}{2}|0\rangle + e^{i\phi}\sin\frac{\theta}{2}|1\rangle$$

- Qubit

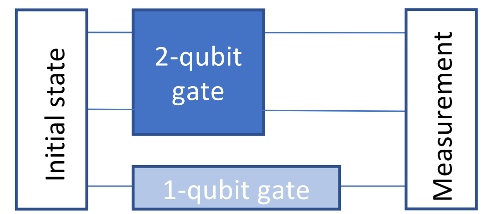
  - 2 dimensional Hilbert space: a generic state is $\alpha|0\rangle + \beta|1\rangle$

  - Computational basis $|0\rangle, |1\rangle$ (orthonormal)

- Entanglement

  - Failure to be written as a product state (e.g. $|\phi\rangle|\varphi\rangle$)

  - e.g. an entangled state for two qubits $\frac{1}{\sqrt{2}}|00\rangle + \frac{1}{\sqrt{2}}|11\rangle$



- Unitary operation

  - Universal set: all 1-qubit rotations and 1 non-trivial 2-qubit gate

  - Examples:

$$X = \sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad Y = \sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad Z = \sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

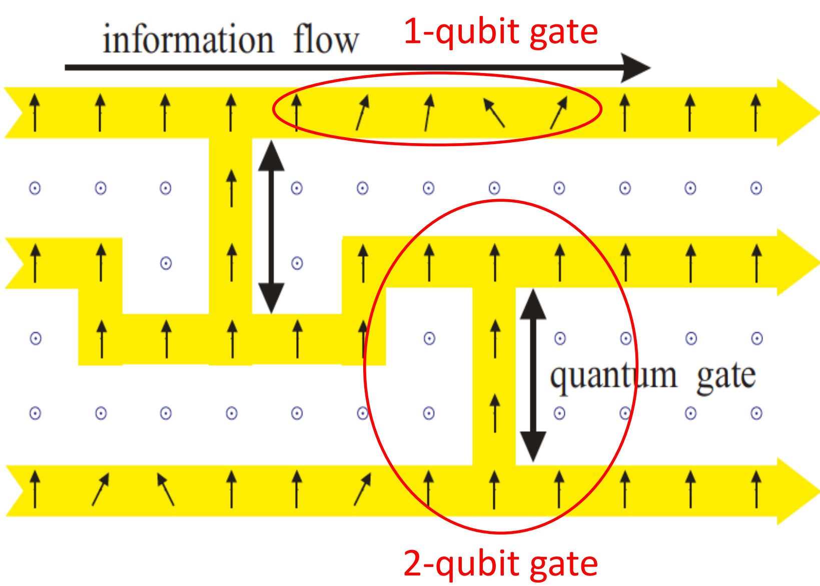
$$H = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}, \quad \mathrm{CNOT} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

Outline

- Quantum computing utilizing physics
  - Measurement based quantum computing
  - Errors in quantum computing
- Quantum computing designed to study physics
- Timeline

Measurement based quantum computing

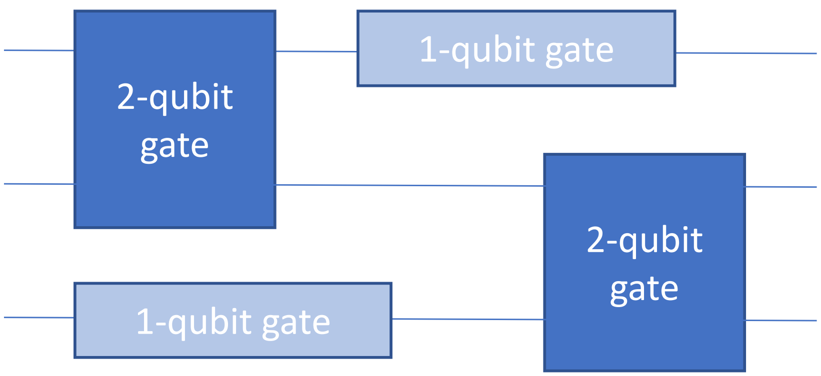
What is it (MBQC)?



