http://www.sfc.wide.ad.jp/aqua/

Surface Code Quantum Error Correction

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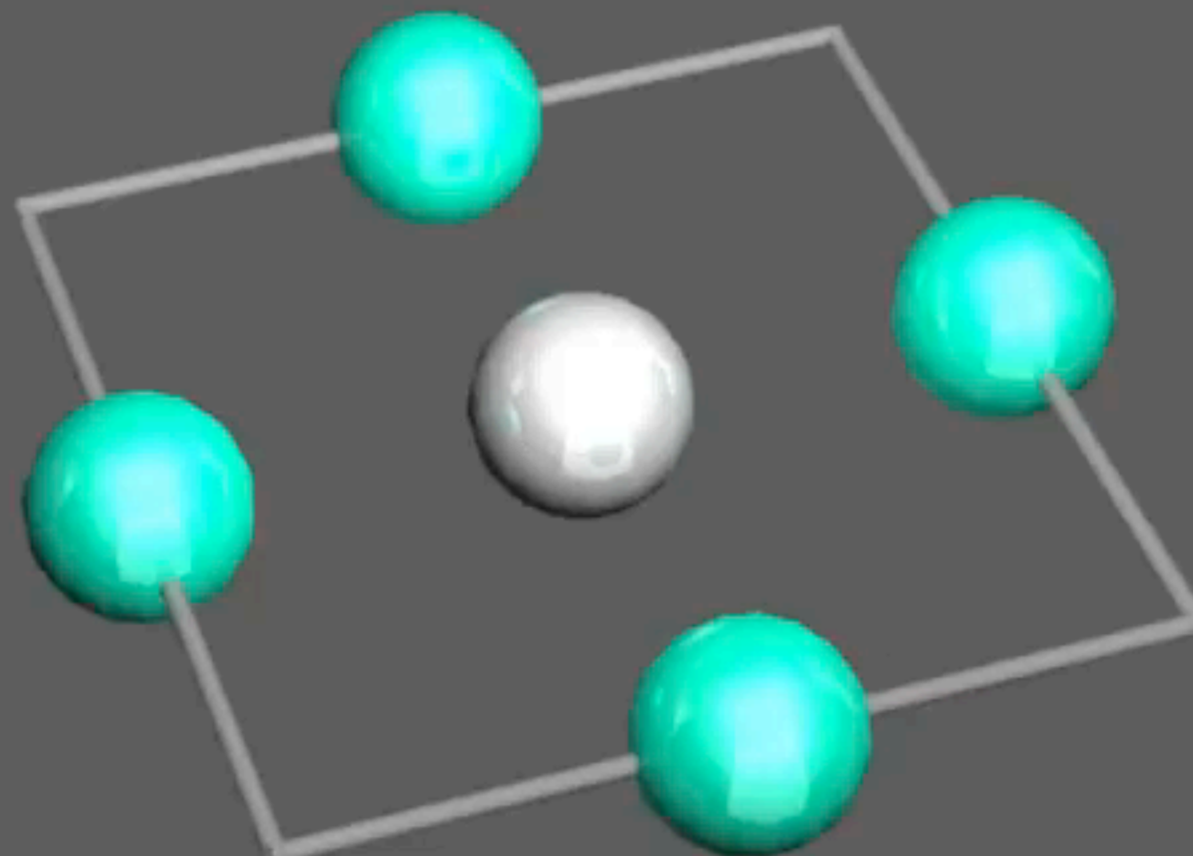
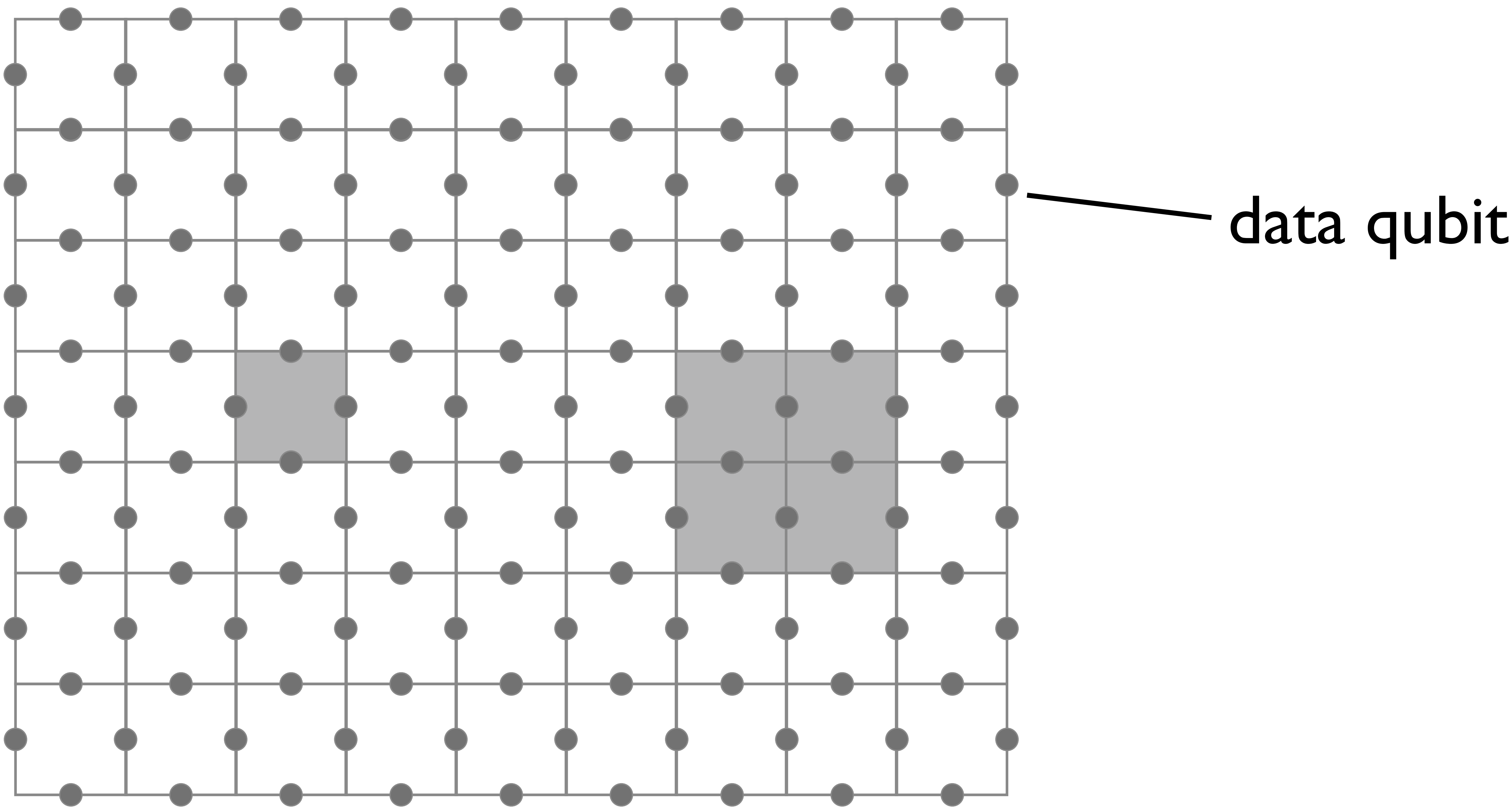
FIRST Project Summer School @ Kyoto U.

2011 Aug 16

(all the good slides and animations are by Shota Nagayama, Austin Fowler and Clare Horsman)



Simplest Example
~Encoding logical qubit~



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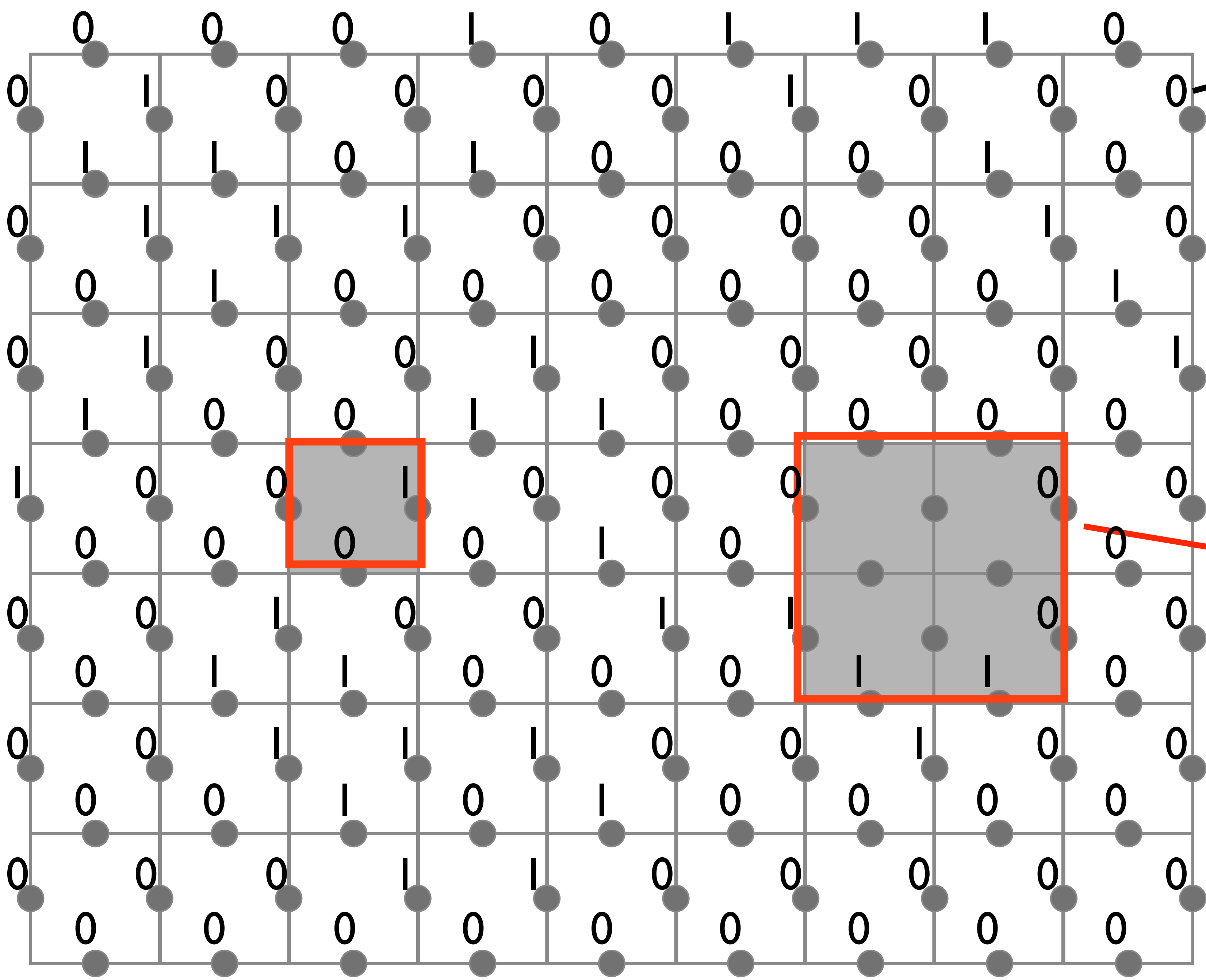


measured eigenvalue

data qubit

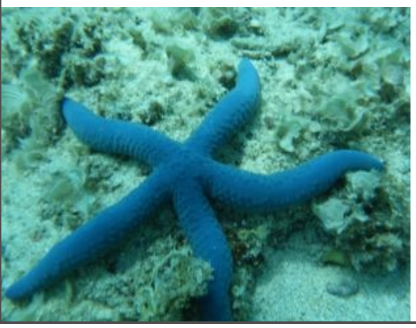
the edge of hole

odd parity: 0

even parity: 1

It's logical 0 here.

Surface Code Strengths



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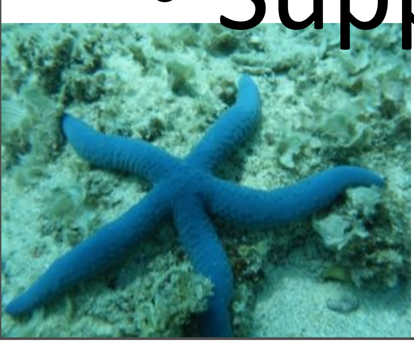
  - software-assigned resources
  - easy movement of logical qubits
- Supporting classical processing achievable



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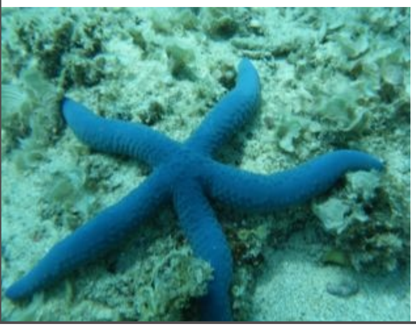
Scalability: fault-tolerance

- Trade-off between resources and threshold
- Thresholds
  - unlimited range, unlimited qubits: ~ 10^{-2}
    Knill, quant-ph/0410199
  - unlimited range, many qubits: ~ 10^{-3}–10^{-4}
    Steane, Phys. Rev. A 68, 042322 (2003)
  - 2D lattice, nearest neighbor: ~ 10^{-5}
    Svore, QIC 7, 297 (2007)
  - bilinear nearest neighbor: ~ 10^{-6}
    Stephens, QIC 8, 330 (2008)
  - linear nearest neighbor: ~ 10^{-8}
    Stephens, in preparation

Surface Code Drawbacks



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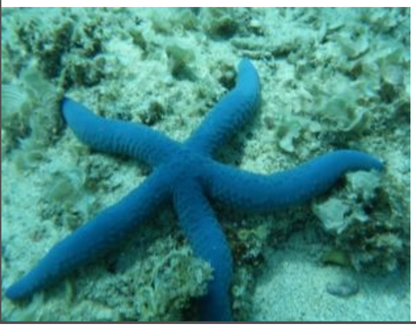

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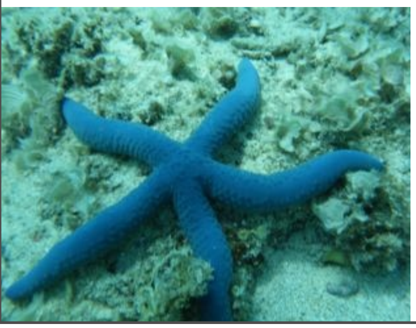
- Non-Clifford group operations difficult
- Direct calculation of residual error rates difficult due to many error chains; determined via simulation
- Almost uniform set of operations across whole device, but not quite!
- *Extremely* difficult to explain to classical computer engineers!



Outline

- Stabilizers
- Surface Code Operation
- Theory of the Surface Code
- Advanced topics
- (system architecture reserved for next lecture)

Stabilizers

$$|0\rangle \equiv \begin{pmatrix} 1 \\ 0 \end{pmatrix} \equiv +1 \text{ eigenstate of } Z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$|+\rangle \equiv \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 1 \end{pmatrix} \equiv +1 \text{ eigenstate of } X = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

$$|0\rangle \quad \text{or} \quad Z$$

$$|+\rangle \quad \text{or} \quad X$$

$$\frac{1}{\sqrt{2}}(|00\rangle + |11\rangle) \quad \text{or} \quad Z_1 Z_2,\ X_1 X_2$$

- n qubits, n independent commuting stabilizers $\Rightarrow$ unique state

Stabilizers

- *n-k* stabilizers on set of *n* qubits leaves *k* degrees of freedom, can encode *k* logical qubits
- Measure set of stabilizers to get error syndrome
- See Gottesman PhD. thesis, and the set of notes by Clare Horsman in download materials

Introduction to stabilizer theory

June 16, 2011

1 Stabilizer definition

In quantum mechanics, a **state** is given by a **vector**, and an **operator** is given by a **matrix**. The state of N qubits is a 1×2^N vector, and an operation on the state is a $2^N \times 2^N$ matrix.

For example, a state of 1 qubit could be

$$|+\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ 1 \end{pmatrix}$$

and an operation on it could be

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

In linear algebra, if for a matrix M there is a **vector V** and a **scalar** v such that

$$\mathrm{M}.\mathbf{V} = v.\mathbf{V}$$

then **V** is an **eigenvector** of M and v is the associated **eigenvalue**.

The vector **V** can be the eigenvector of more than one matrix. The vector **V** can be **fully defined** by the set $\{\mathrm{M}, v\}$ of matrices that **V** is an eigenvector of.

The **stabilizers** of a state $|\psi\rangle$ are the operators $\frac{1}{v}.\mathrm{M}$ where $|\psi\rangle$ is an eigenvector of M with eigenvalue v.

We see that

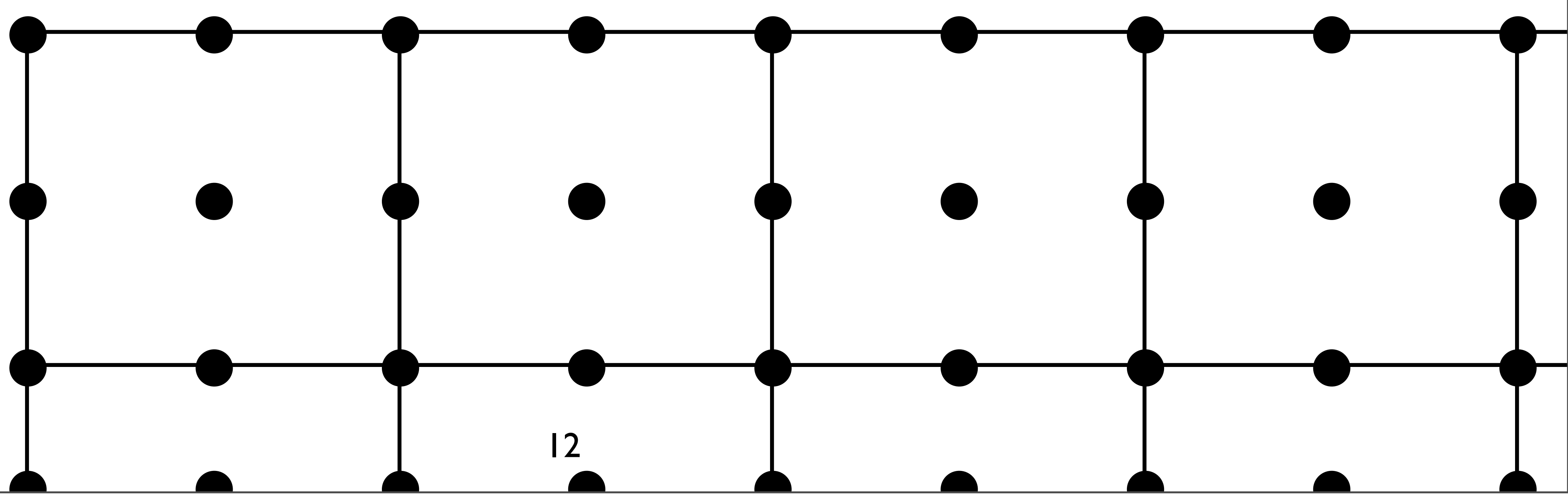
$$X|+\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}\begin{pmatrix} 1 \\ 1 \end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ 1 \end{pmatrix} = |+\rangle$$

so X is a stabilizer of $|+\rangle$.

Operations

- Lattice cycle
- Detecting & correcting errors
- Holes as logical qubits
- Single-qubit X and Z gates
- Moving holes
- Braiding for CNOT (Primal & dual lattice)
- Non-Clifford gates using singular qubits
- “Singular factories”
- Measuring a logical qubit

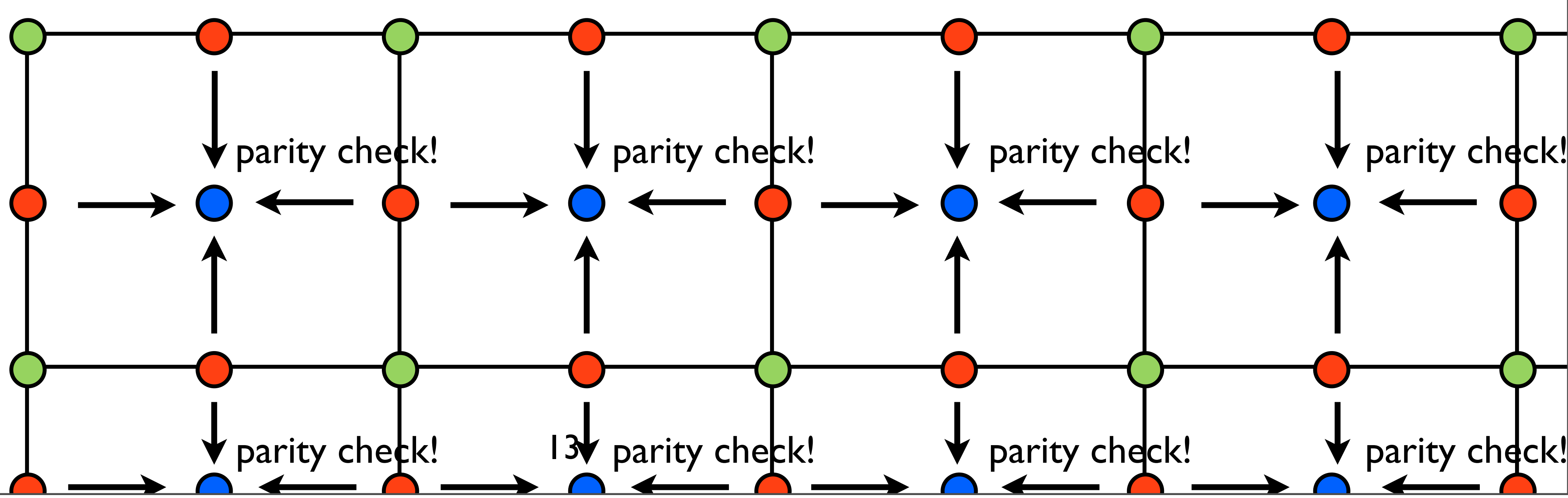
Surface Code



Surface Code

edges of two holes =logical qubit

- data qubit
- phase-flip checker
- bit-flip checker



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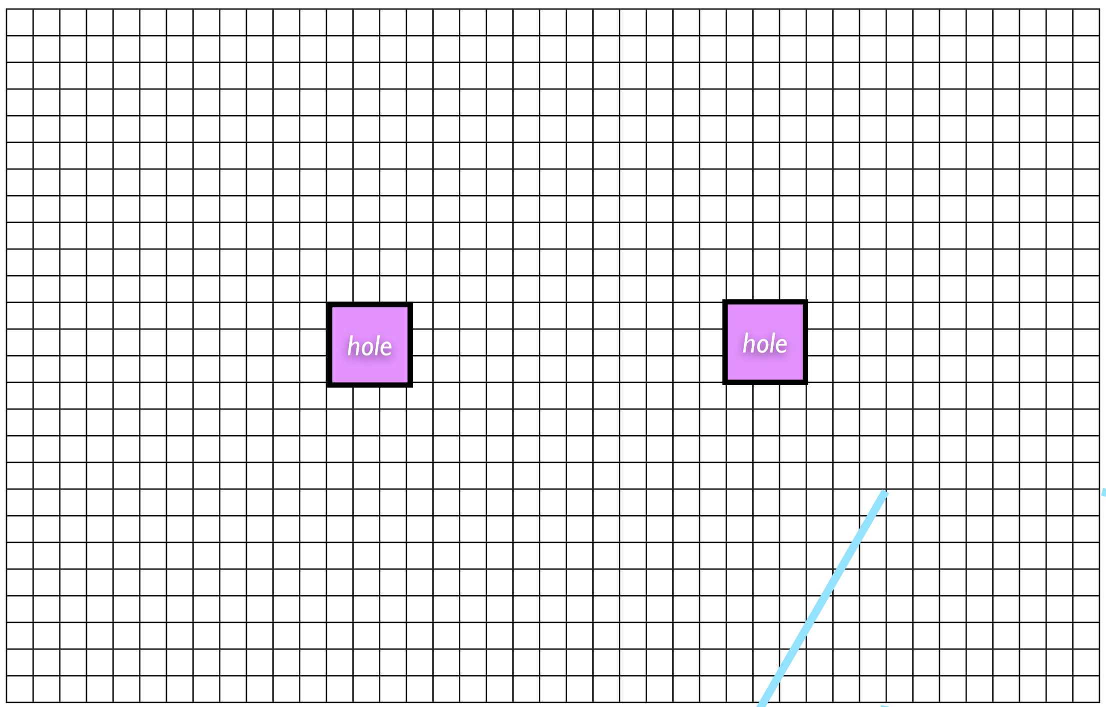