Recall Entanglement

- Failure to be written as a product state (e.g. $|\phi\rangle|\varphi\rangle$)
- e.g. an entangled state $\frac{1}{\sqrt{2}}|00\rangle + \frac{1}{\sqrt{2}}|11\rangle$

Corresponding circuit diagram:

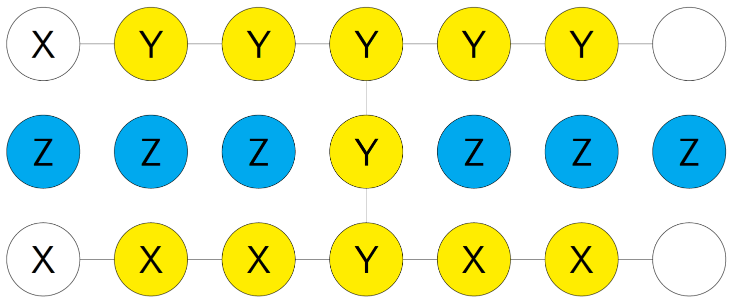


R. Raussendorf, and H. J. Briegel, Phys. Rev. Lett. 86(22):5188-5191, 2001.

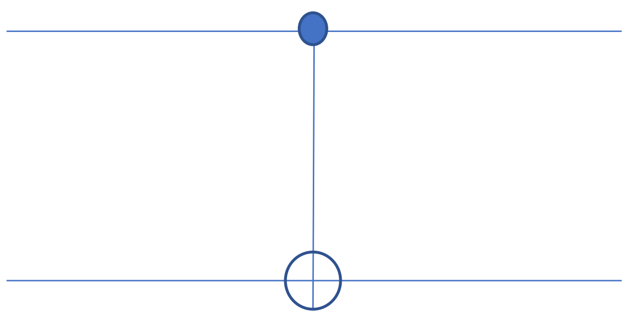
Measurement based quantum computing

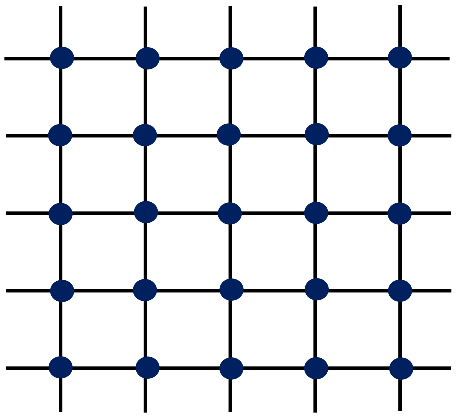
What is it (MBQC)?

Example: 2-qubit gate (CNOT)



Corresponding circuit diagram





The first and most studied resource state: cluster state

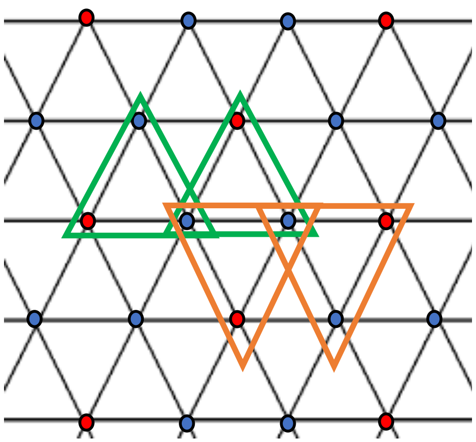
$$|\psi_c\rangle = \left(\prod_{\langle i,j\rangle} CZ_{ij}\right)\left(\otimes_k |+\rangle_k\right)$$

Each qubit is in the $|+\rangle$ state; every pair of neighbors are entangled by CZ gate

R. Raussendorf, and H. J. Briegel, Phys. Rev. Lett. 86(22):5188-5191, 2001.

Measurement based quantum computing

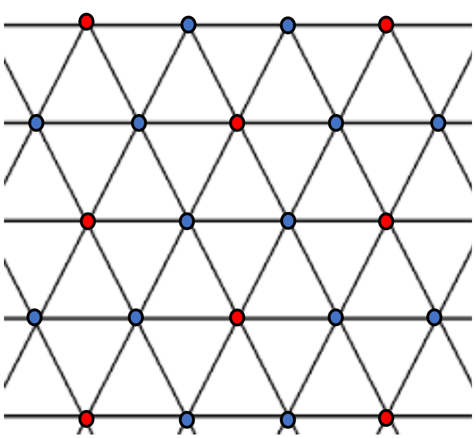
Past work*: qudit MBQC with symmetry protected topological (SPT) states



A class of symmetry protected topological states:

$$|\phi_k\rangle = \left(\prod_{\Delta(a,b,c)} CCZ_{abc}^{k}\right)\left(\prod_{\nabla(d,e,f)} CCZ_{def}^{\dagger k}\right)\left(\otimes_i |+\rangle_i\right)$$

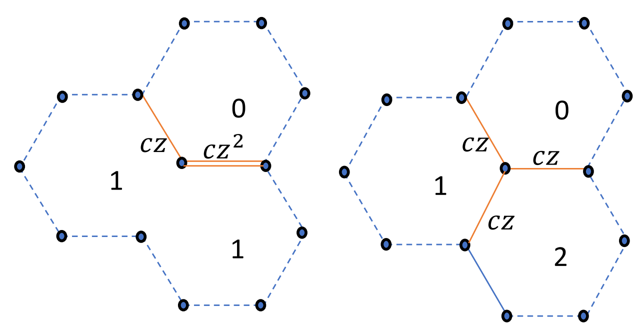
Each qubit is in the $|+\rangle$ state; every triangle of qubits are entangled by $CCZ^k/CCZ^{\dagger k}$ gate



Idea: convert the state to the cluster state.

Here: measure the red qubits in the computational basis.

Examples of three neighboring measurement outcomes:



*Y-C, A. Prakash, and T.-C. Wei. Phys. Rev. A 97(2):022305, 2018.

Measurement based quantum computing

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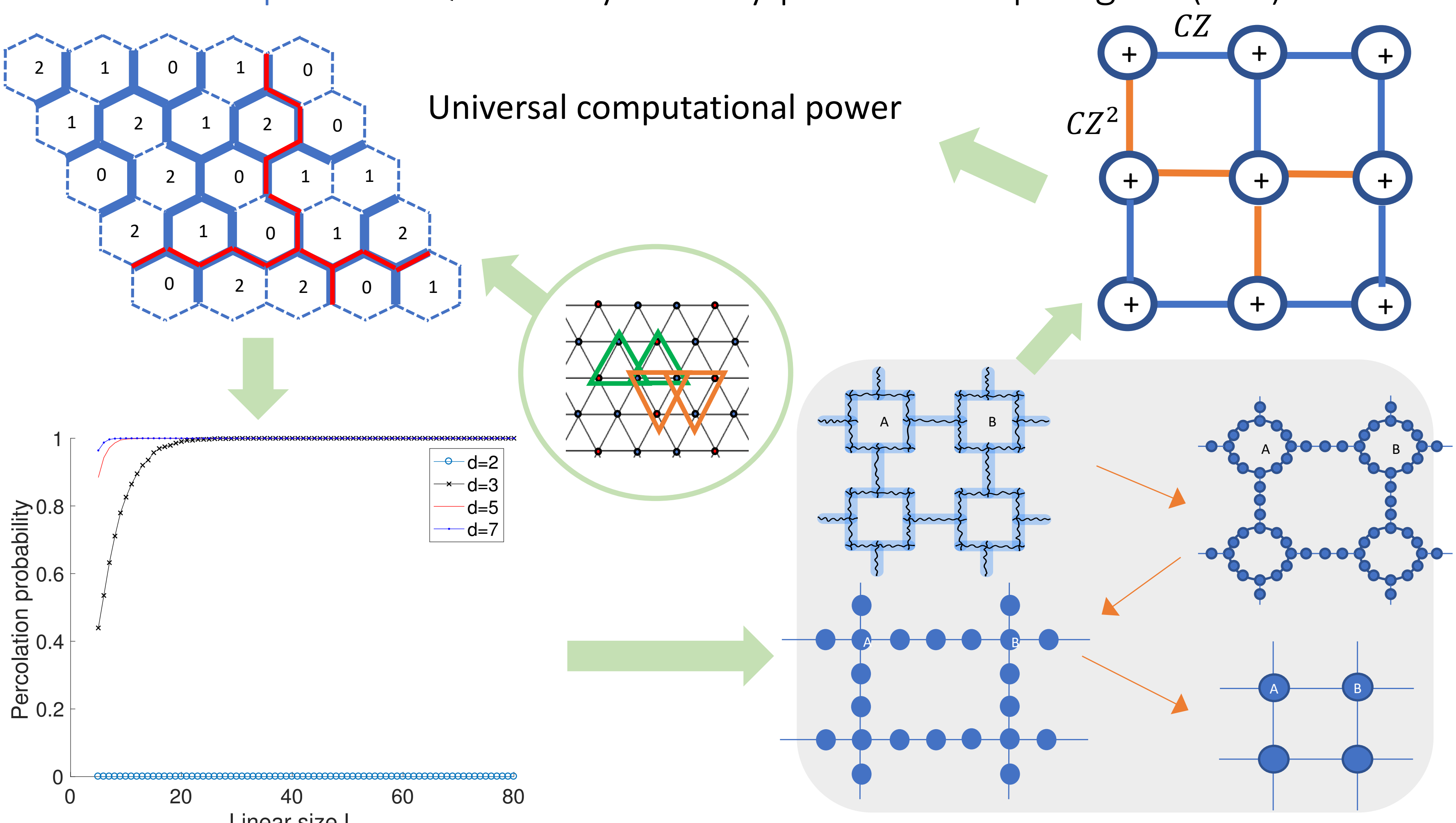