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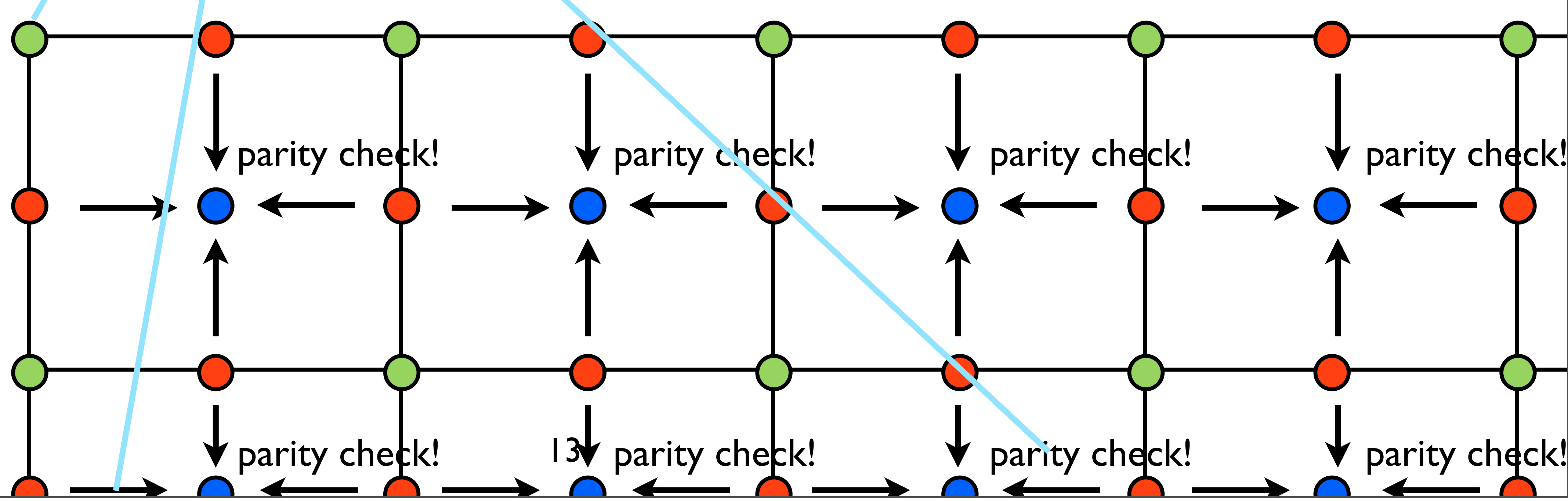
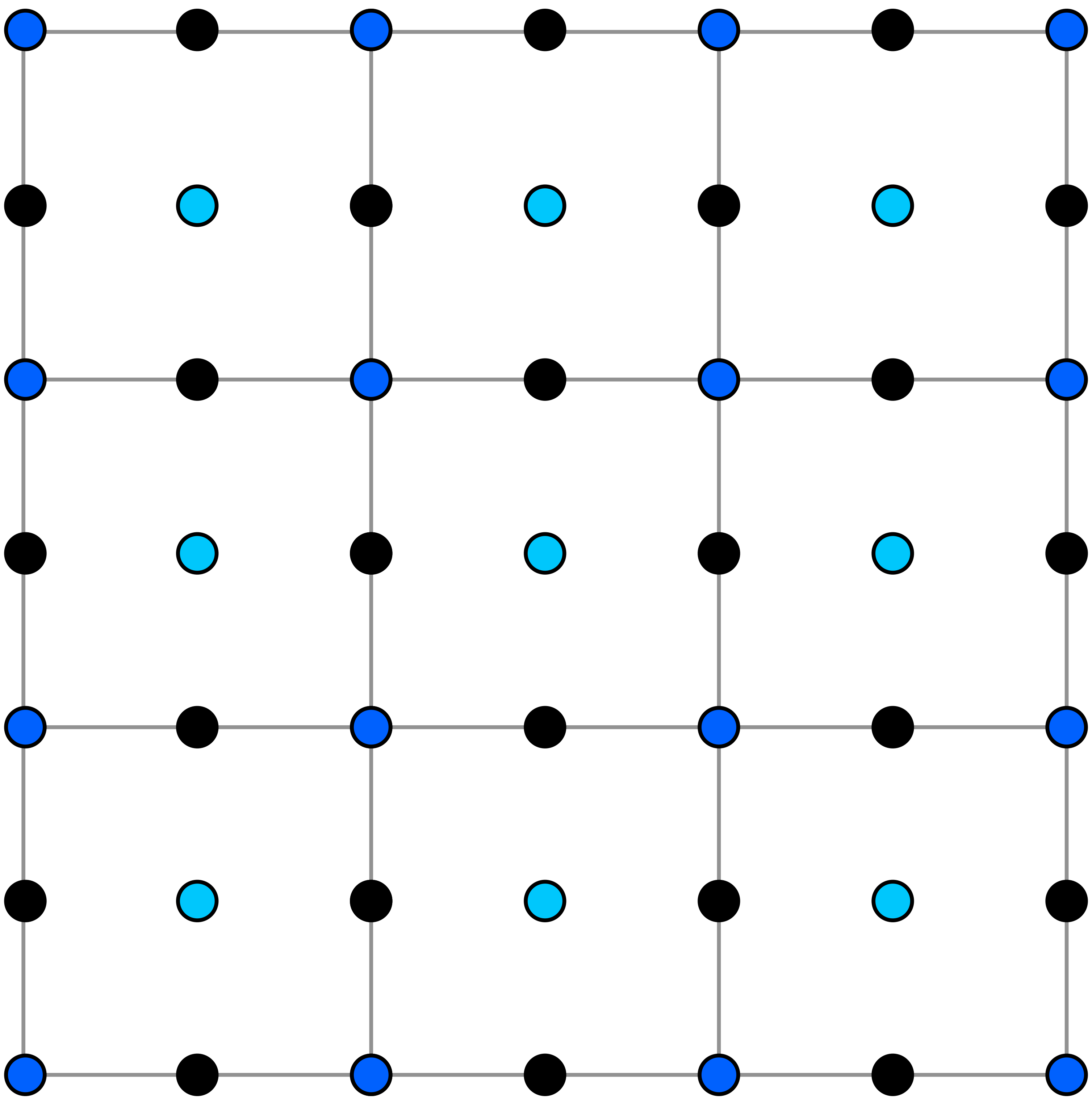
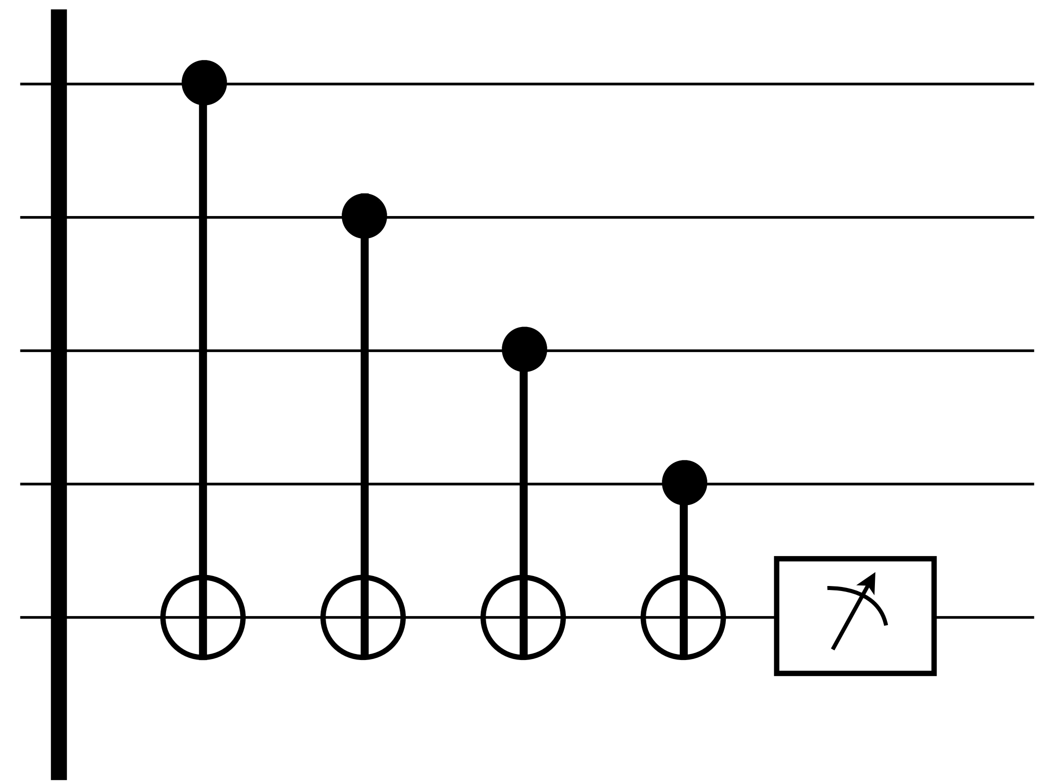


Entangling the Lattice





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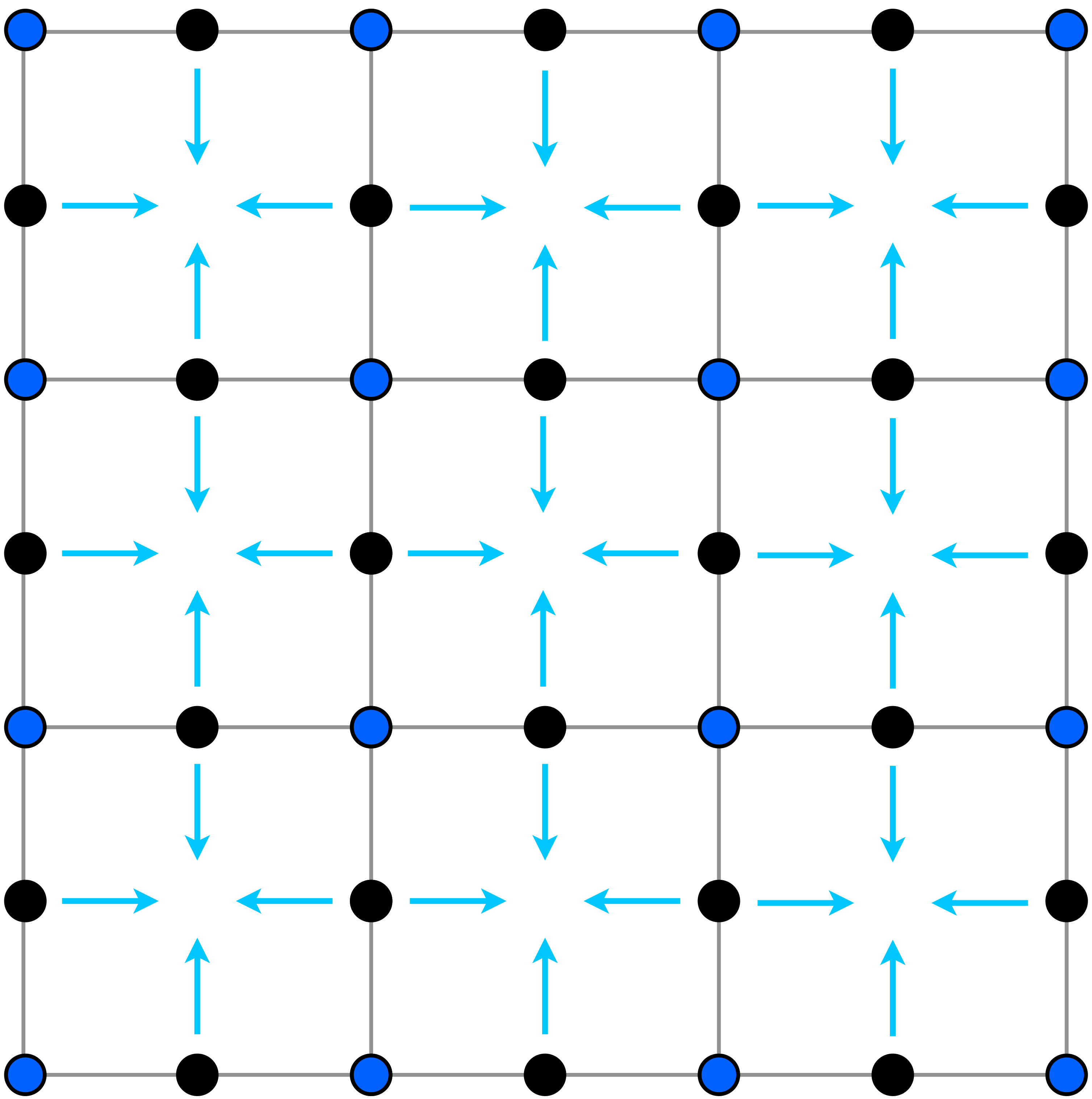

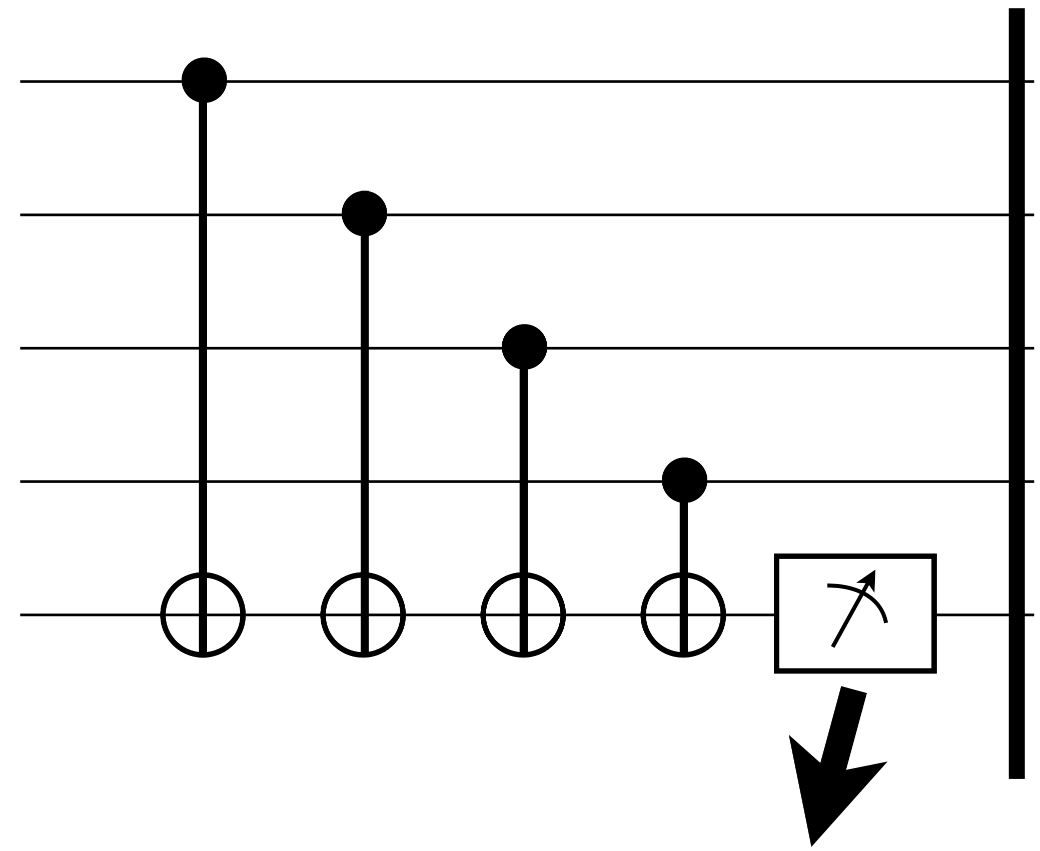

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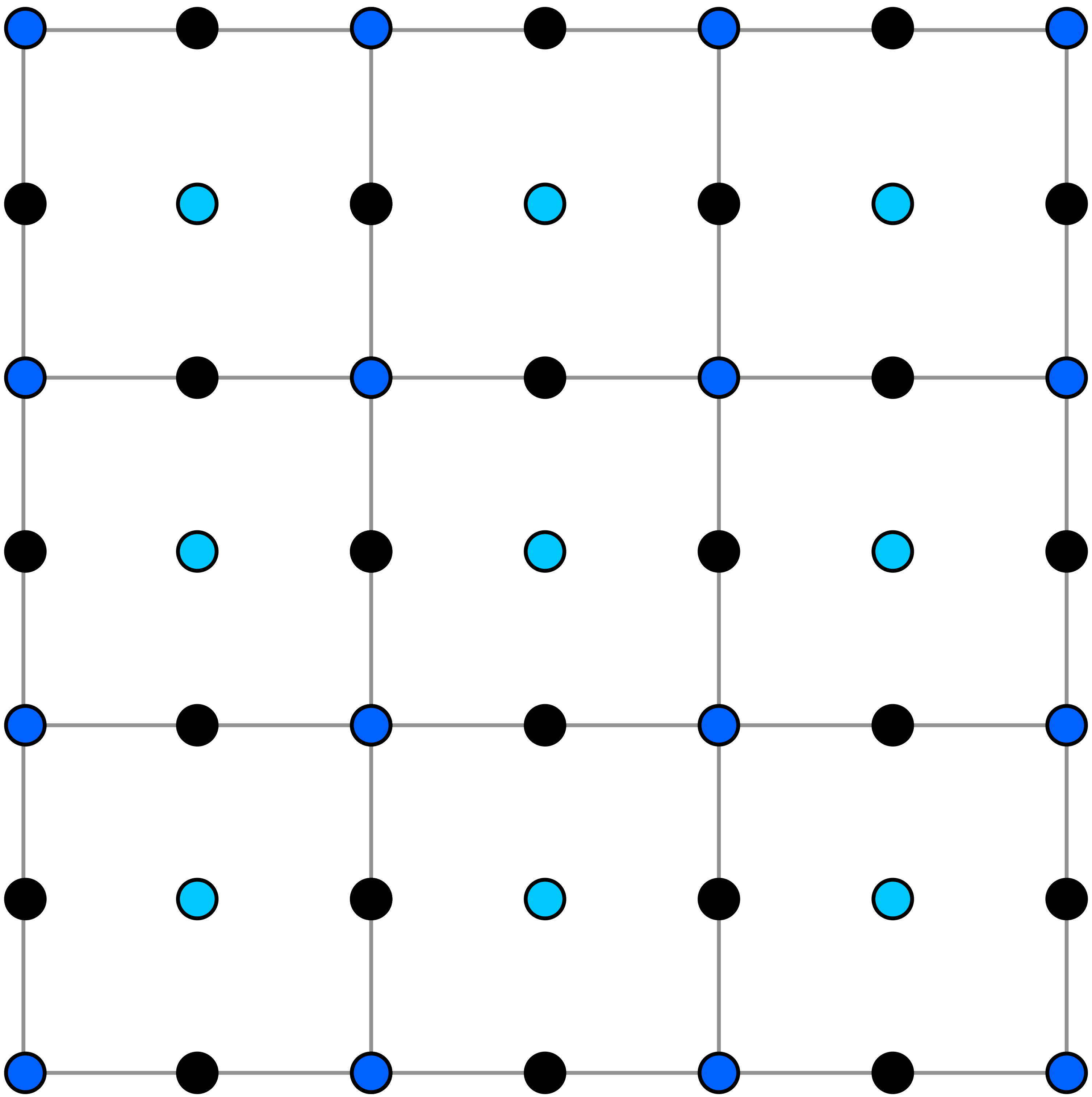
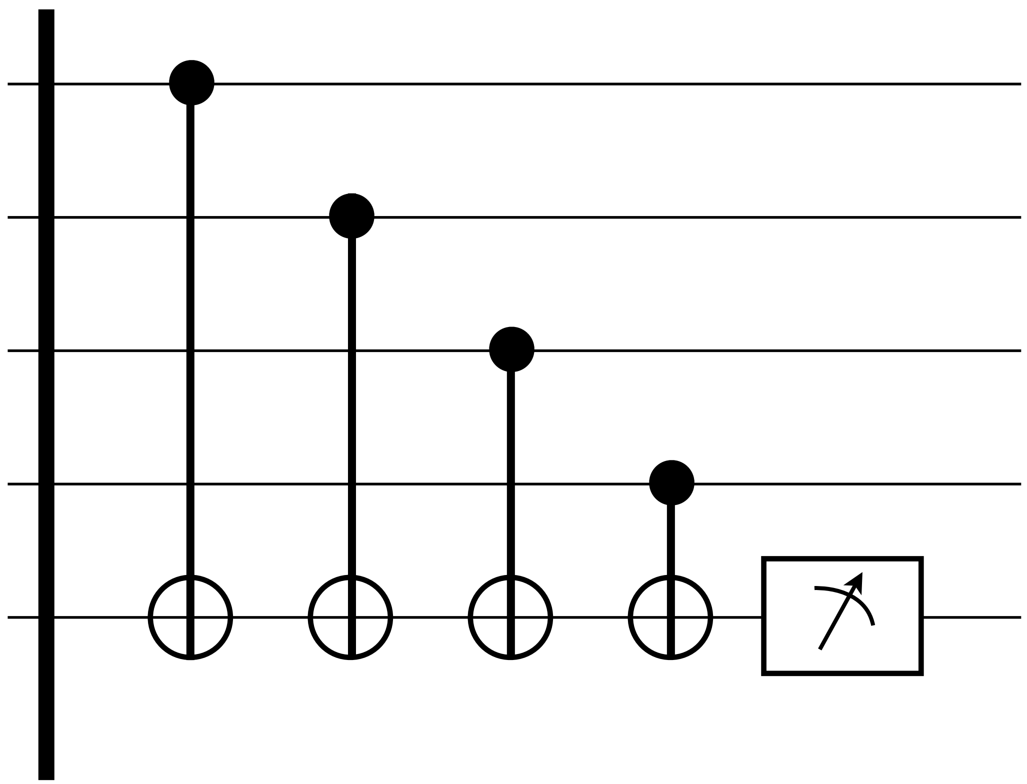
Measuring Z stabilizers





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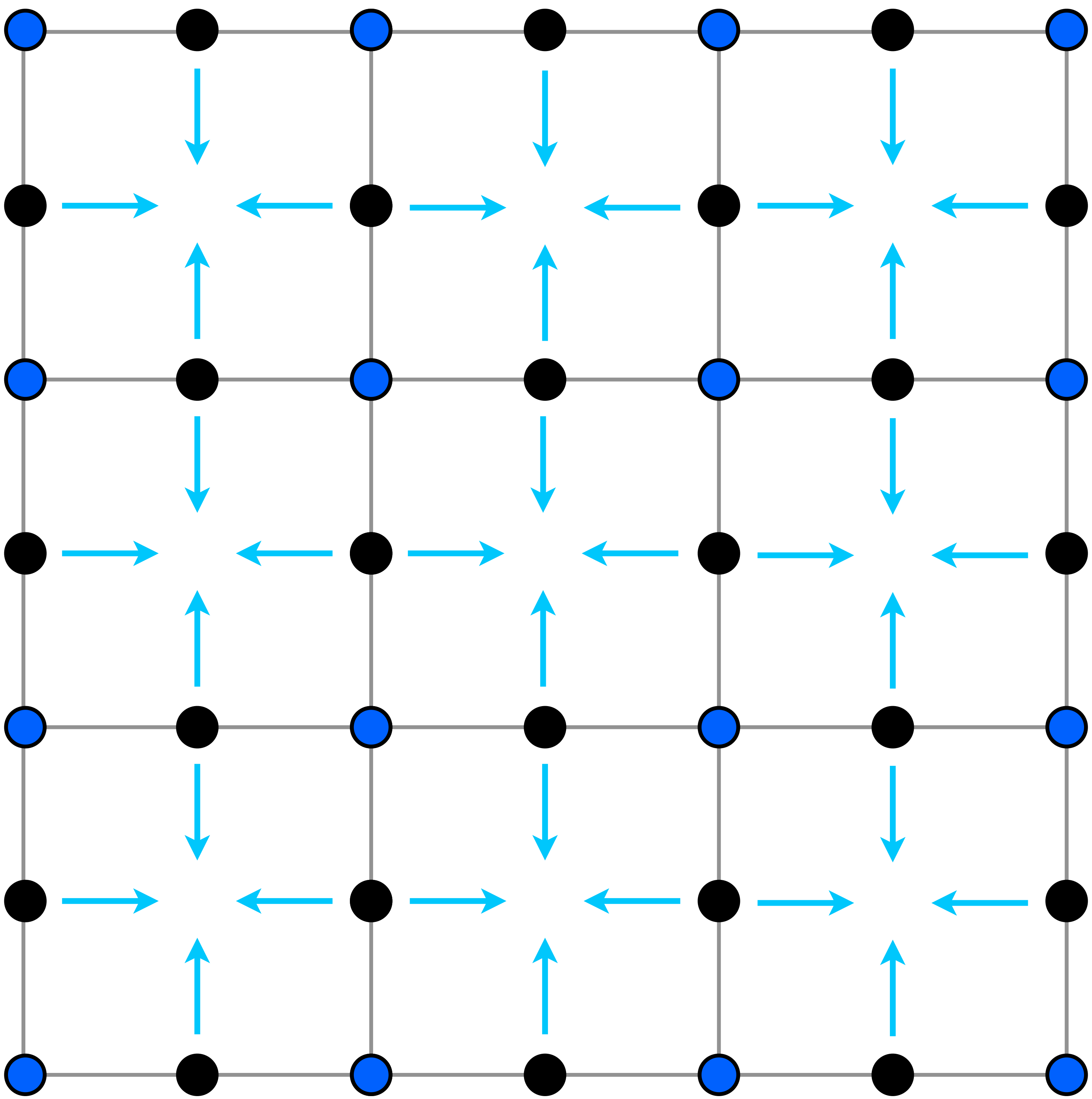