*Y-C, A. Prakash, and T.-C. Wei. Phys. Rev. A 97(2):022305, 2018.

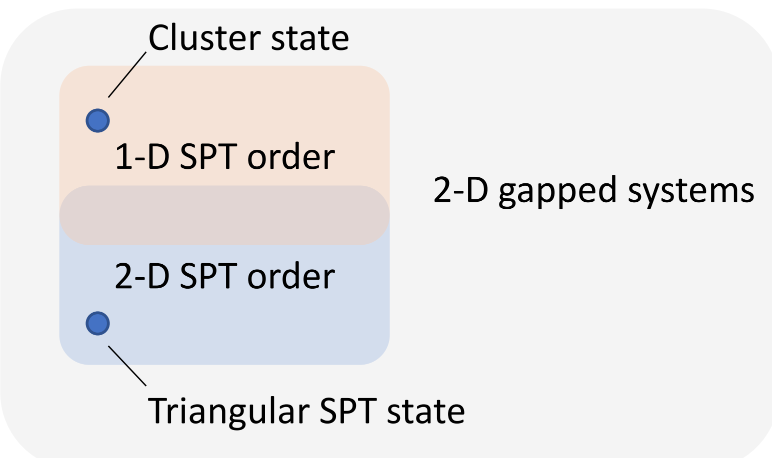
Measurement based quantum computing

Future work:

- Computational power of symmetry protected topological (SPT) phases

  - Modifications to the computation scheme?

  - Types of symmetry other than internal symmetry?



Initial Idea:

Else, et al. Phys. Rev. Lett., 108:240505, 2012.
Stephen, Wang, Prakash, Wei, and Raussendorf. Phys. Rev. Lett., 119:010504, 2017.

Progress in literature:

Wei and Huang. Phys. Rev. A, 96:032317, 2017.
Raussendorf, et al. Phys. Rev. Lett., 122:090501, 2019.
Stephen, et al. Quantum 3:142, 2019.

Errors in quantum computing

- Density matrix ρ

  - Pure state $\rho = |\psi\rangle\langle\psi|$

  - Mixed state

- Types of error

  - Relaxation, decoherence, depolarizing, …

- Characterizing realistic quantum computing

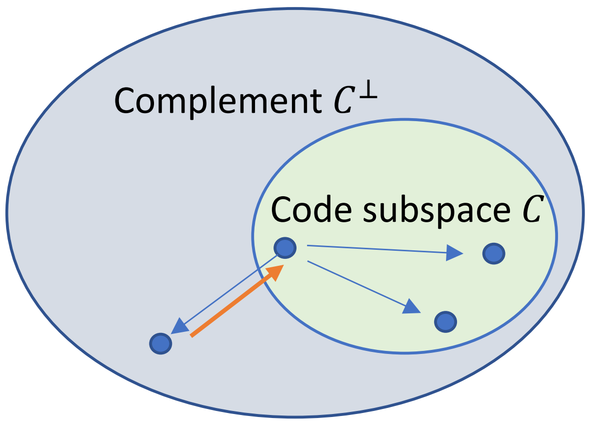
  - State/process/detector tomography, randomized benchmarking, …