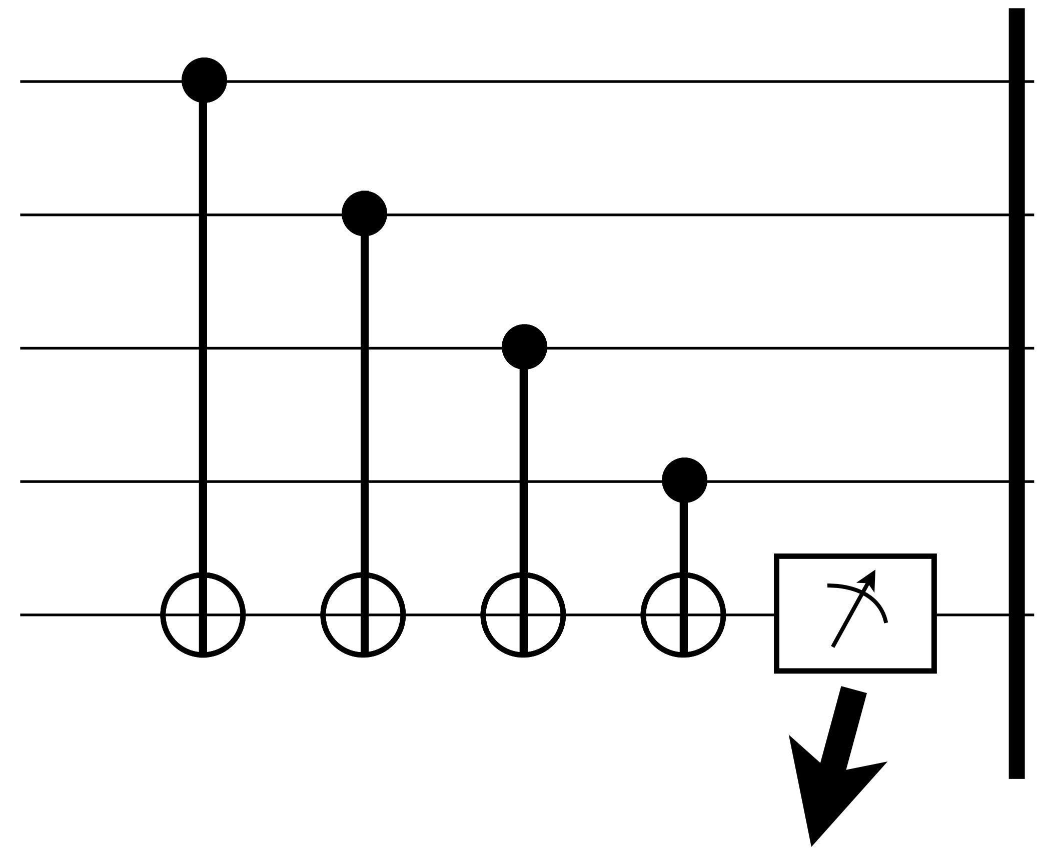

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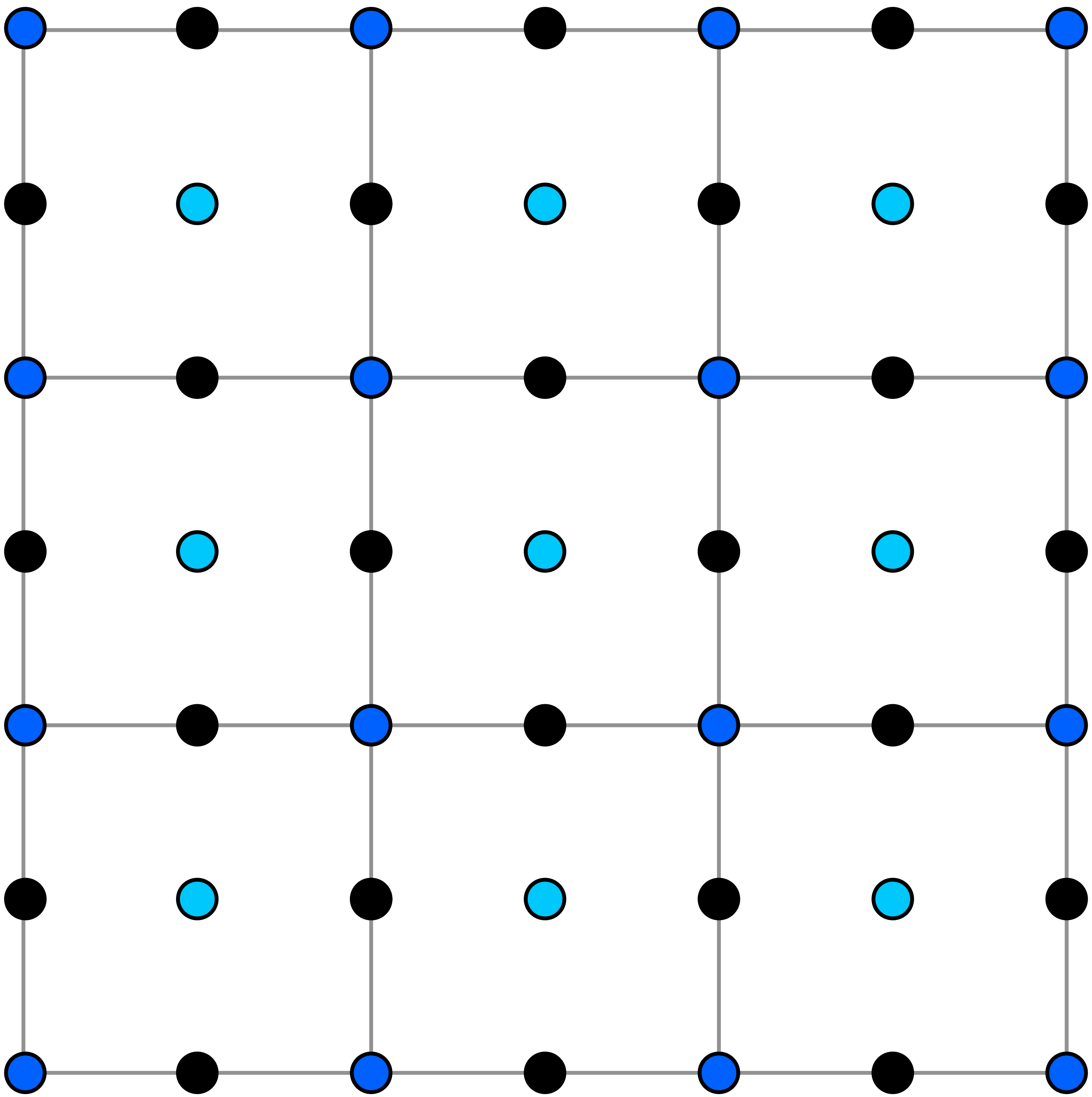
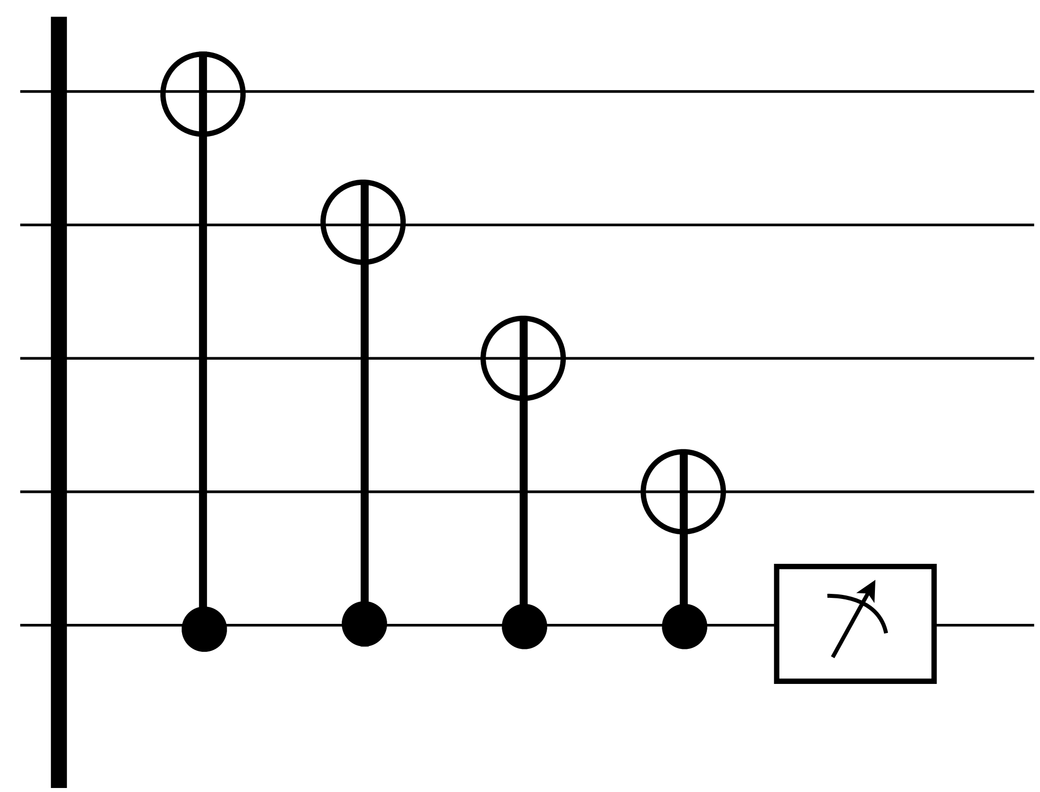
Measuring X stabilizers





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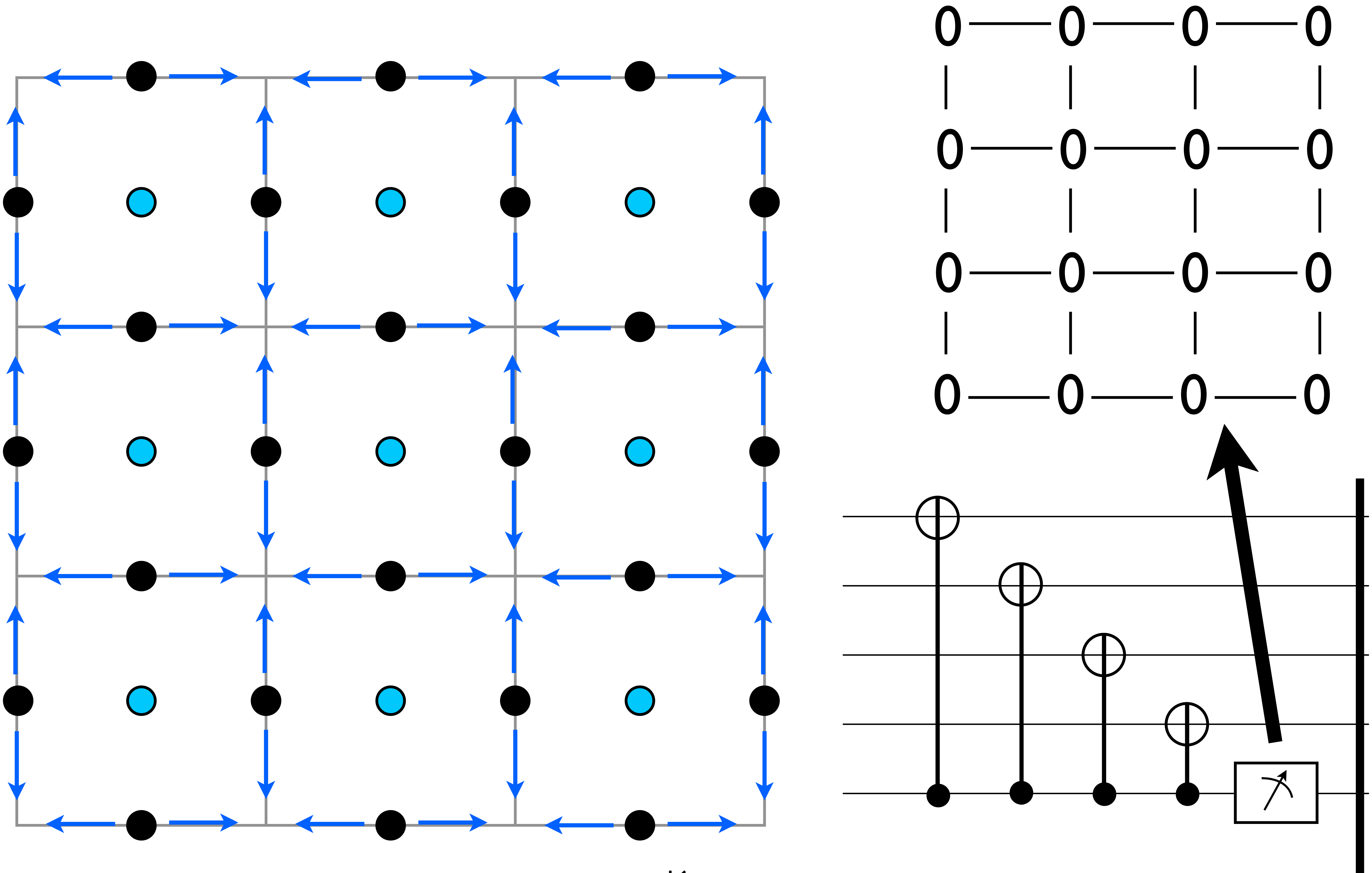
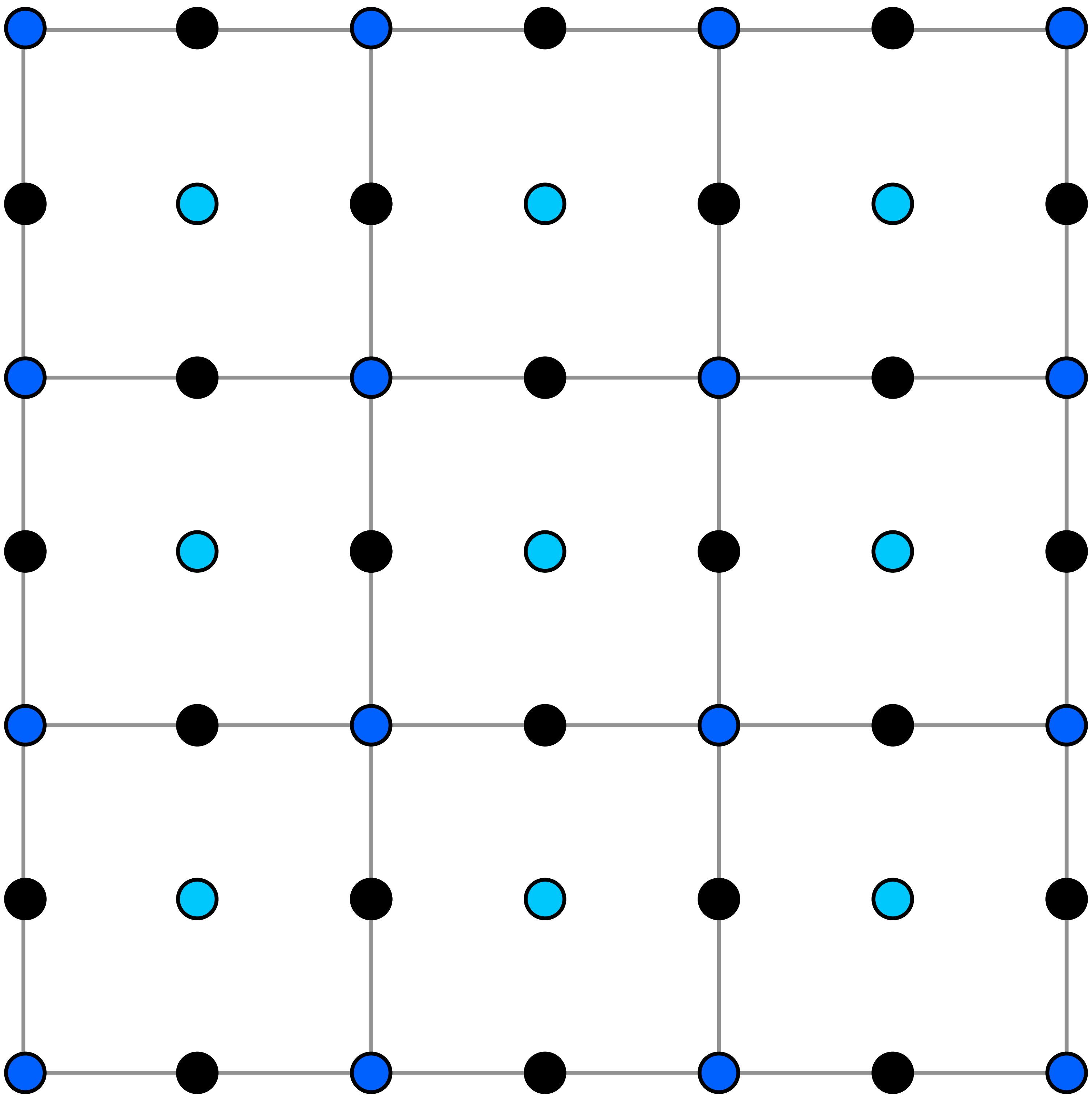
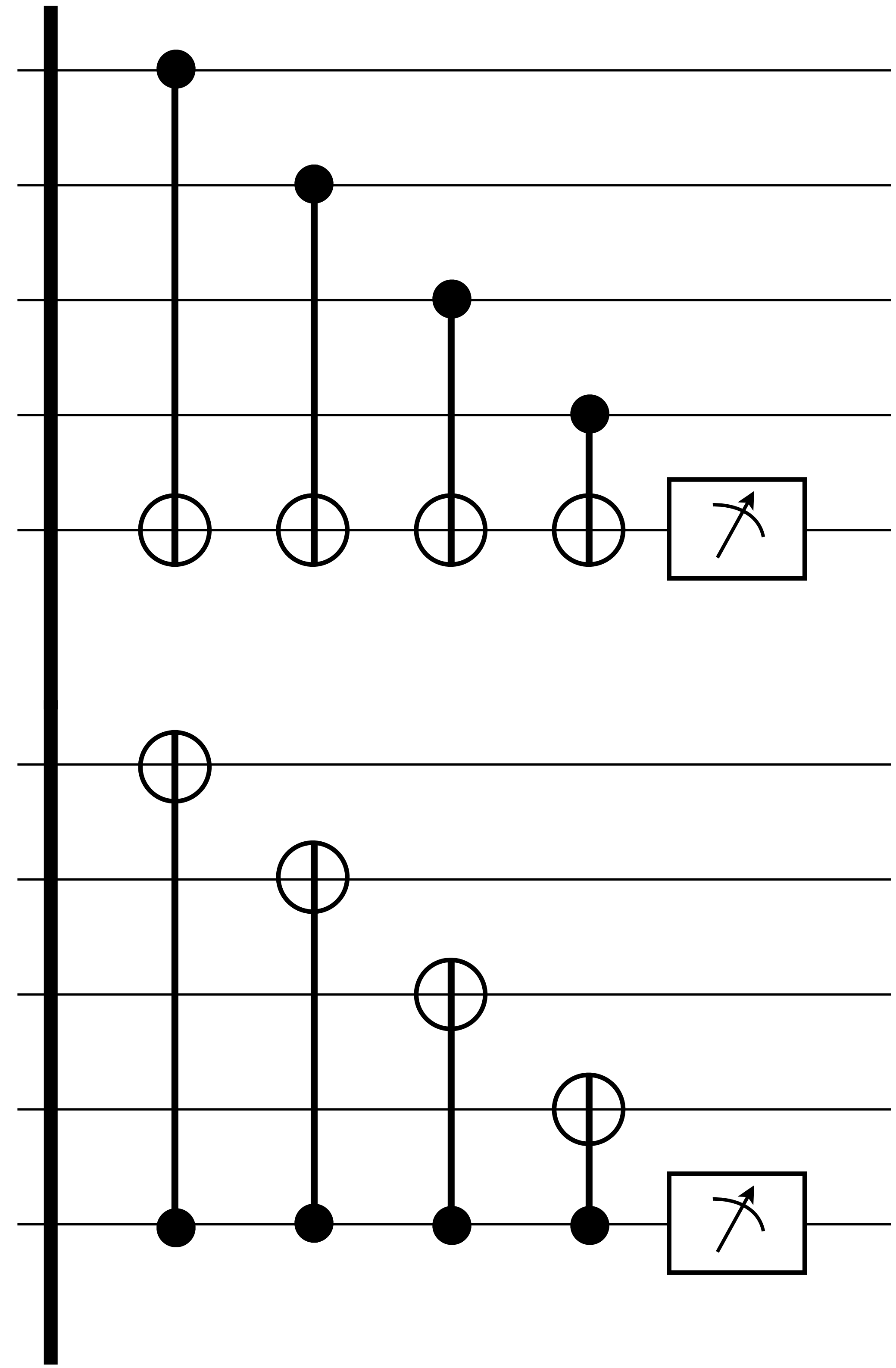


Full lattice cycle





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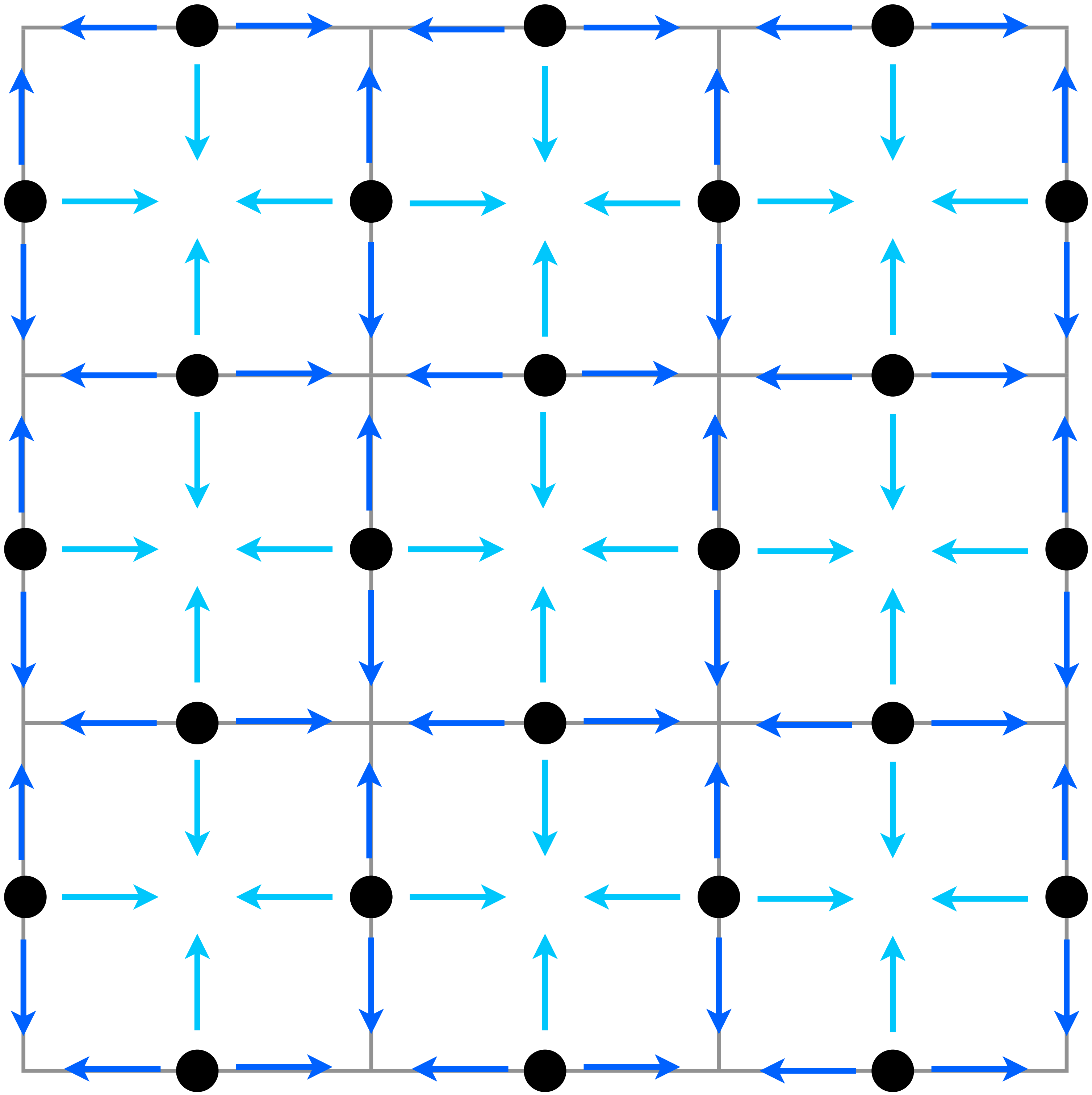