- Error mitigation

  - Dynamical decoupling, zero error extrapolation, …

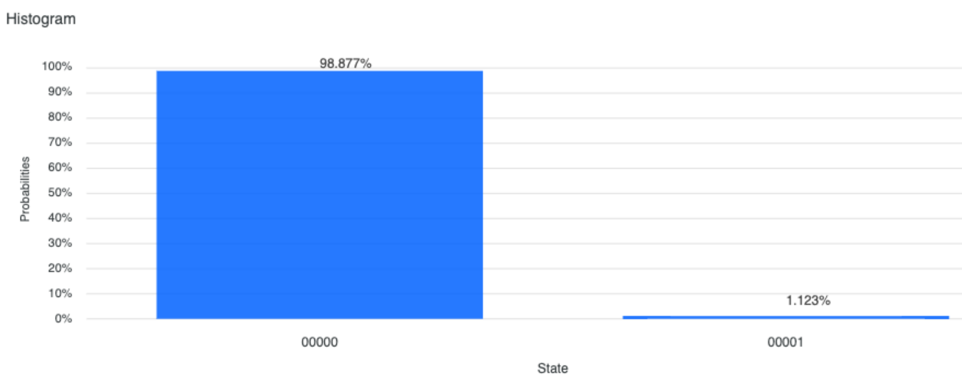
- Error correction

  - Threshold theorem



Errors in quantum computing

Past work*: quantum detector tomography in IBM quantum computers



Histogram showing measurement of the first qubit prepared in state $|0\rangle$.

A 1-qubit detector:

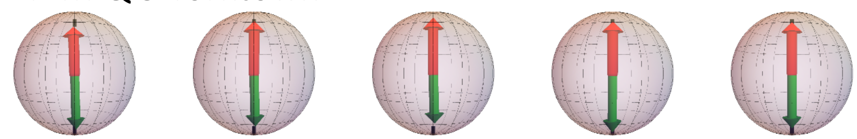
$$\pi^{(0)} = a^{(0)}\left(1 + \vec{r}^{(0)} \cdot \vec{\sigma}\right)$$

$$\pi^{(1)} = a^{(1)}\left(1 + \vec{r}^{(1)} \cdot \vec{\sigma}\right)$$

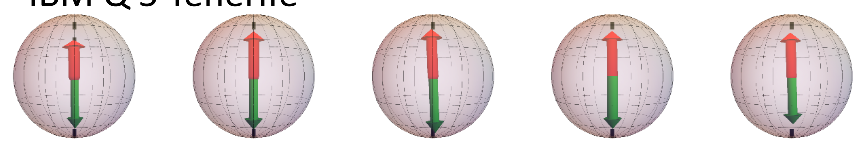
An N-qubit detector:

$$\pi^{(\vec{n})} = \sum_{\vec{i}} c_{\vec{i}}^{(\vec{n})} \sigma_{i_1} \otimes \cdots \otimes \sigma_{i_N}$$

IBM Q 5 Yorktown



IBM Q 5 Tenerife



The arrow on the Bloch sphere indicates the vector $\vec{r}^{(0)}$ or $\vec{r}^{(1)}$, while the width of the arrow represents magnitude $a^{(0)}$ or $a^{(1)}$.

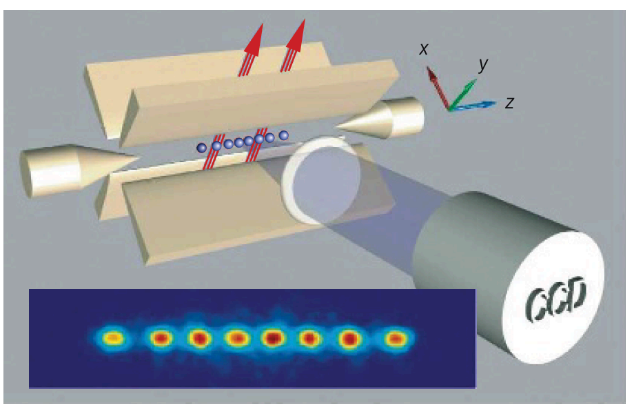
Sign of crosstalk between qubits!

*Y-C, M. Farahzad, S. Yoo, and T.-C. Wei. arXiv:1904.11935, 2019.