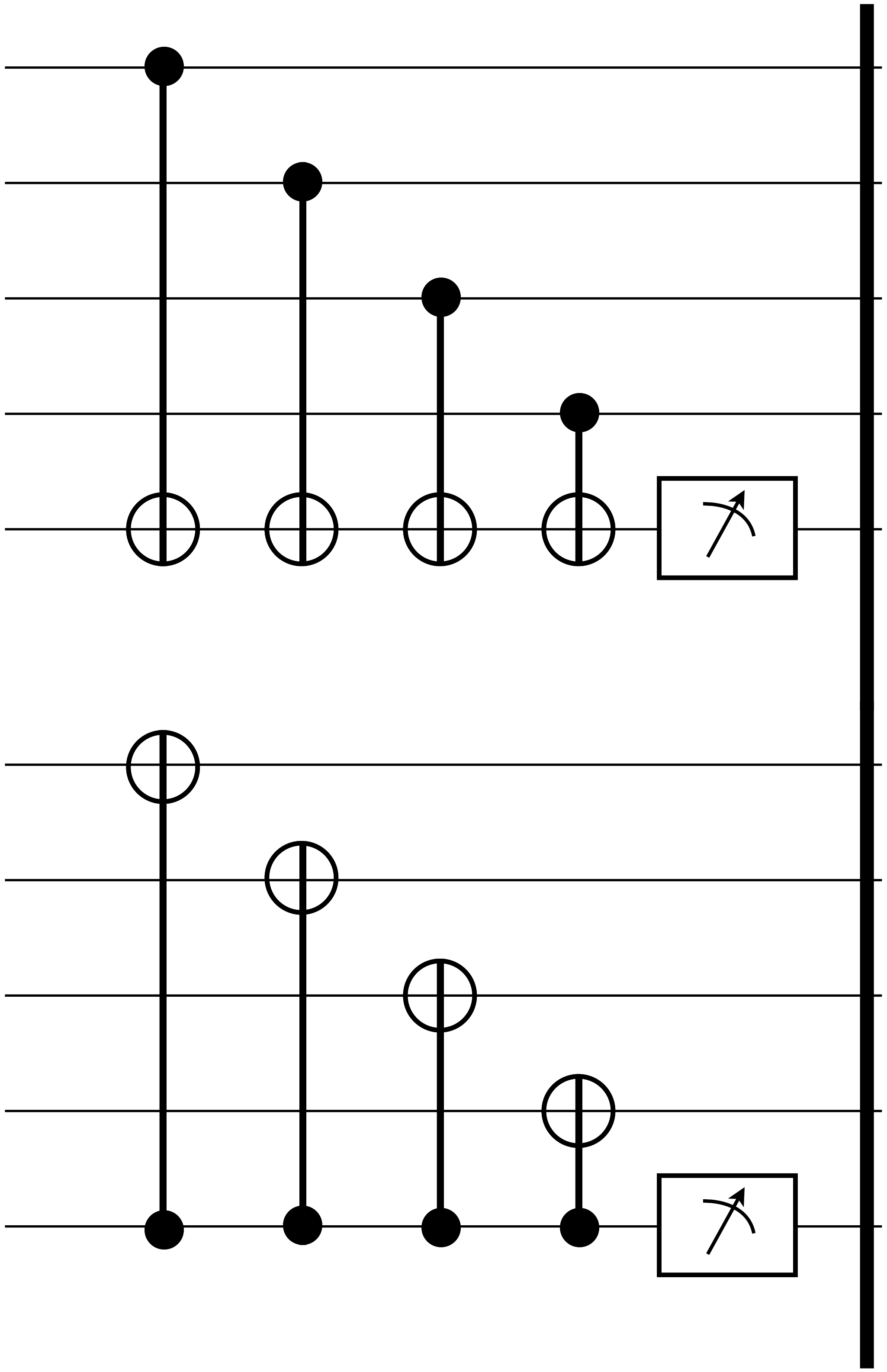

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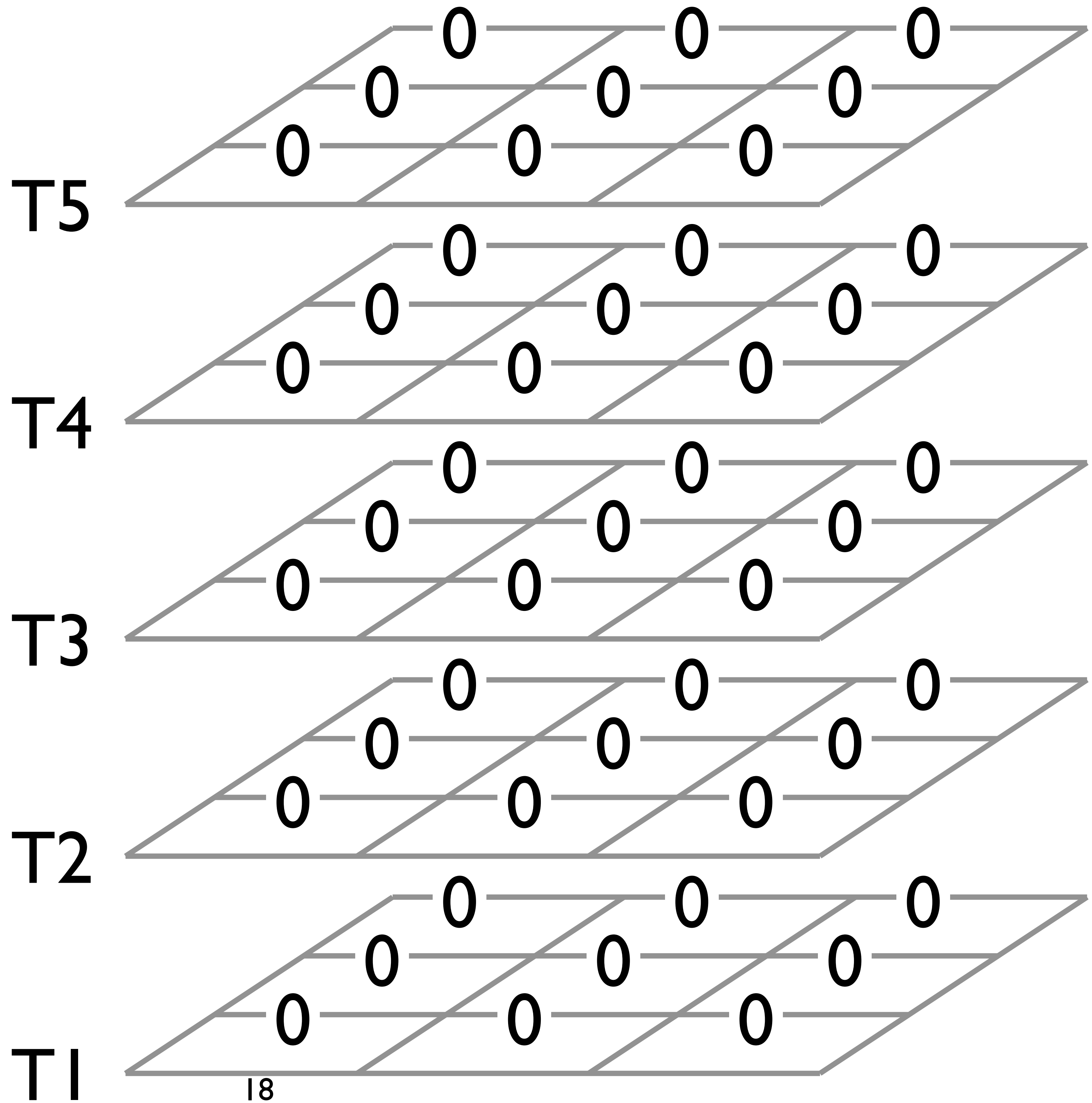
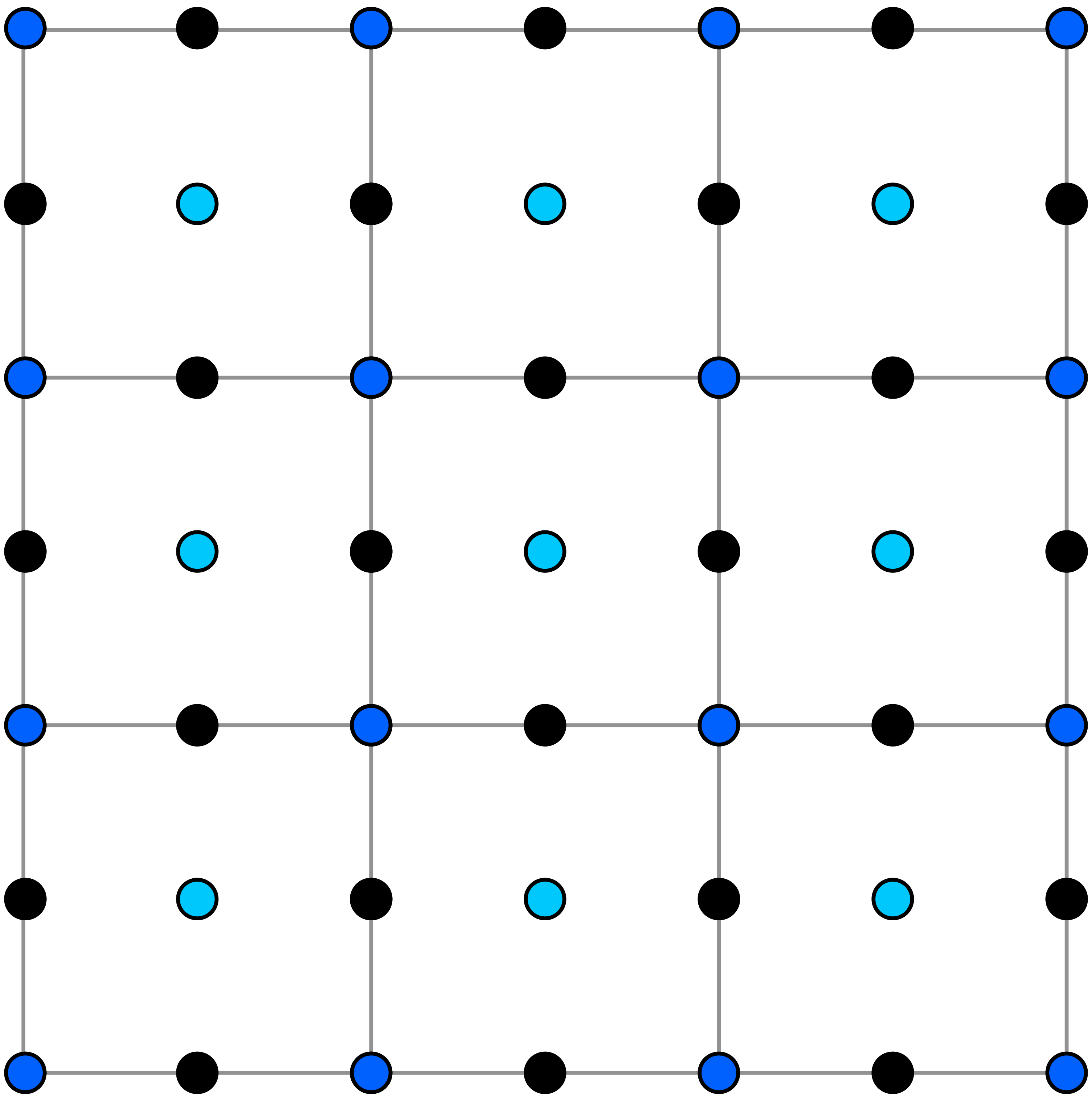
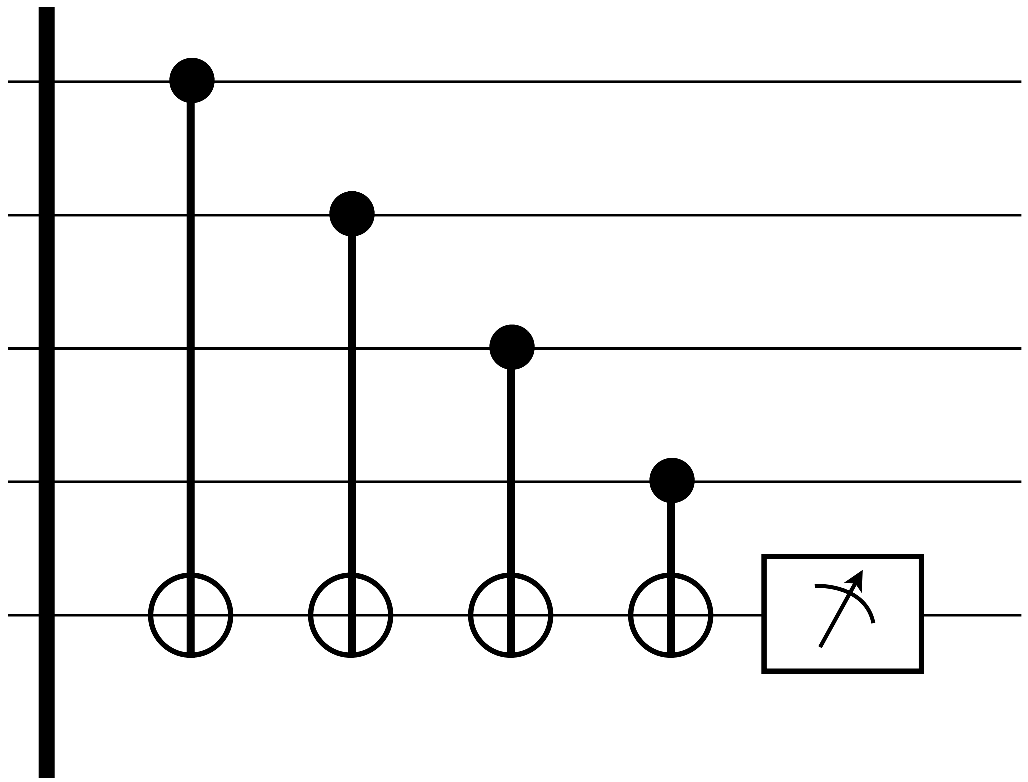
Error syndromes



Memory Error 1





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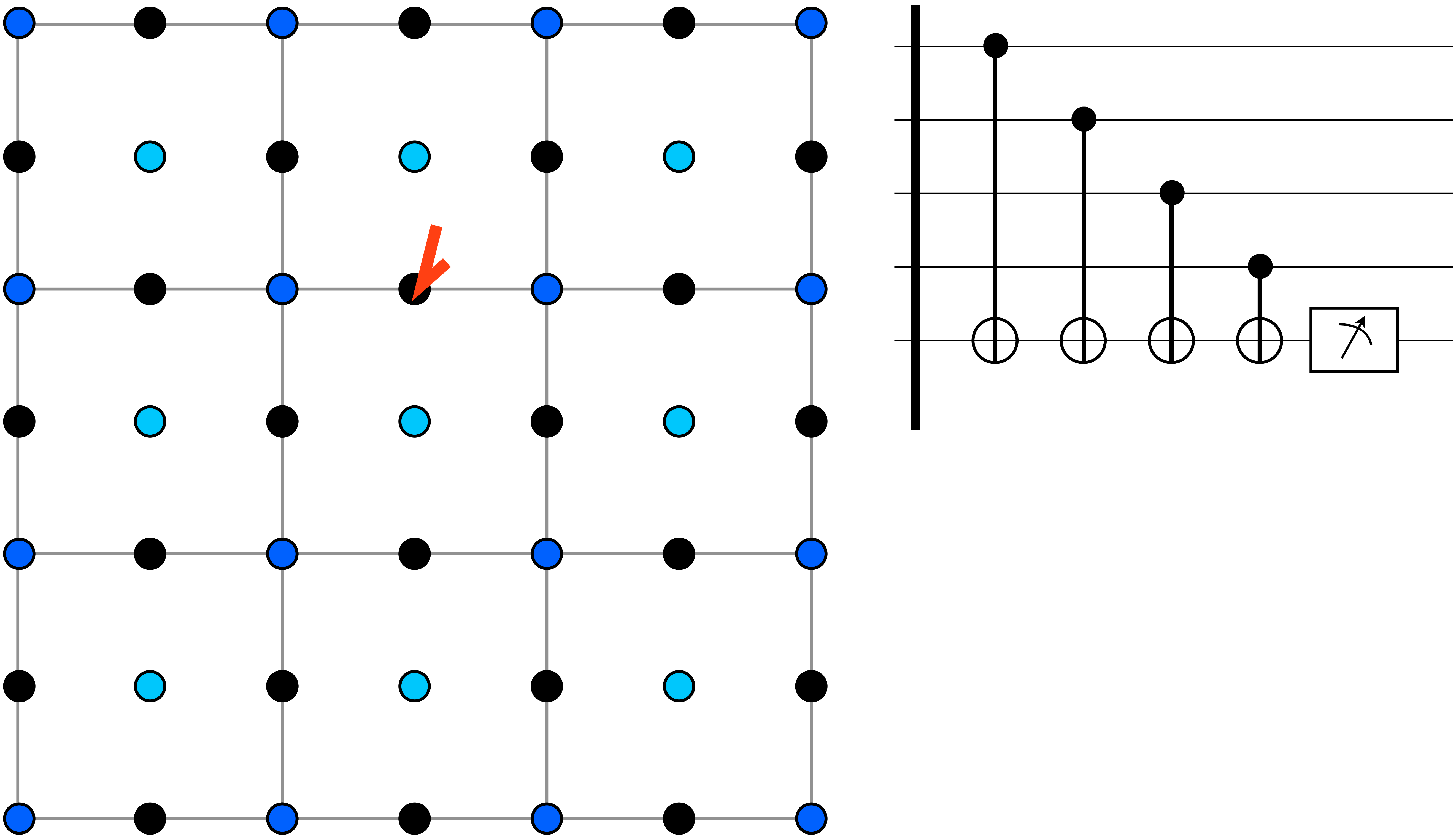

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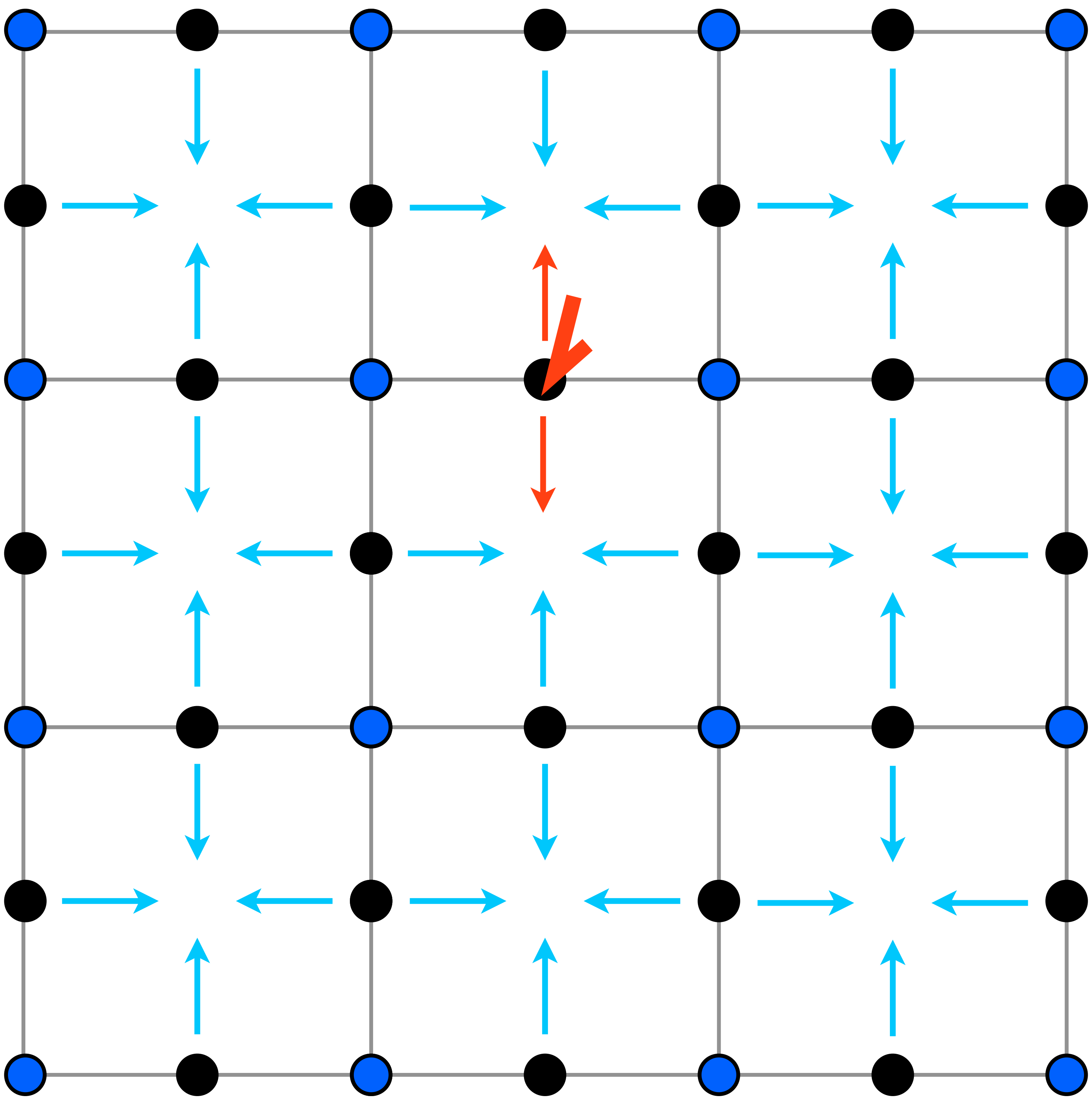

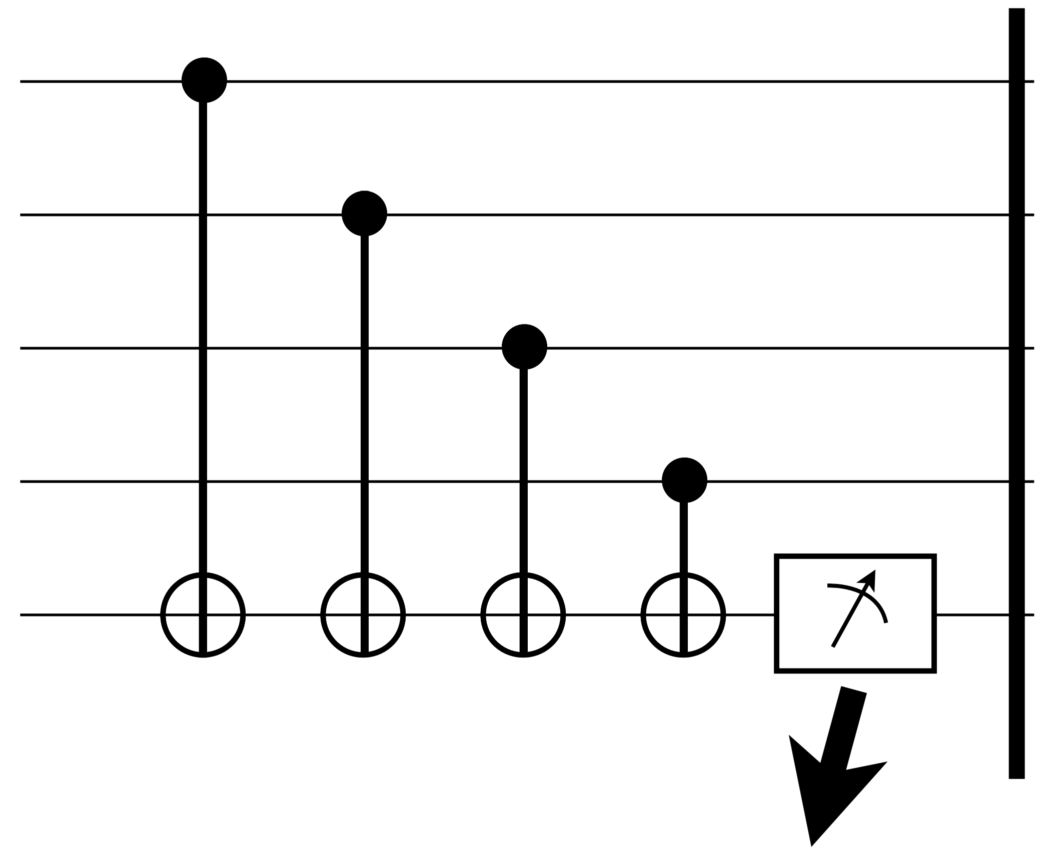

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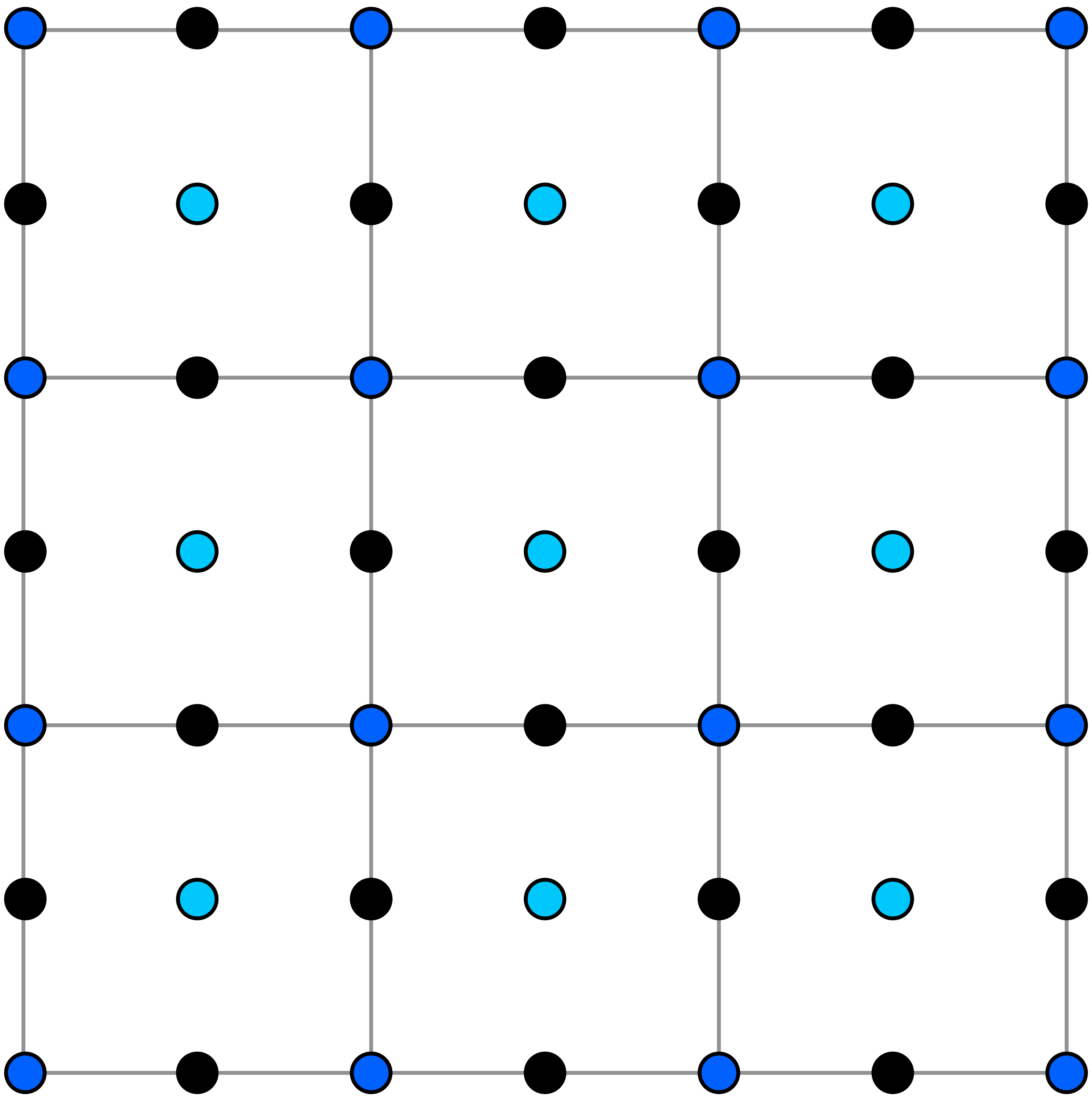
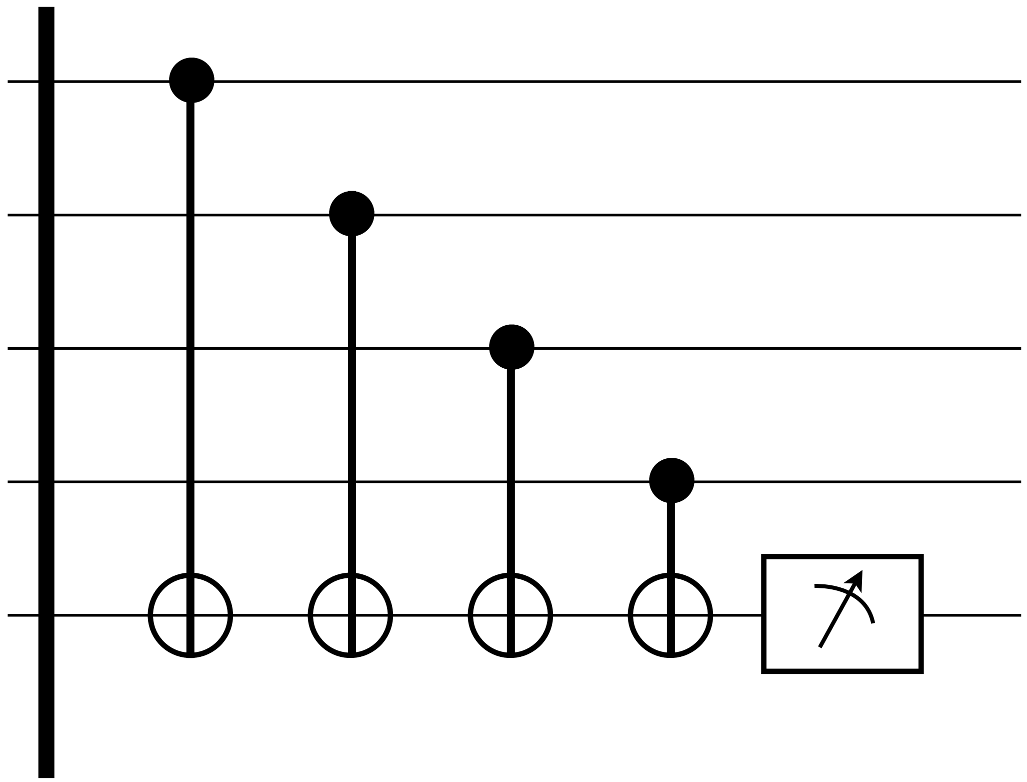
Memory Error 2





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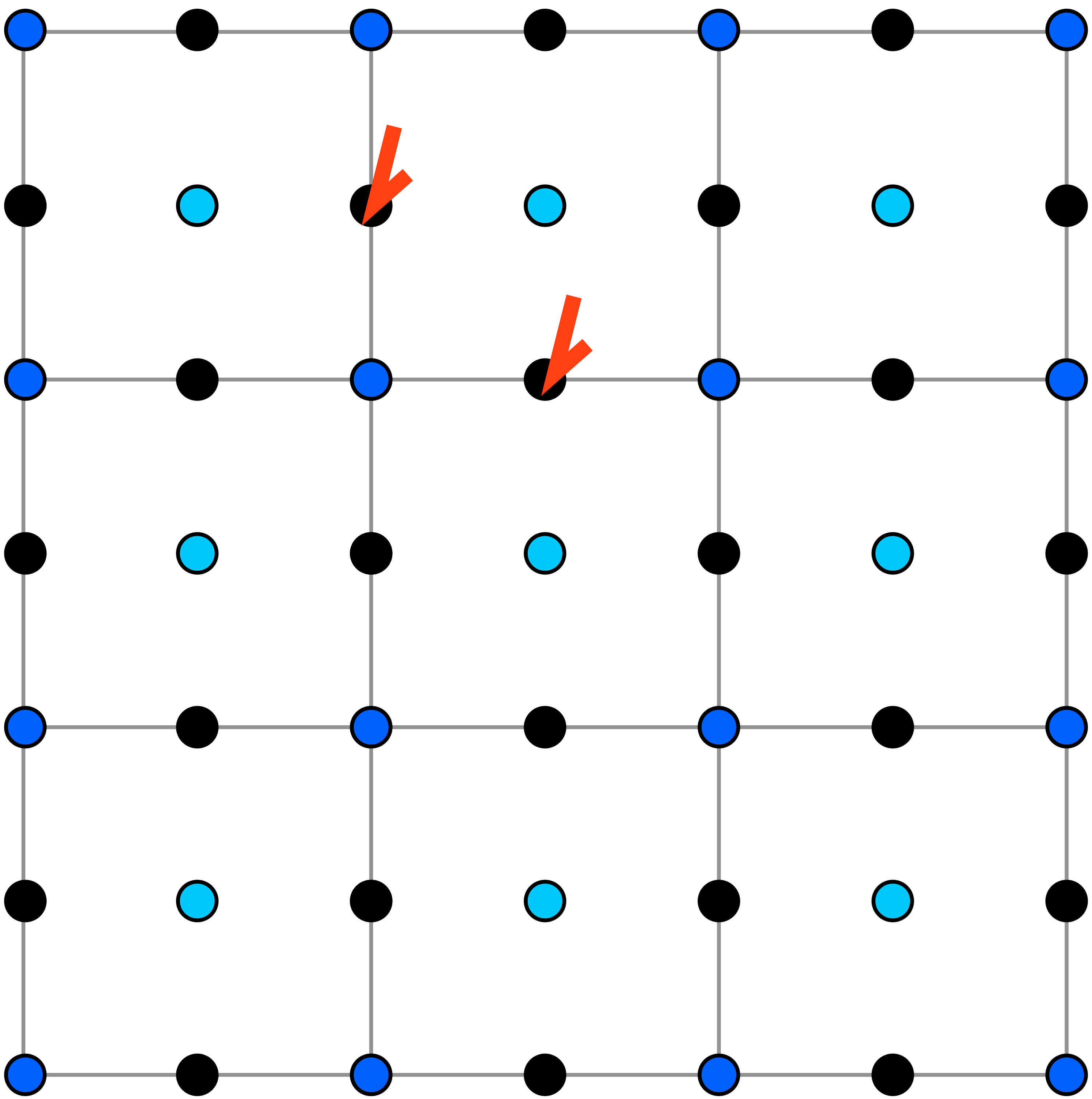

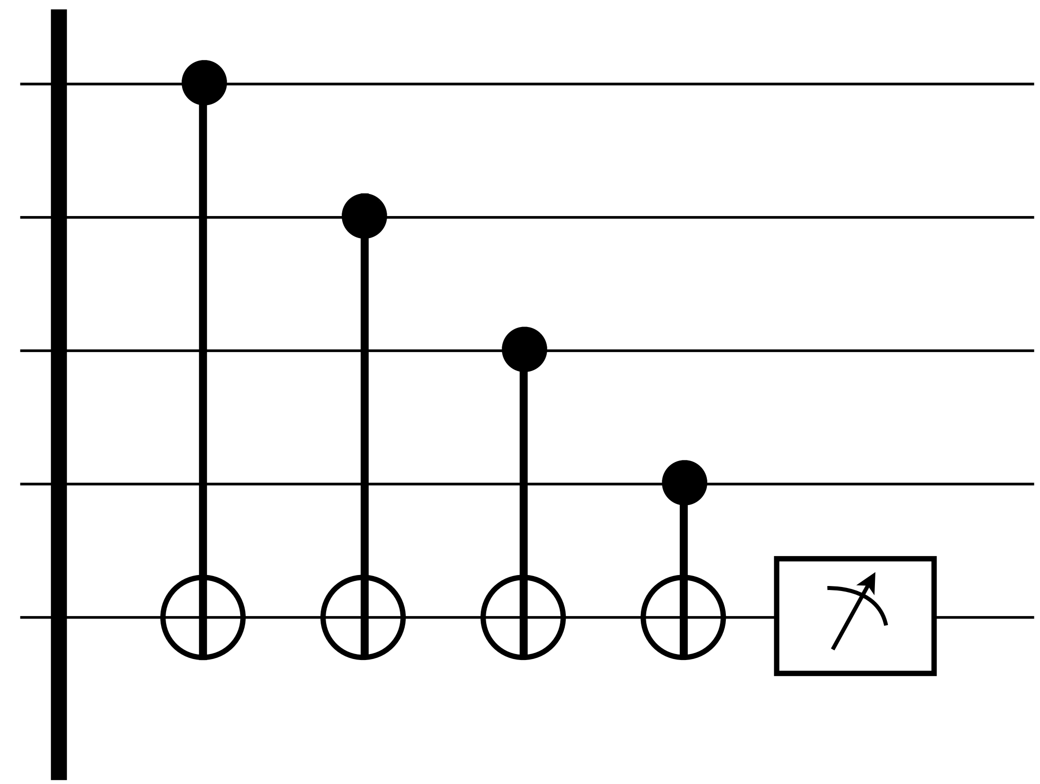

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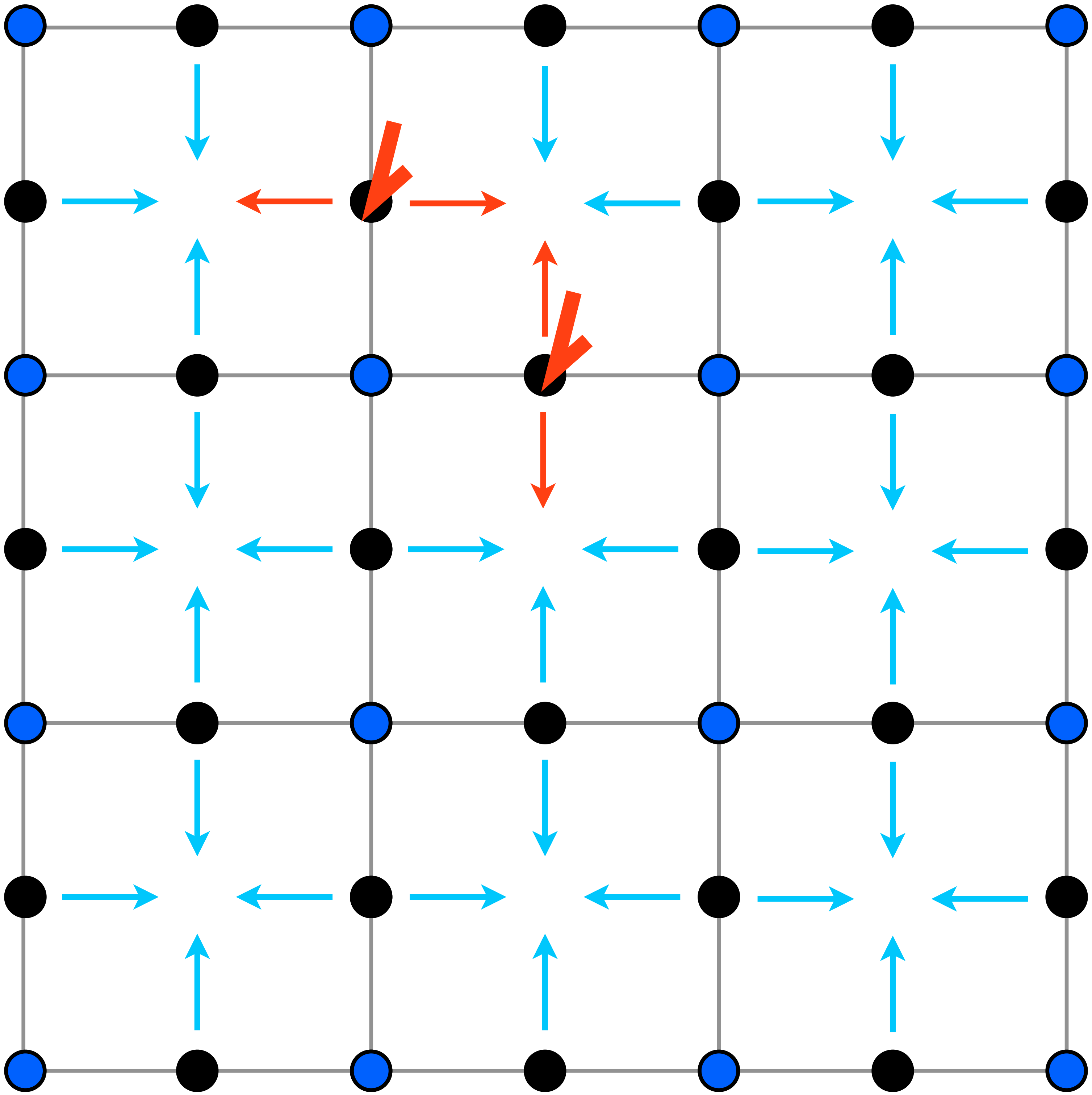

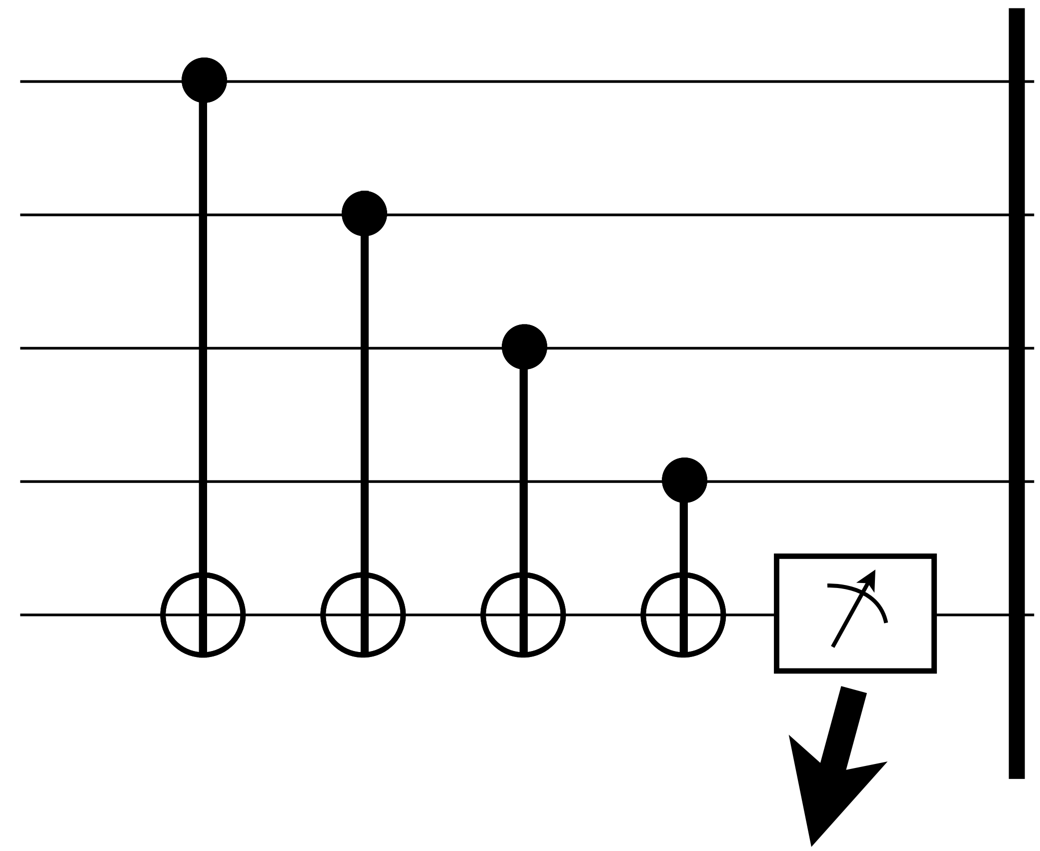

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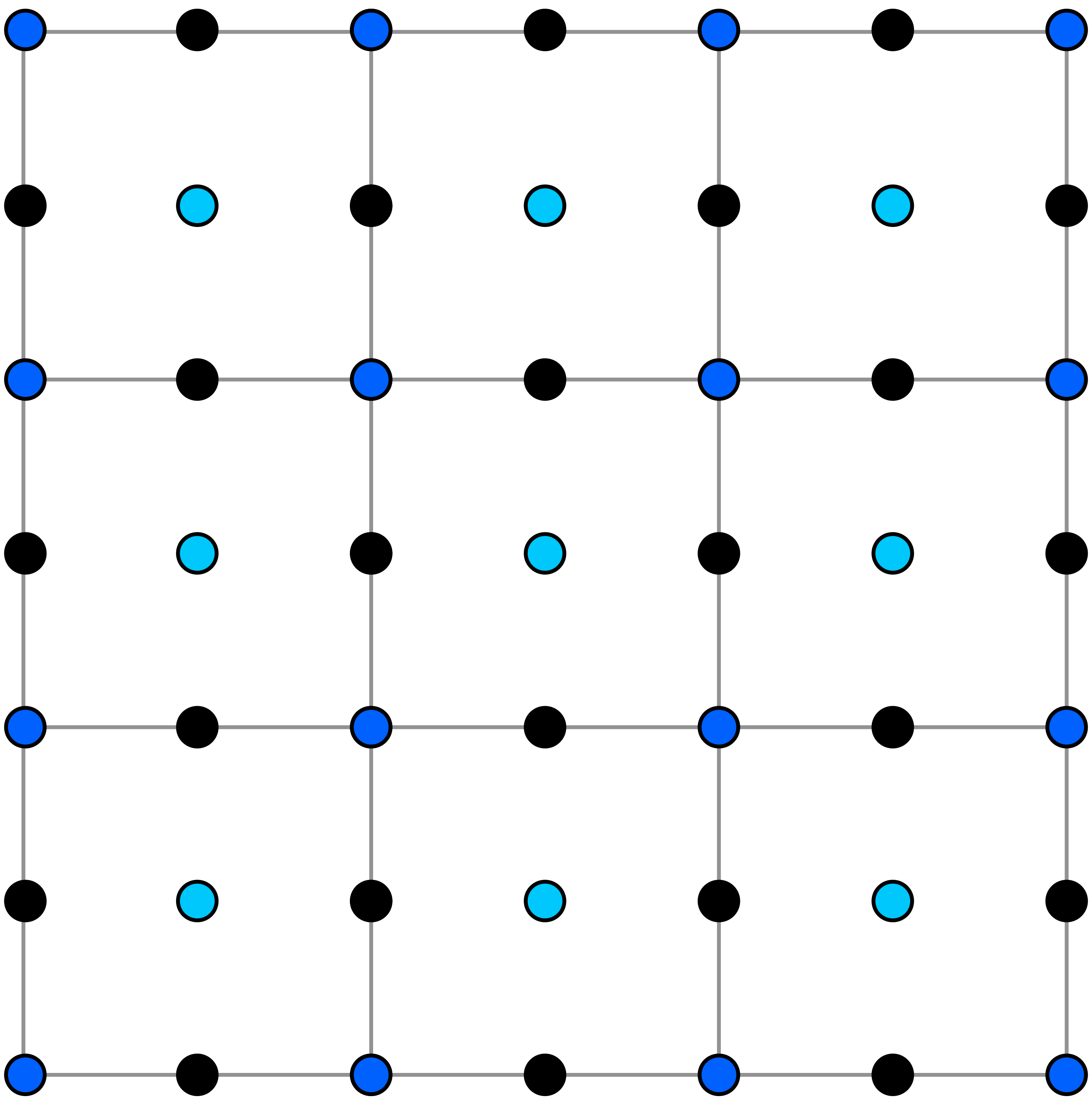
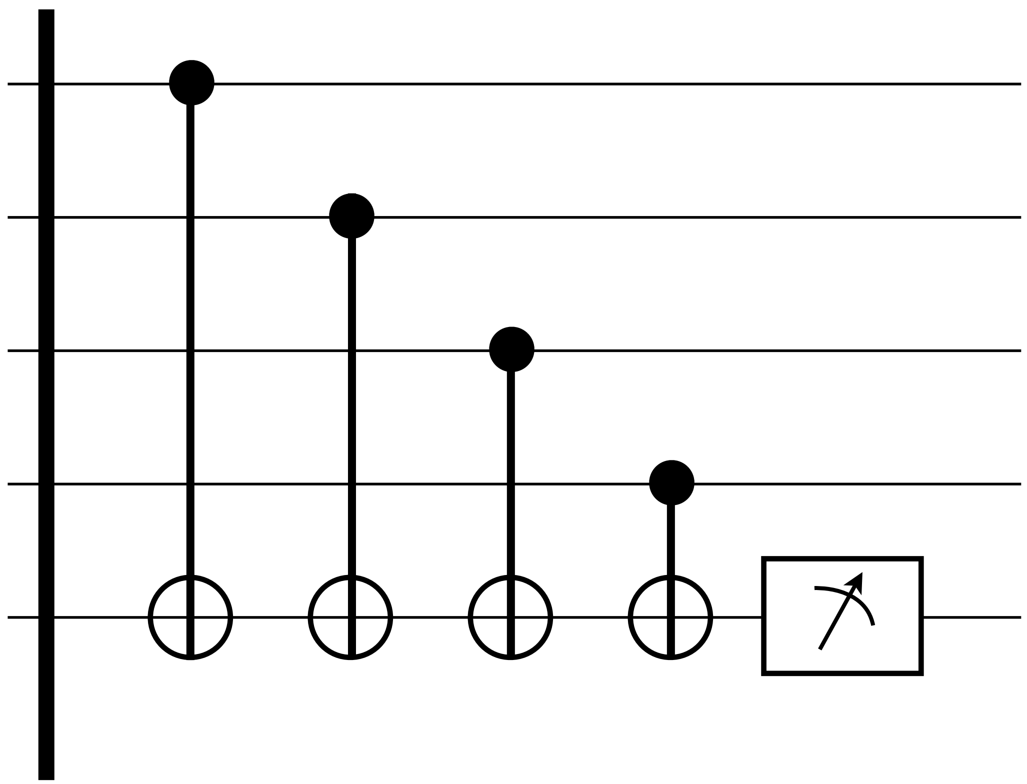
Measurement Error 1