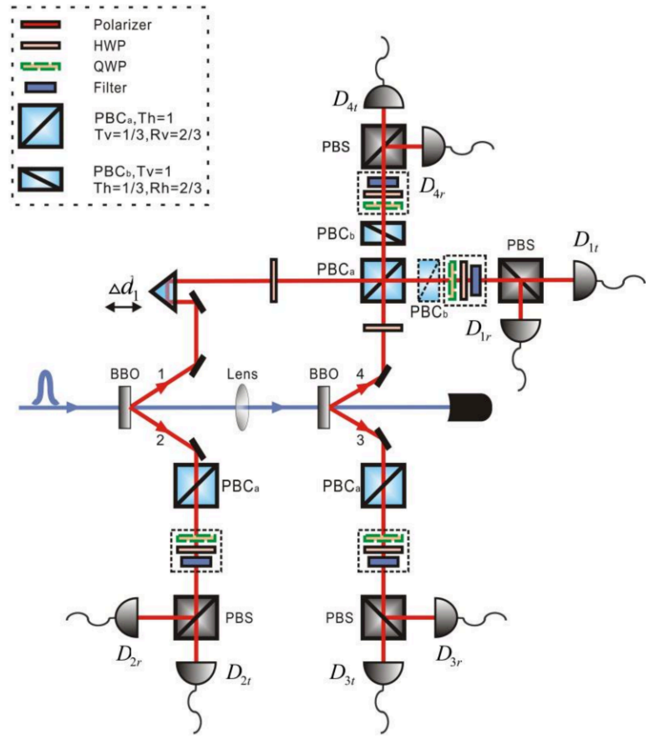
Errors in quantum computing

Future work:

- Errors in MBQC
  - Photonic system
  - Trapped ion system



Trapped ion system. Picture from R. Blatt and D. Wineland, Nature 453, 1008–1015, 2008.



Experimental setup to generate a 4-qubit entangled state. Picture from Gao, et al.

Gao, et al. Nat. Photonics, 5:117-123, 2011.

Lanyon, et al. Phys. Rev. Lett., 111(21):210501, 2013.

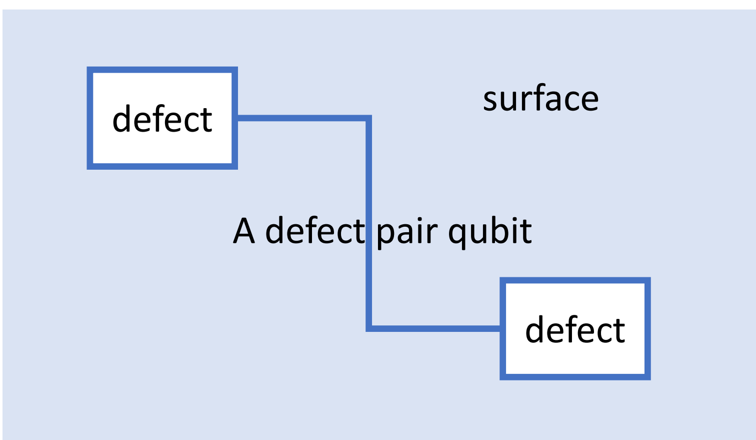
Errors in quantum computing

Future work:

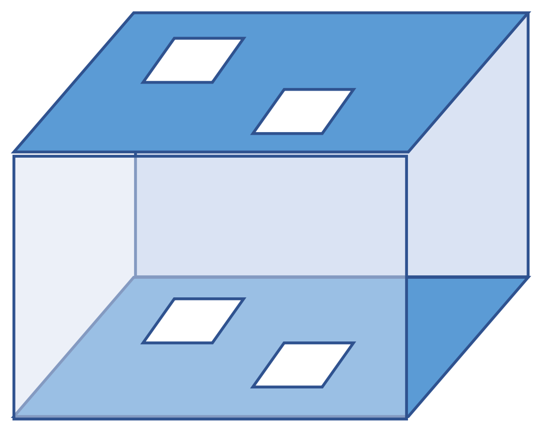
- Measurement based topological codes

  - Topological MBQC (best threshold currently)

  - Method based on 3-D color codes



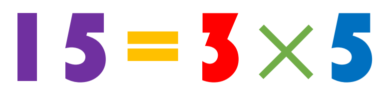
Fujii. arXiv:1504.01444, 2015.
Bombin. arXiv:1810.09571, 2018.

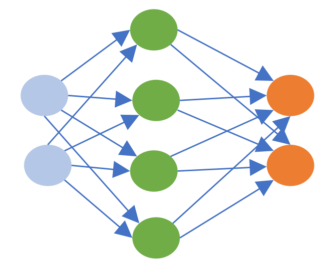


Design algorithms to study physics

- Questions quantum computing may address:

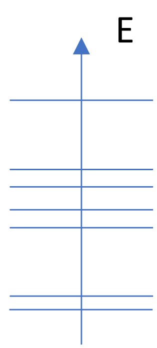
  Factoring, solving linear equations, machine learning, …