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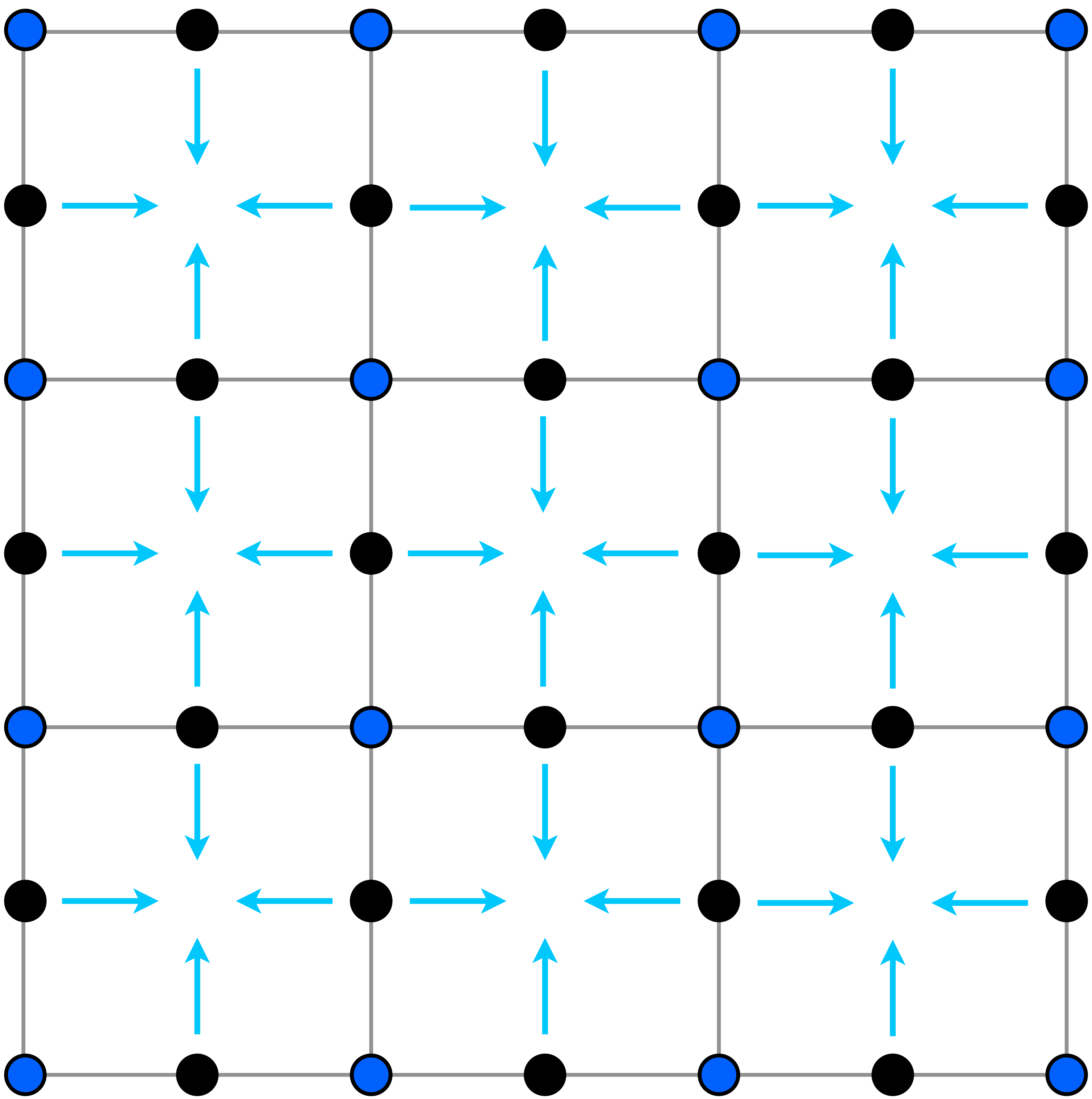

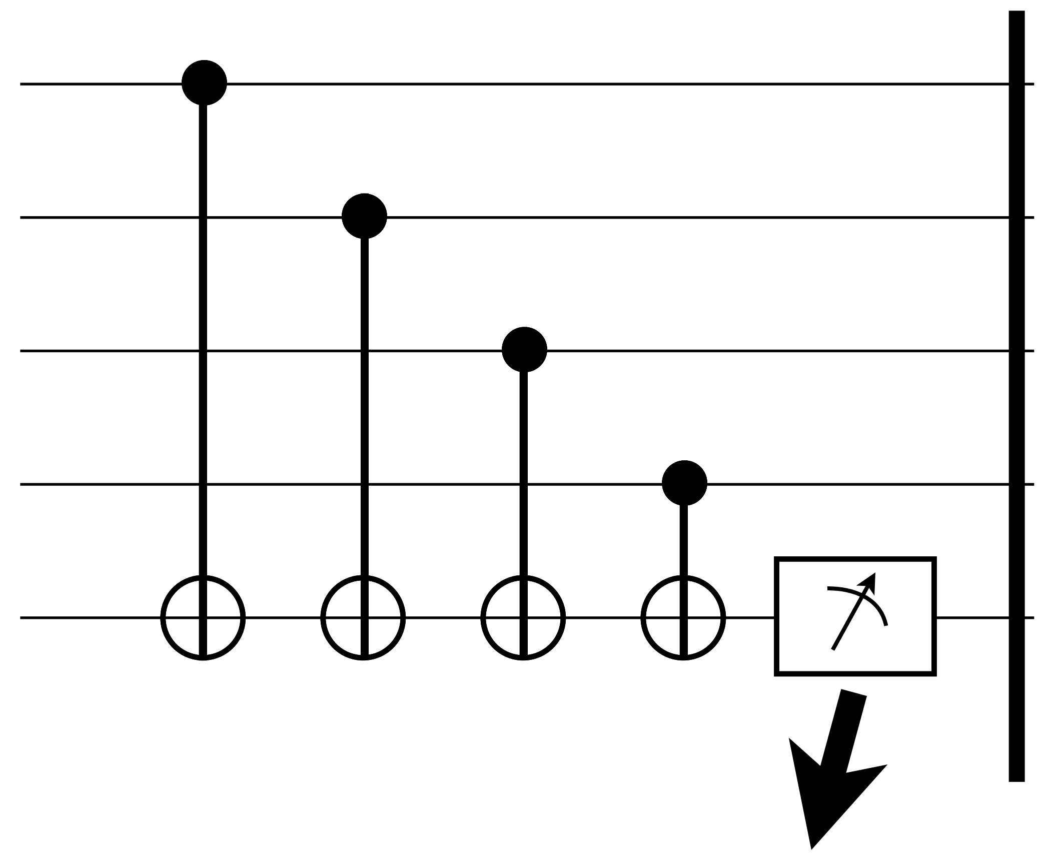

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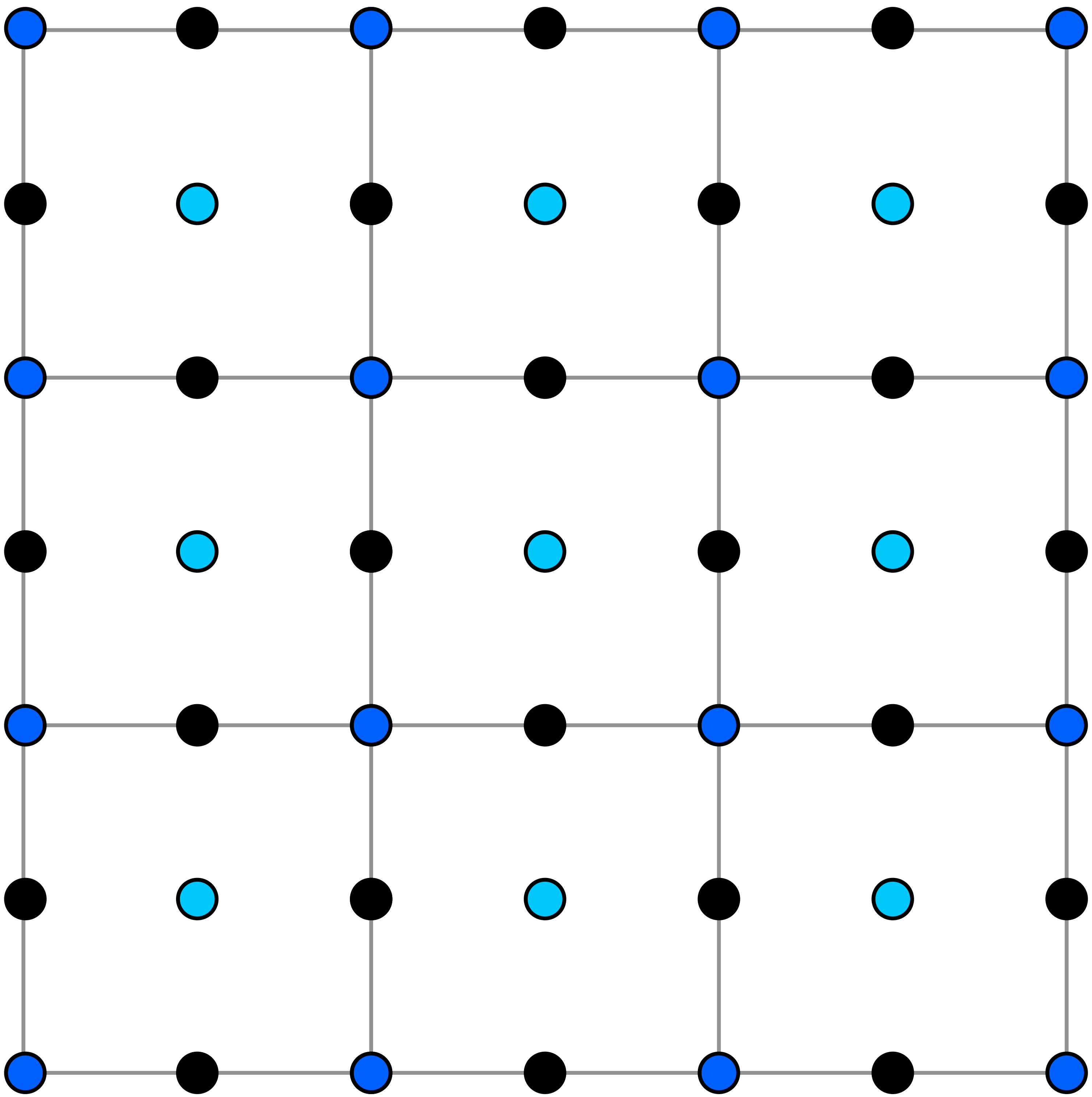
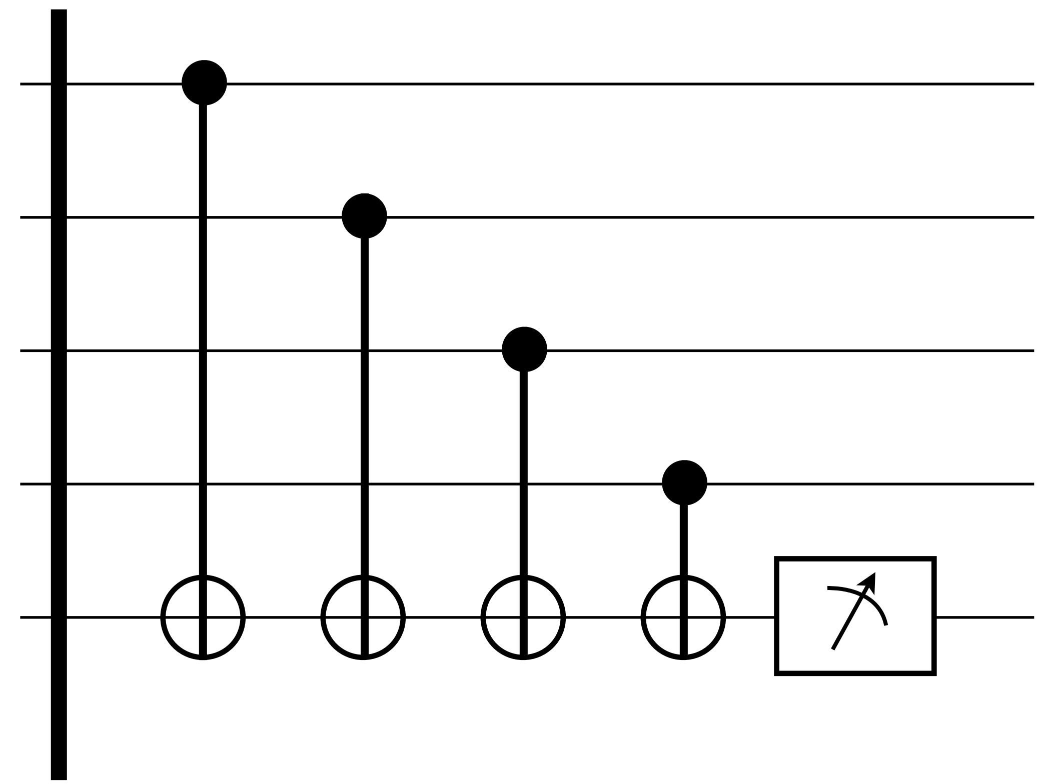
0	0	0

Measurement Error 2

Next Step





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Measurement Error 2

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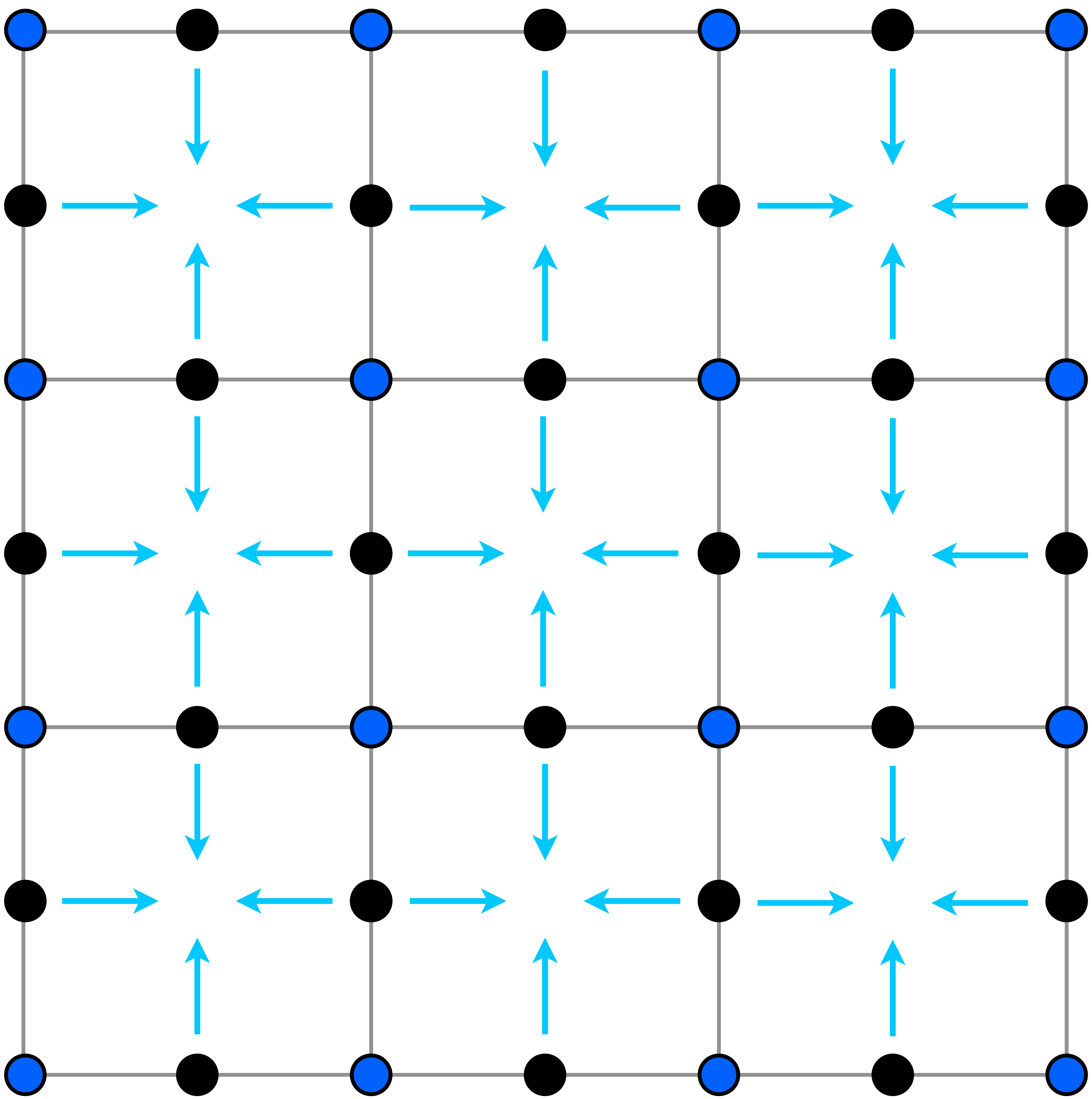
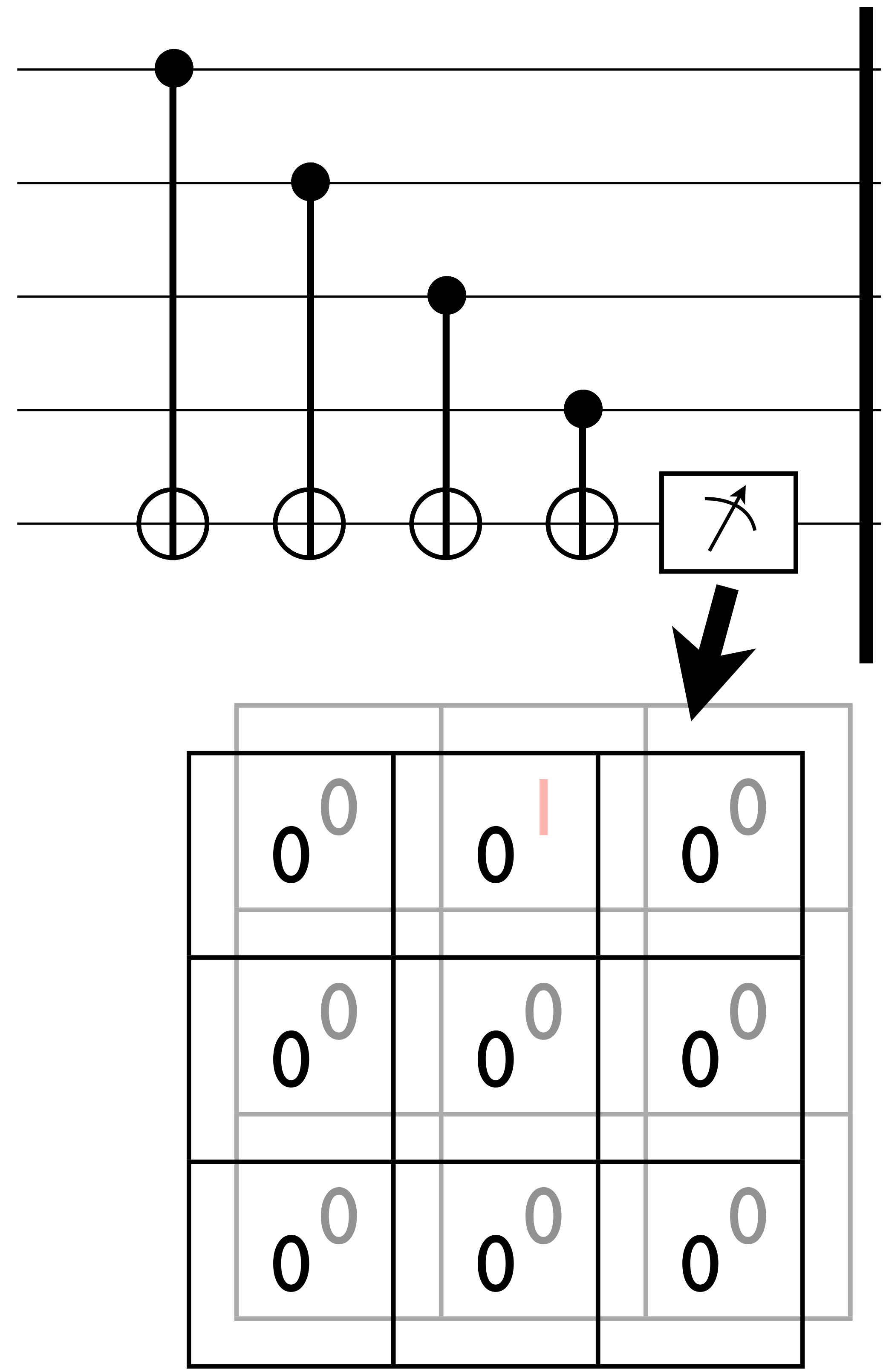
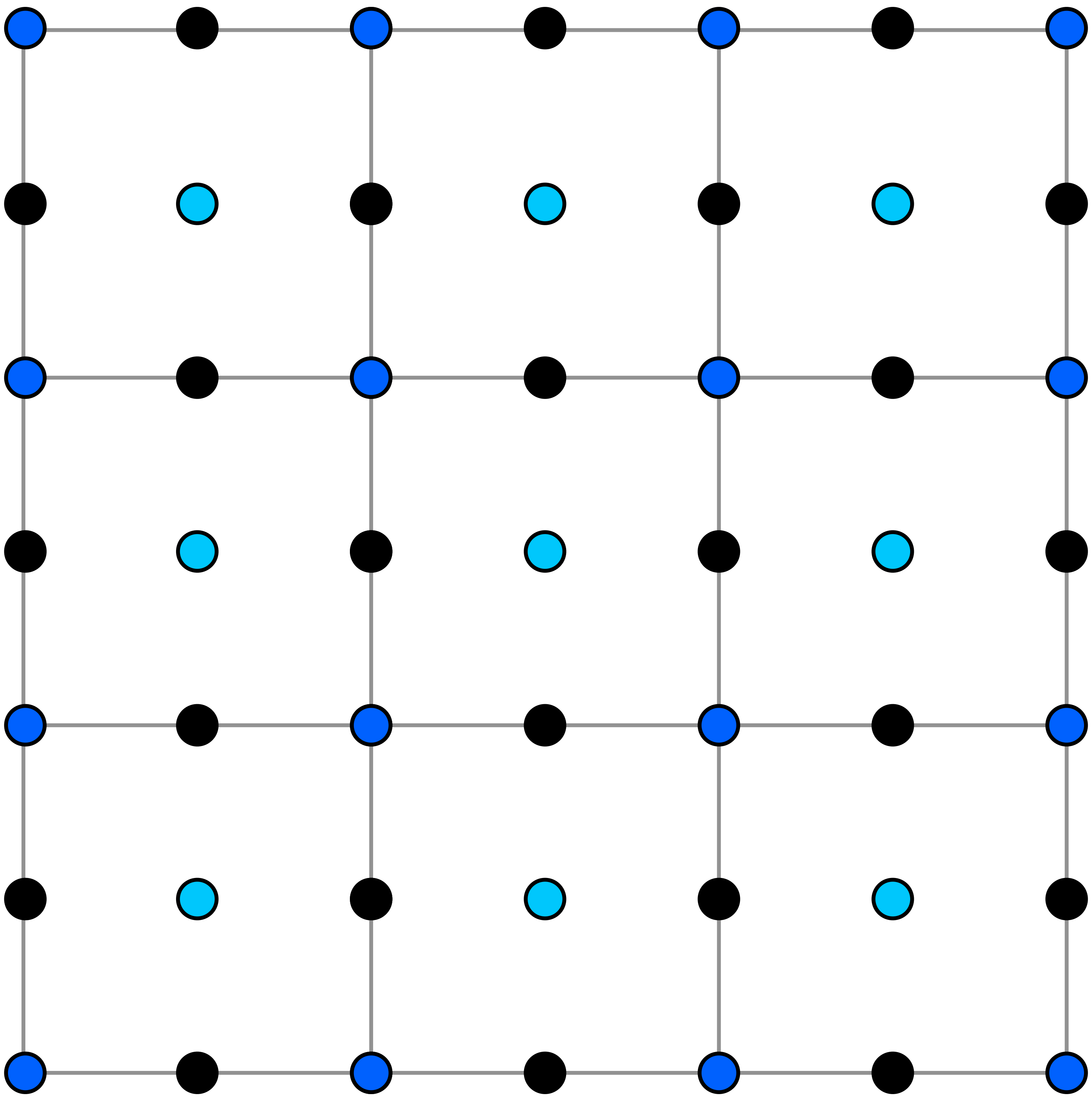
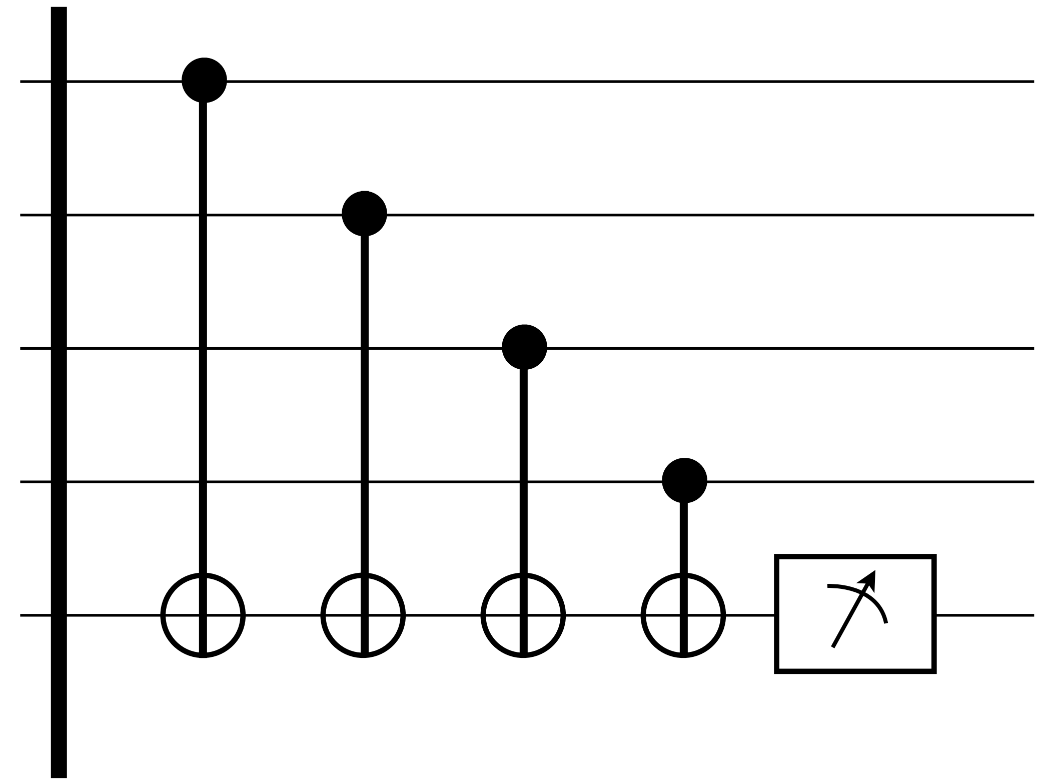




Gate Error 1





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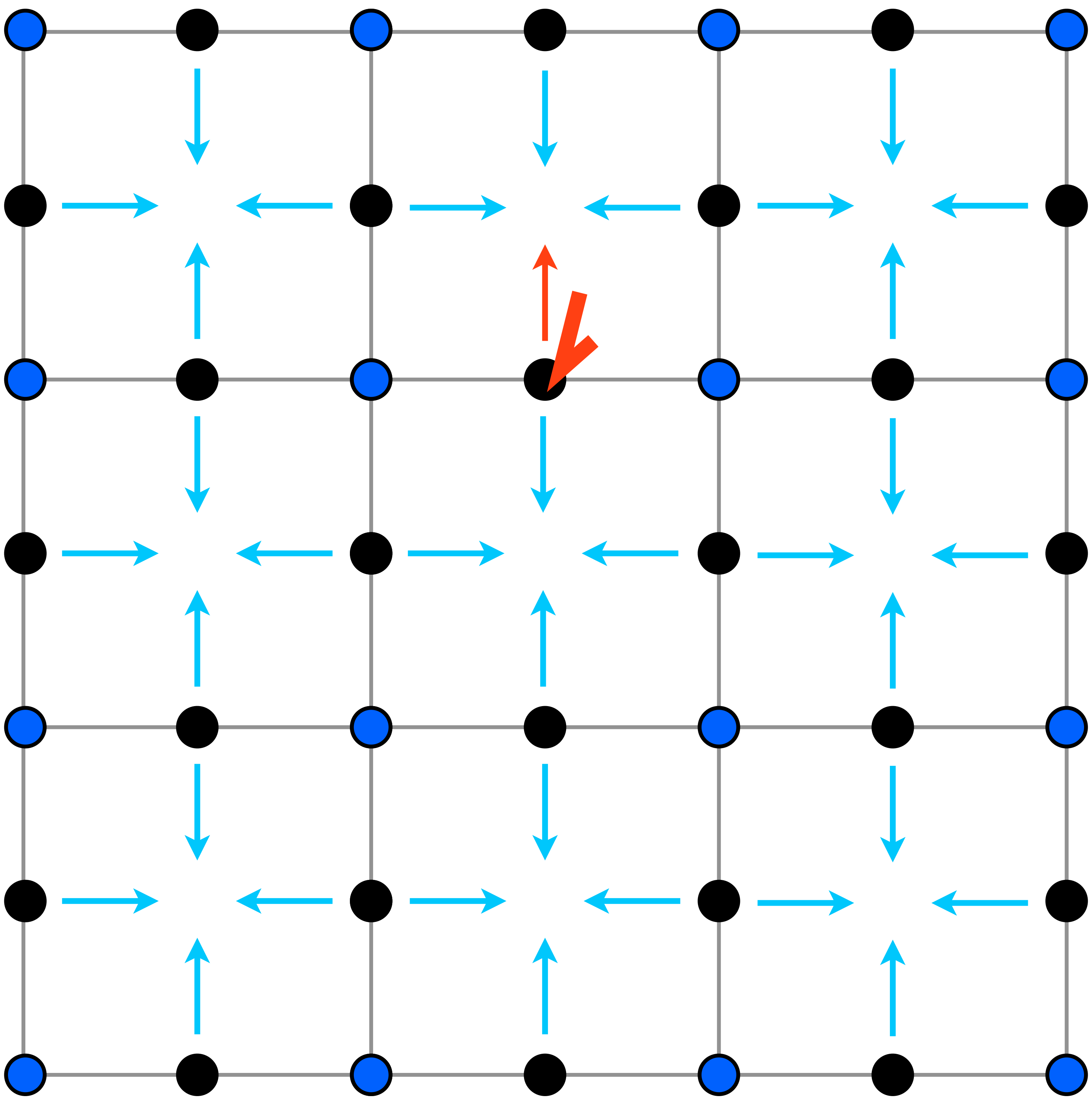
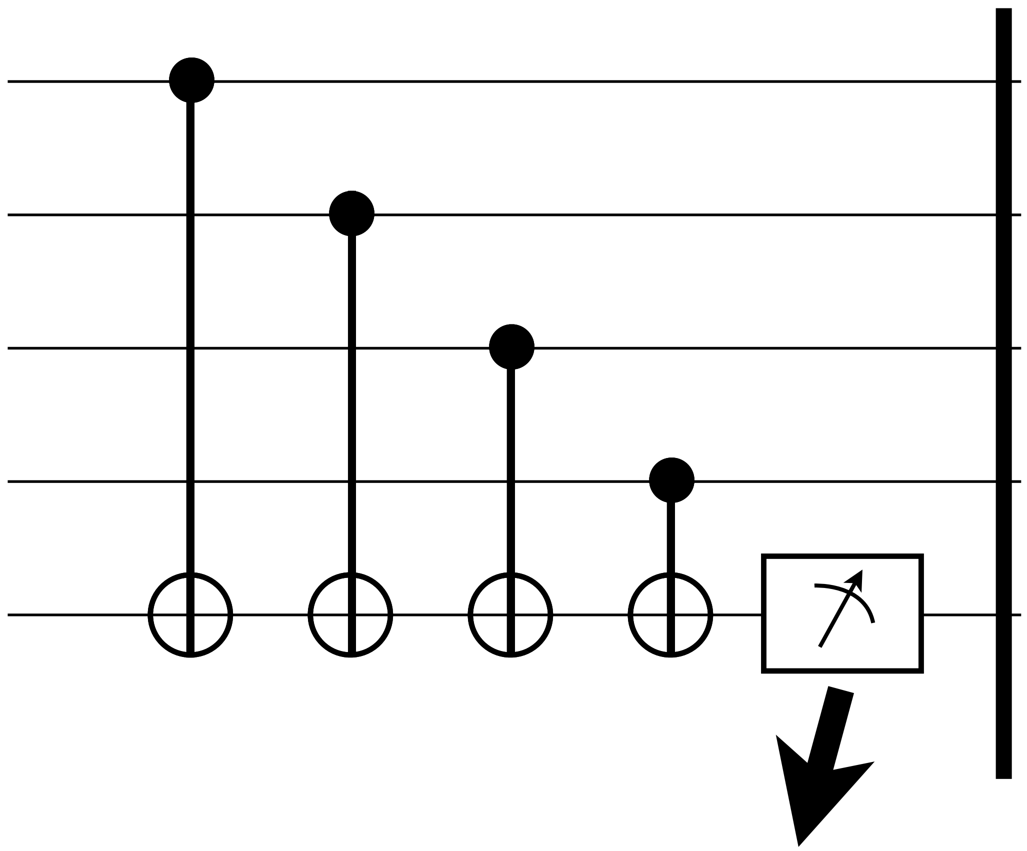
Gate Error 1





0	1	0
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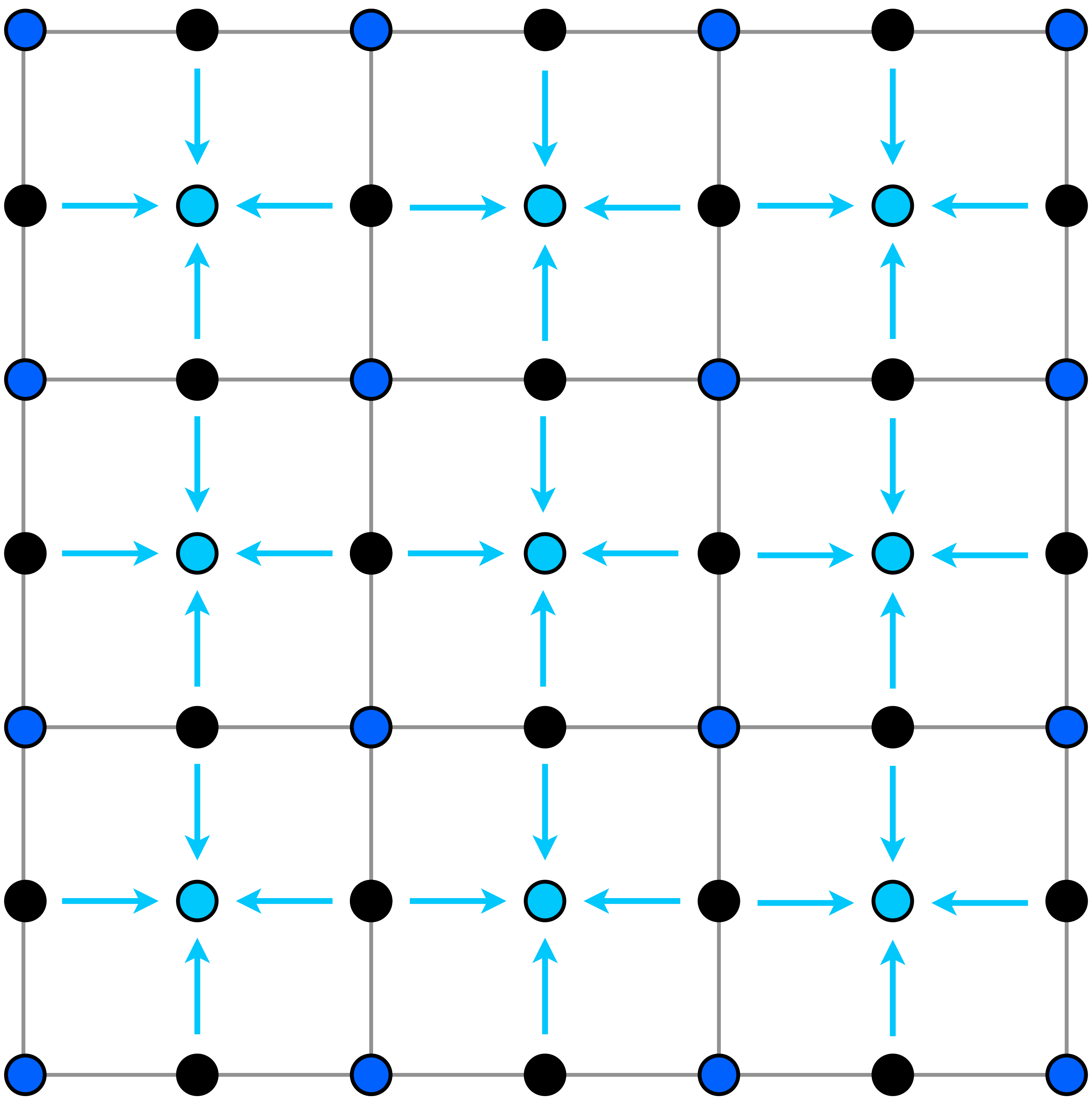
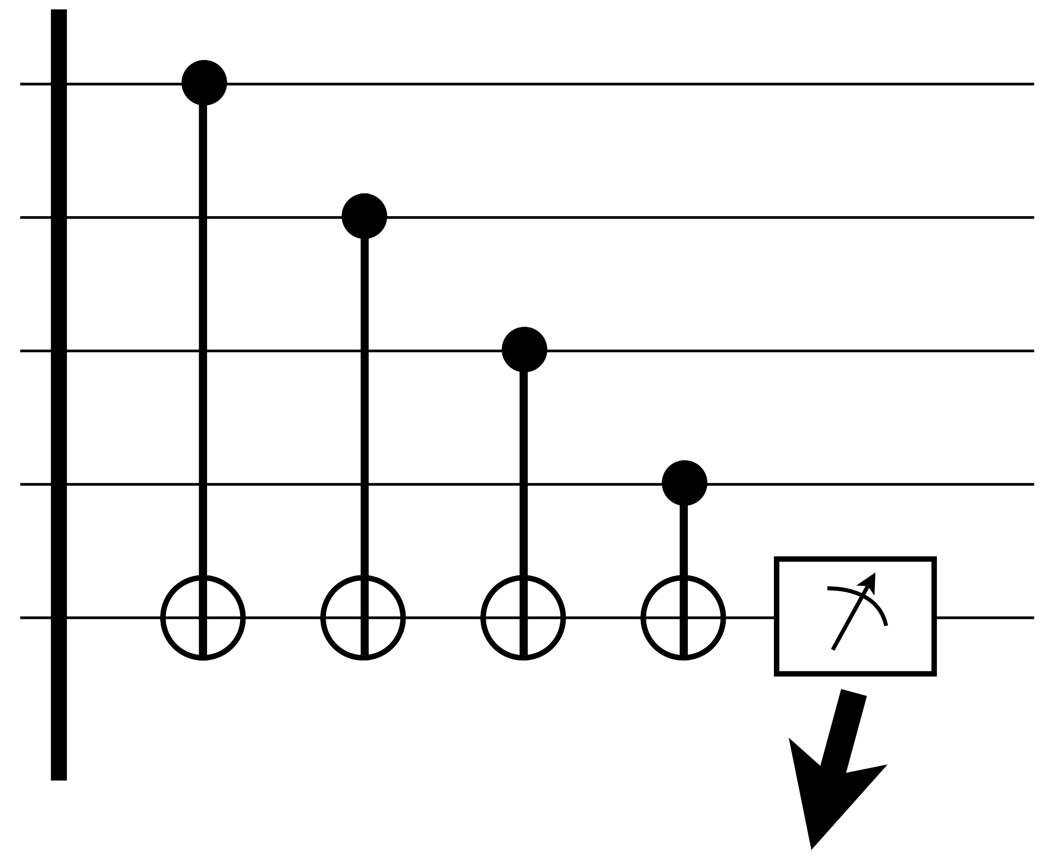
Measurement Error





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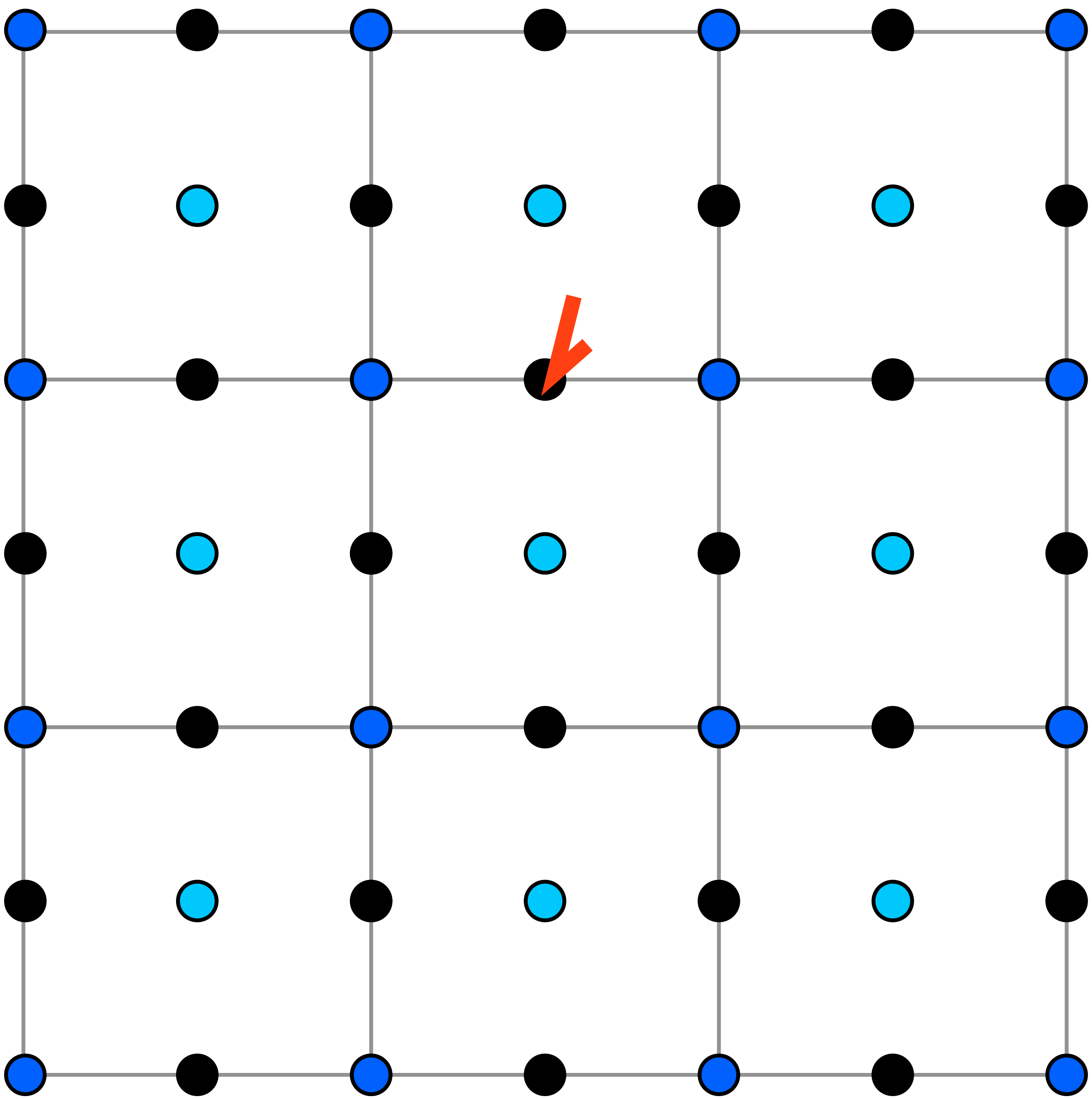
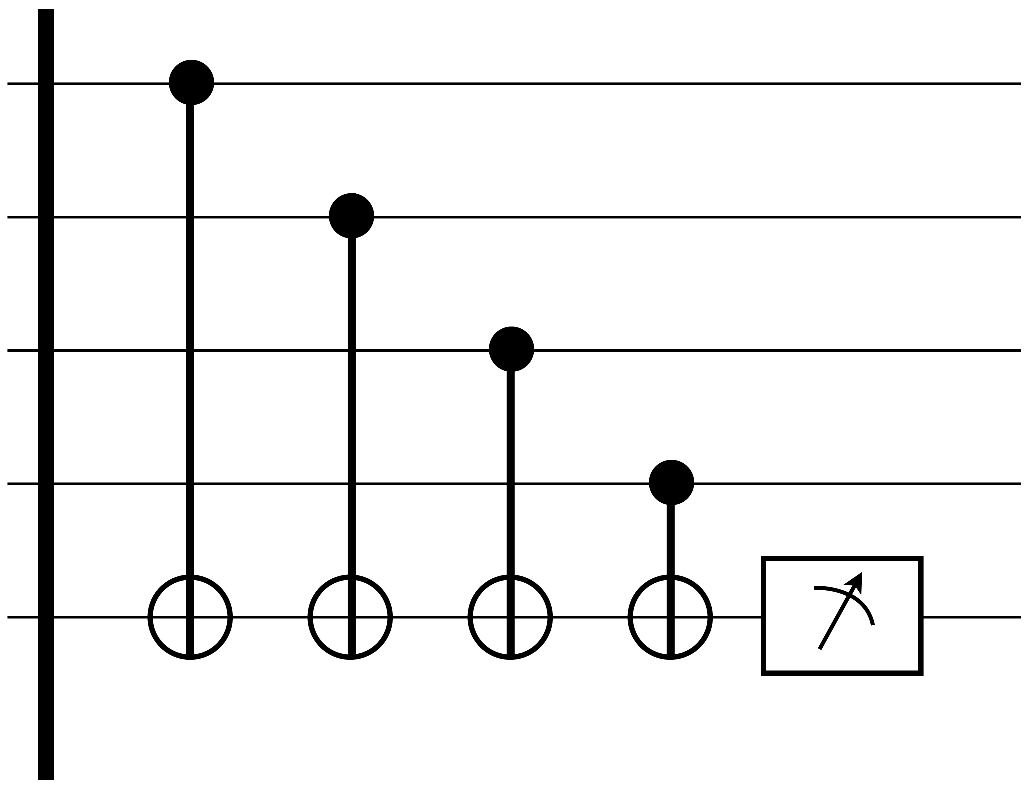
Gate Error 2