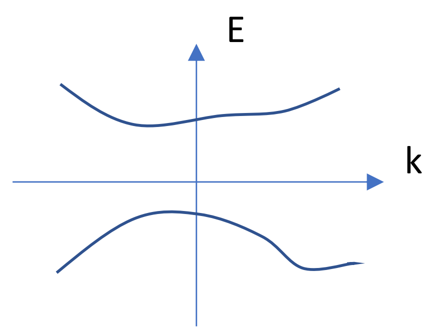


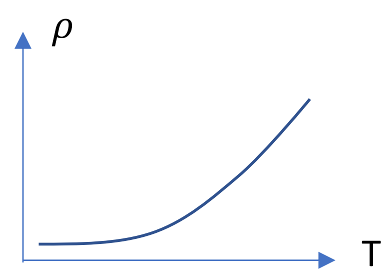


- Questions in physics:

  Ground state and its energy, the entire spectrum, thermal distribution, dispersion, interactions, evolution of systems, transport properties, …







Design algorithms to study physics

- Features of physical systems

  Symmetry

  B. T. Gard, et al. arXiv:1904.10910, 2019.

  Locality

  M. Motta, et al. arxiv:1901.07653, 2019.

- What is computing

  "Do not have to imitate nature"

  D. Poulin, et al. Phys. Rev. Lett., 121:010501, 2018.

- Single-qubit measurement

  Y-C and T.-C. Wei. arXiv:1903.11999, 2019.

Design algorithms to study physics

Future work:

- Eigenstate preparation and spectral measurement
  - What kind of physical systems?
  - Main challenges?
  - Existing methods and limitations?
  - How to approach?

HELP!

from material scientists, mathematicians and computer scientists

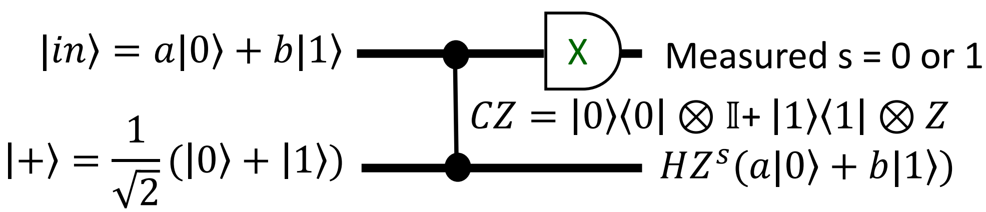
Timeline in the following 1-2 years

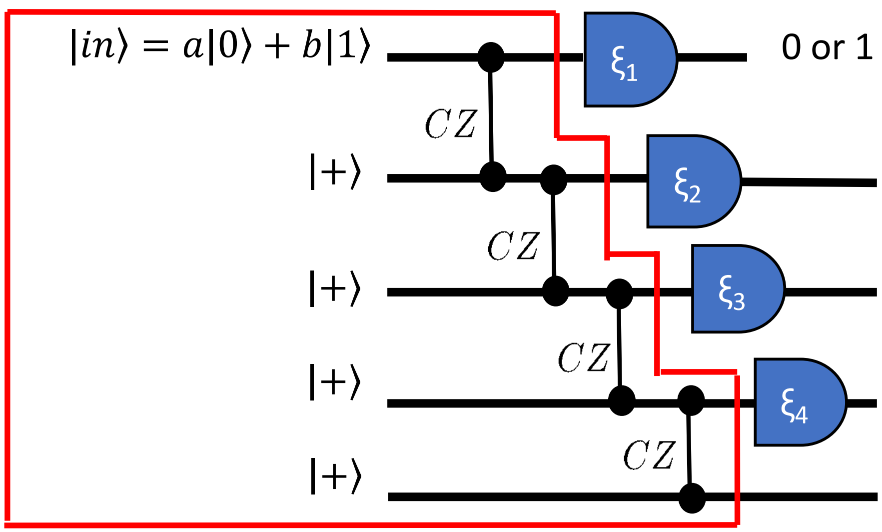
Topic	Stage	Estimated time
Computational power of symmetry protected topological phases	Review: the modified MBQC scheme, 1-D case, 2-D subsystem symmetry	1-2 months
	Explore computational power of SPT phases protected by internal symmetry and/or crystalline symmetry	3-4 months
Errors in MBQC	Review: typical errors in physical systems for MBQC	1 month
	Explore the effects of errors in MBQC; propose mitigation schemes	2-3 months
Measurement based tpological codes	Review: measurement based topological codes	2 months
	Identify challenges and approachable problems; solve the problems	3-4 months
Quantum algorithm	Review: existing techniques	1-2 months
	Improve algorithm for some specific problem	3-4 month

THANKS

Appendix: MBQC by teleportation

What is it (MBQC)?





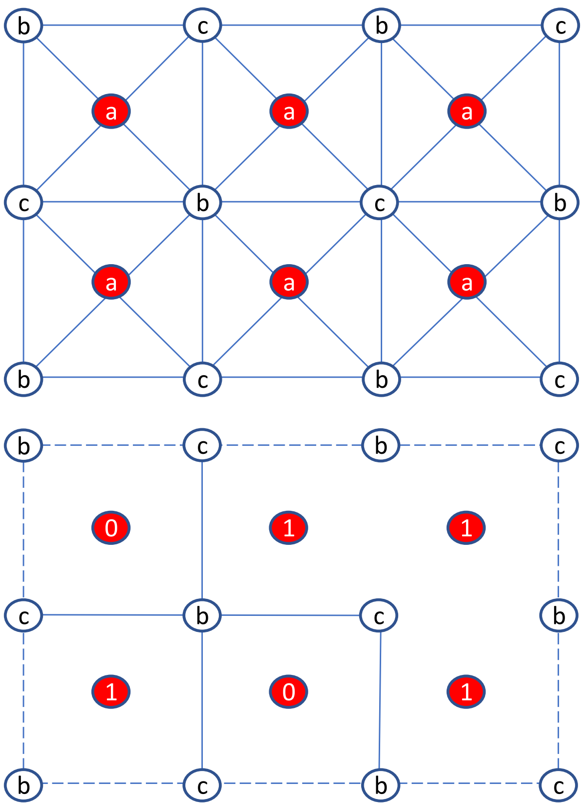
Information of the input state is teleported to another qubit; such information can be recovered given the measurement outcome.

With chosen measurement bases, the qubit at the end will be in the state $U|in\rangle$ for a desired unitary operation U, up to byproduct operators determined by measurement outcomes.

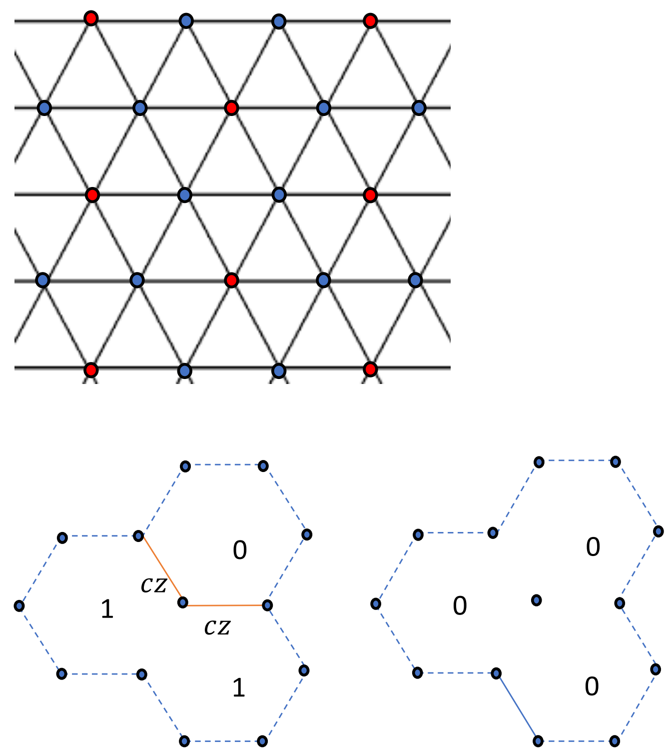
R. Raussendorf, and H. J. Briegel, Phys. Rev. Lett. 86(22):5188-5191, 2001.

Appendix: MBQC using SPT states

Qubit SPT state on union-jack lattice



Qubit SPT state on triangular lattice



J. Miller, and A. Miyake, Nature Partner Journals Quantum Information, 2:16036, 2016.

Appendix: Some quantum algorithms in physics

- Spectral measurement using function of Hamiltonian

  D. Poulin, et al, Phys. Rev. Lett., 121(1):010501, 2018.

- Quantum-classical hybrid

  - Quantum imaginary time evolution

    M. Motta, et al, arxiv:1901.07653, 2019.

  - Variational search for eigenstates combined with iterative phase estimation ("witness assisted")

    R. Santagati, et al, Sci. Adv. 4, eaap9646, 2018.

- Spectral measurement utilizing single-qubit measurement

  Y-C and T.-C. Wei. arXiv:1903.11999, 2019.