Next Step





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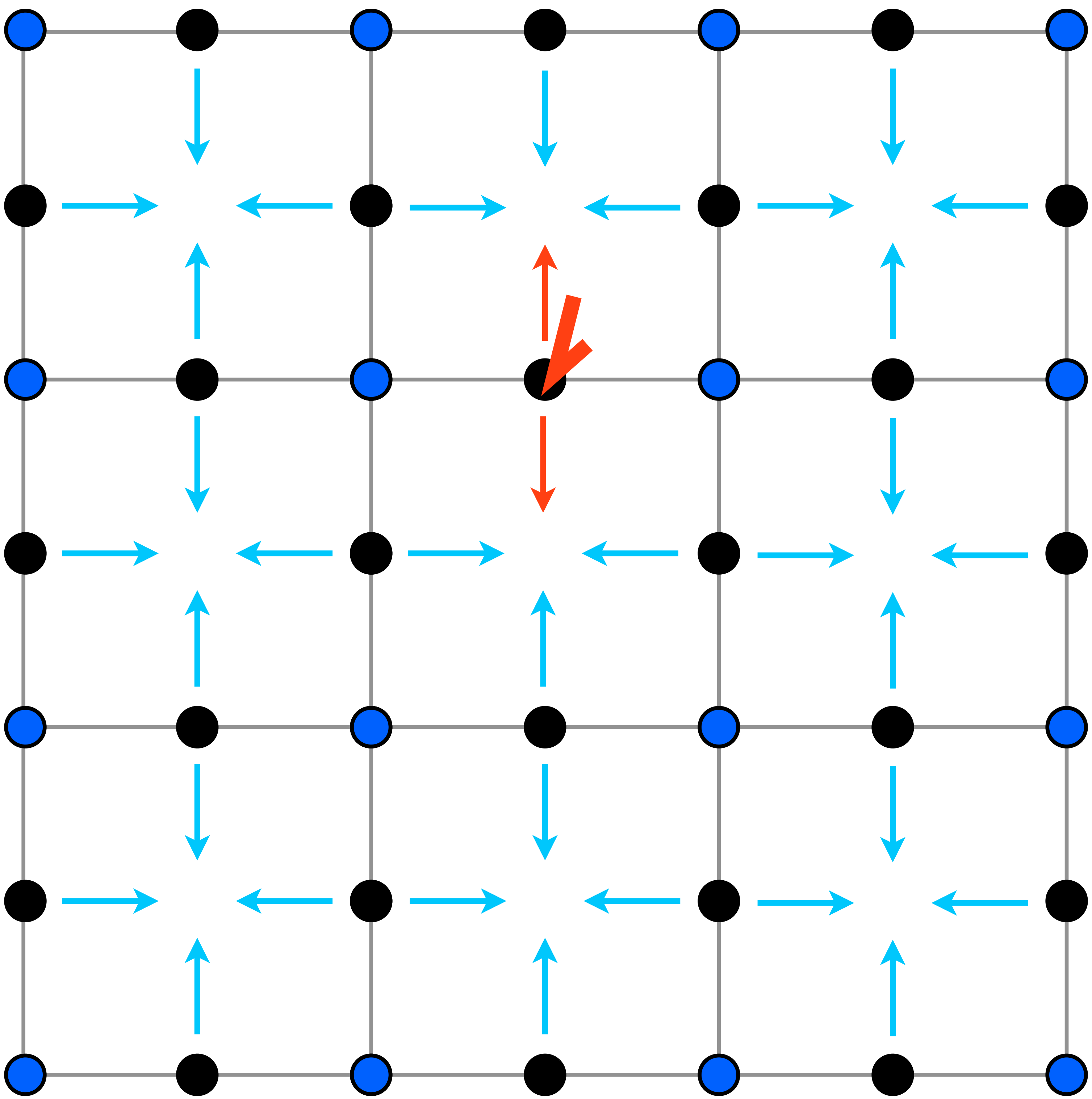
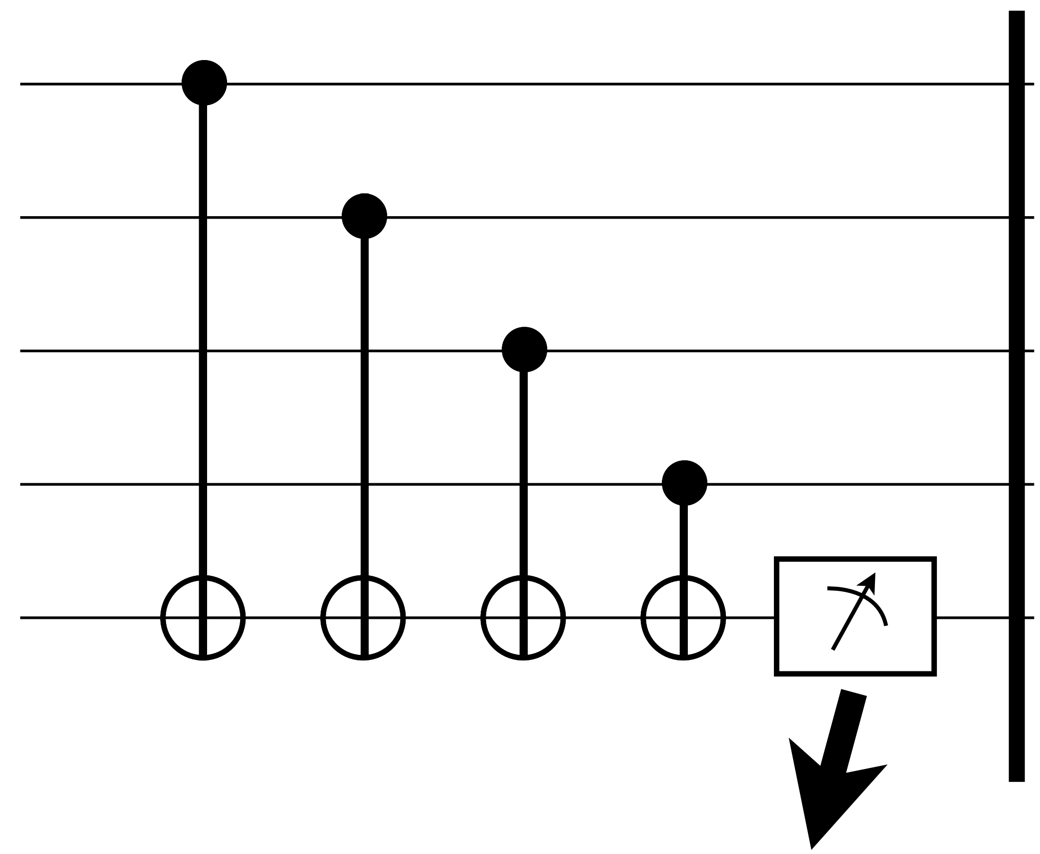
Gate Error 2

Next Step





0	1	0
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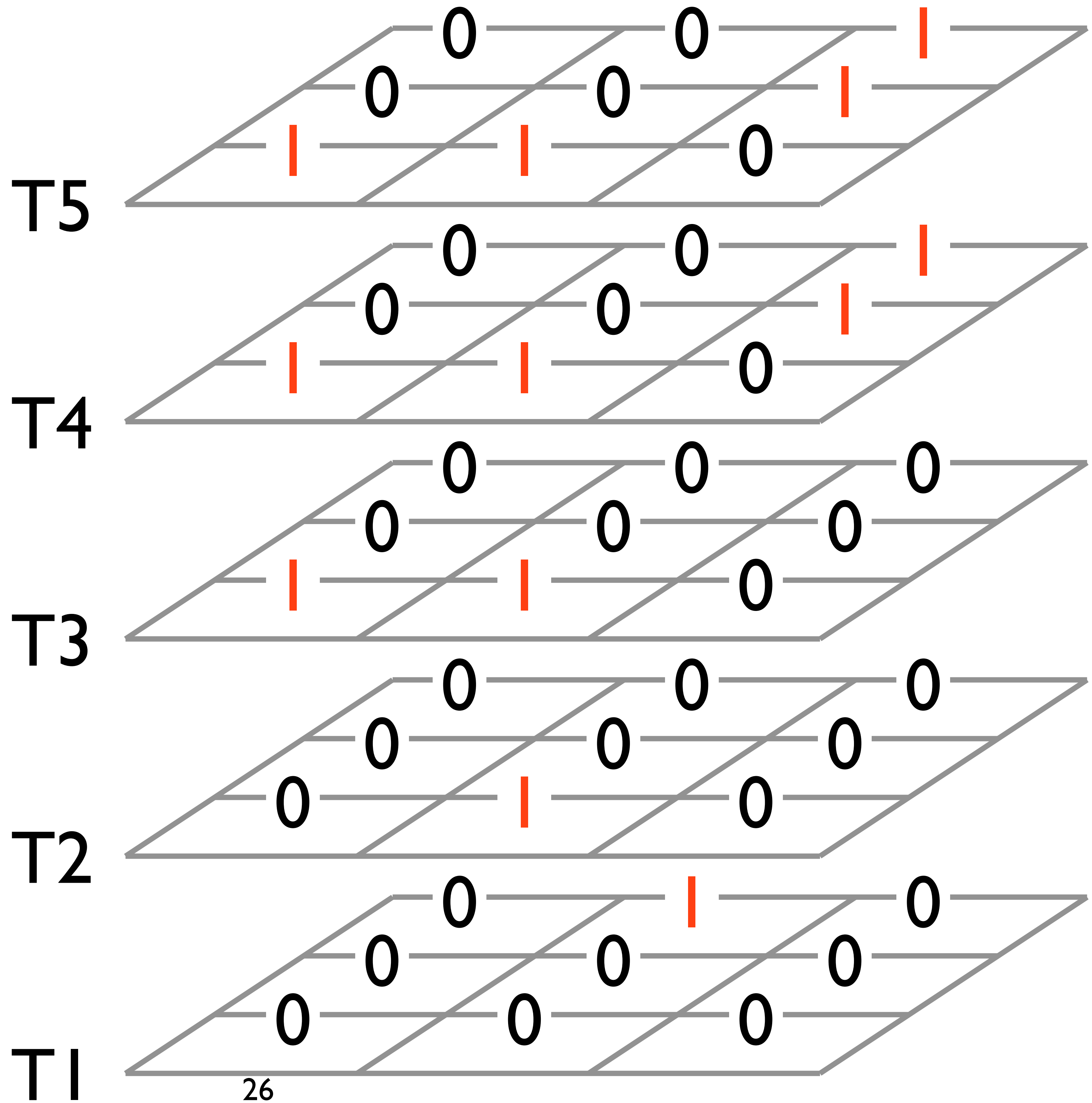
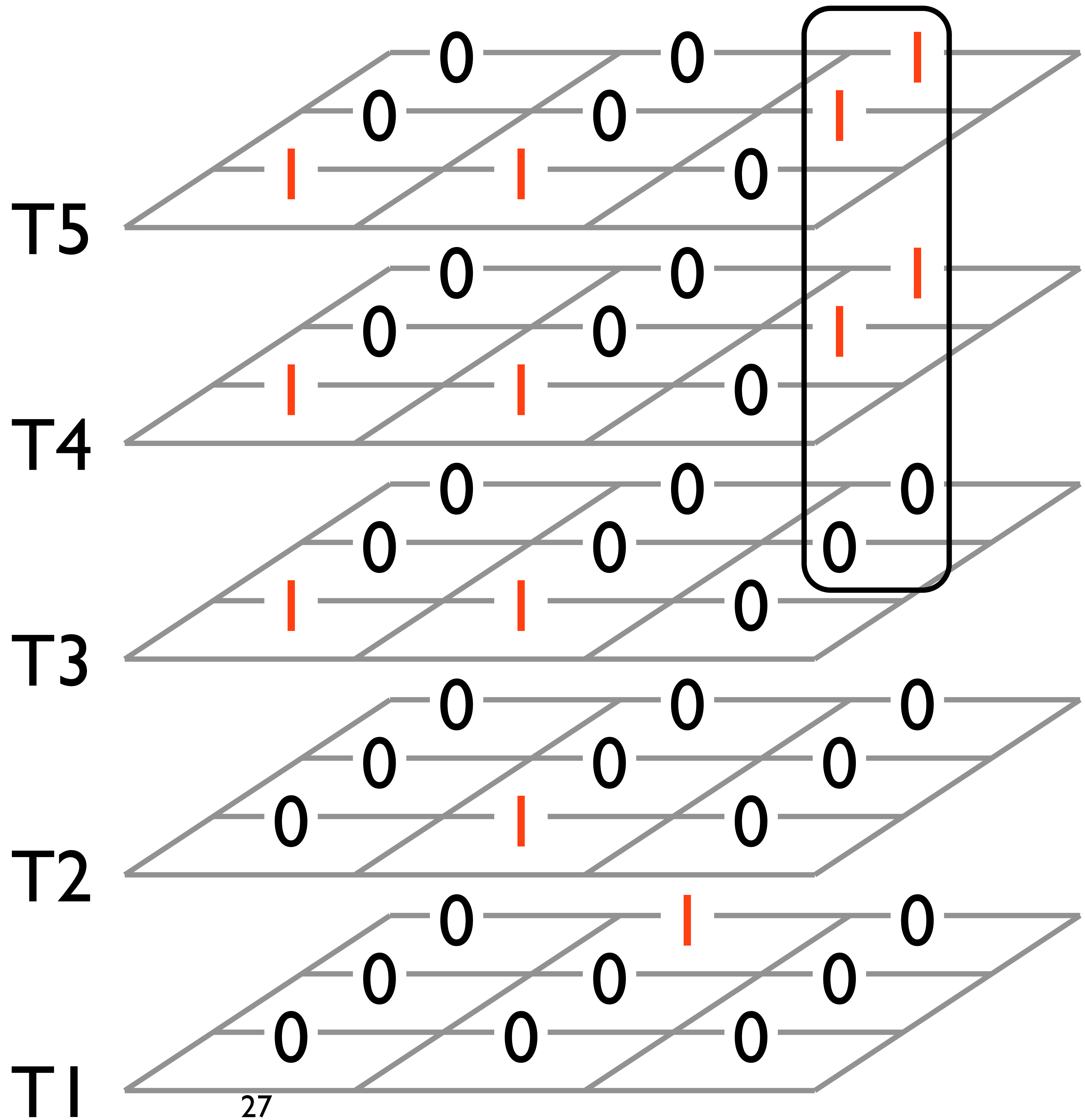
Error syndromes



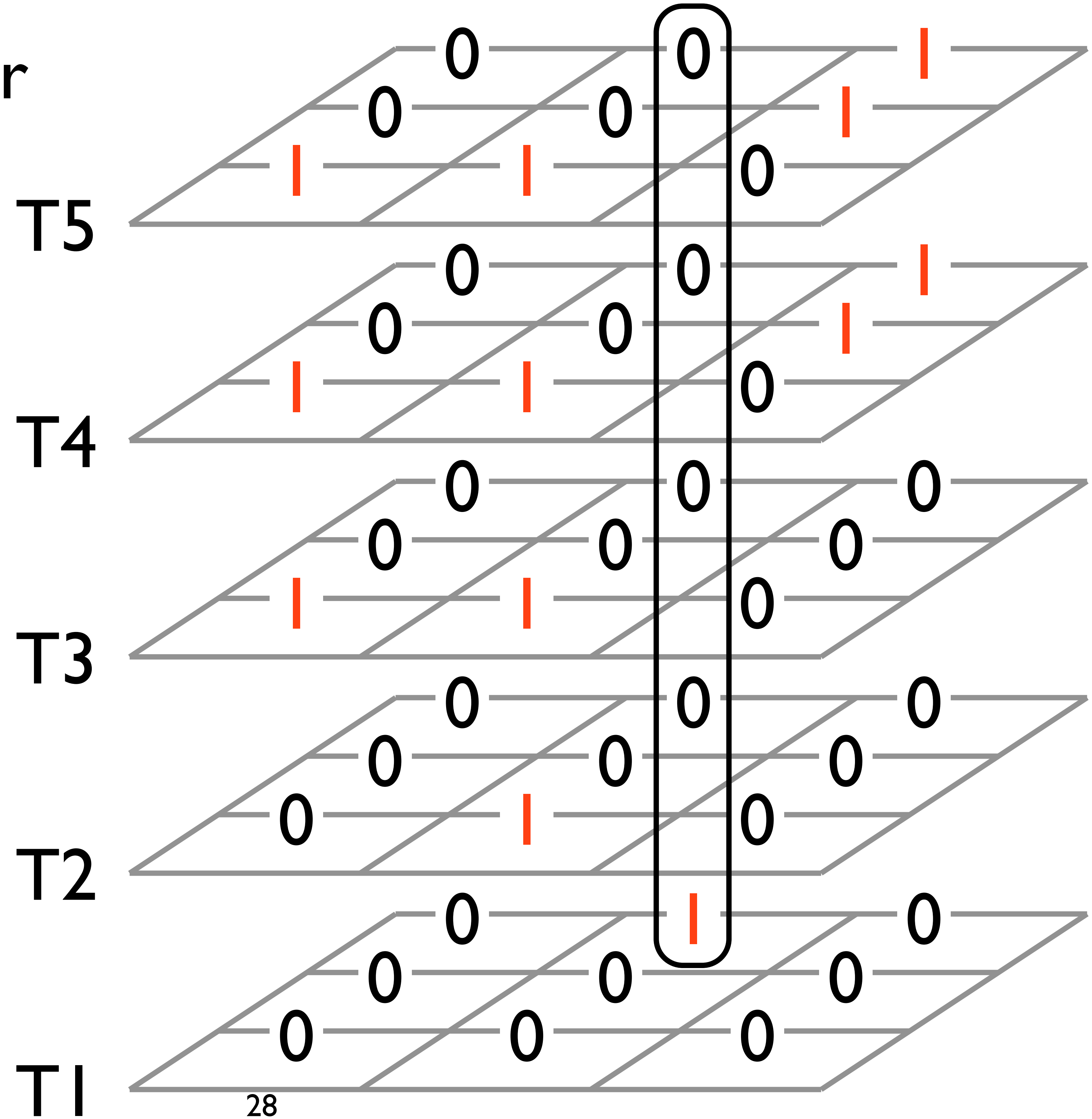
Error syndromes

memory error



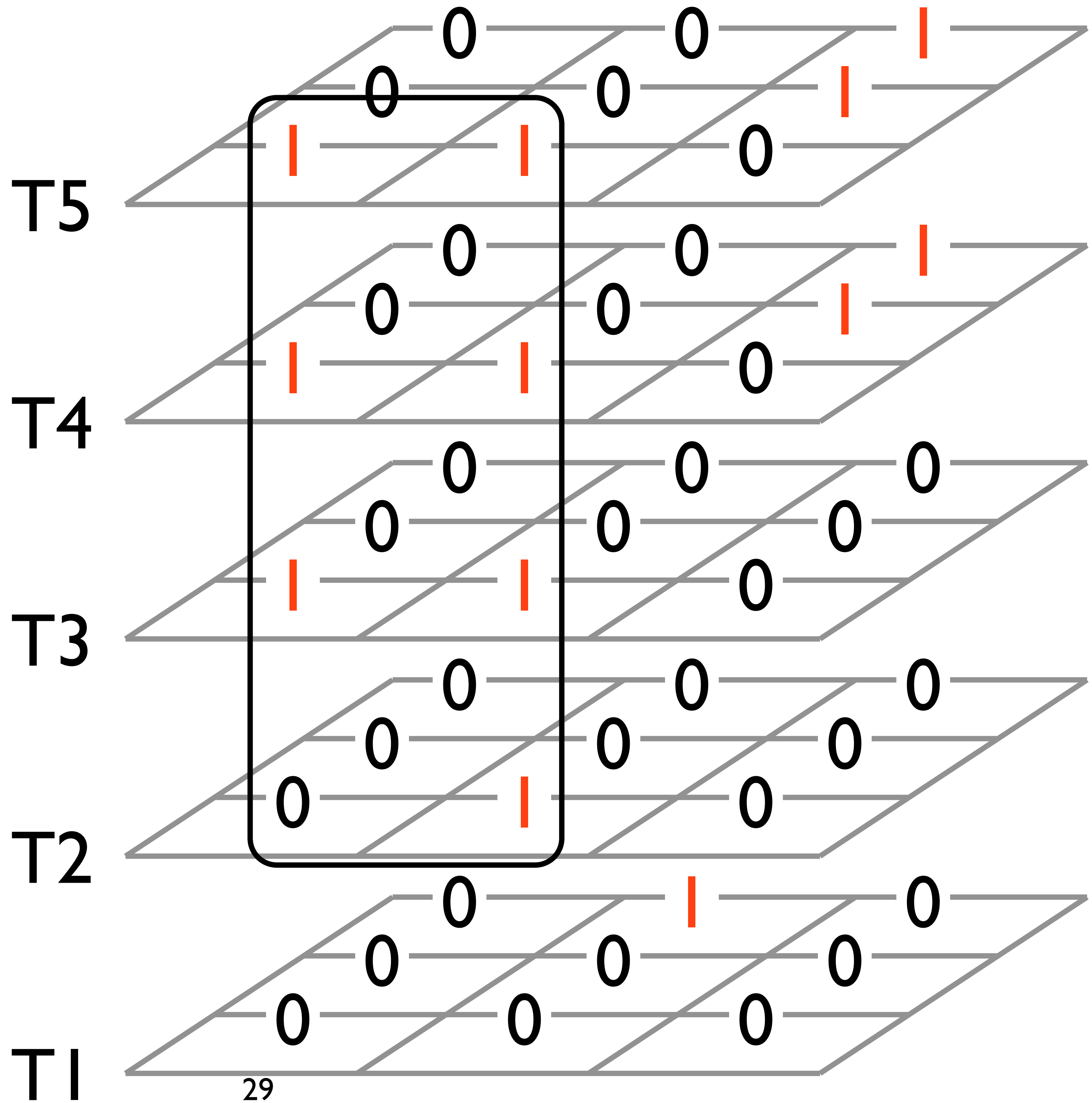
Error syndromes

measurement error



Error syndromes

gate error



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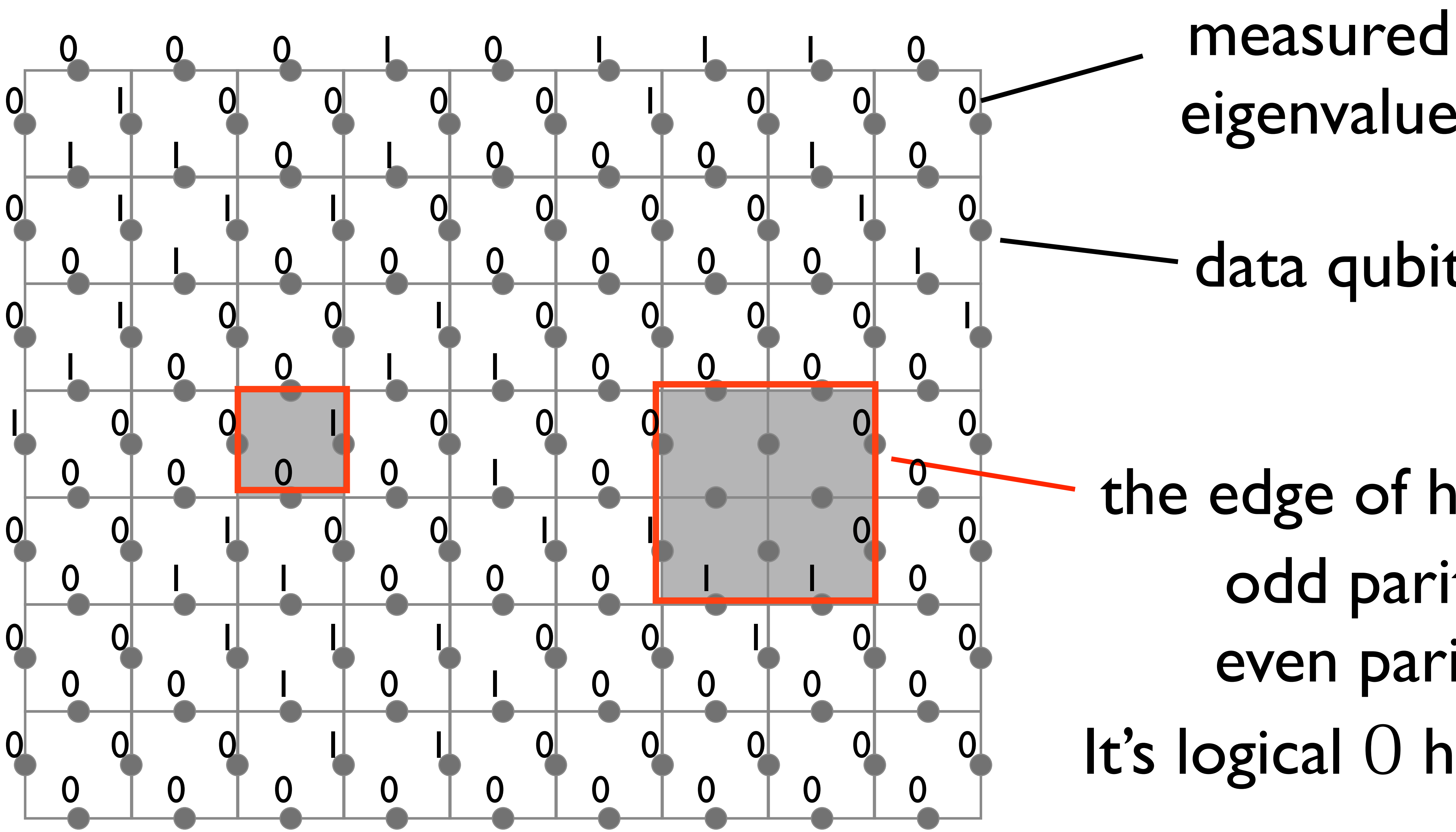
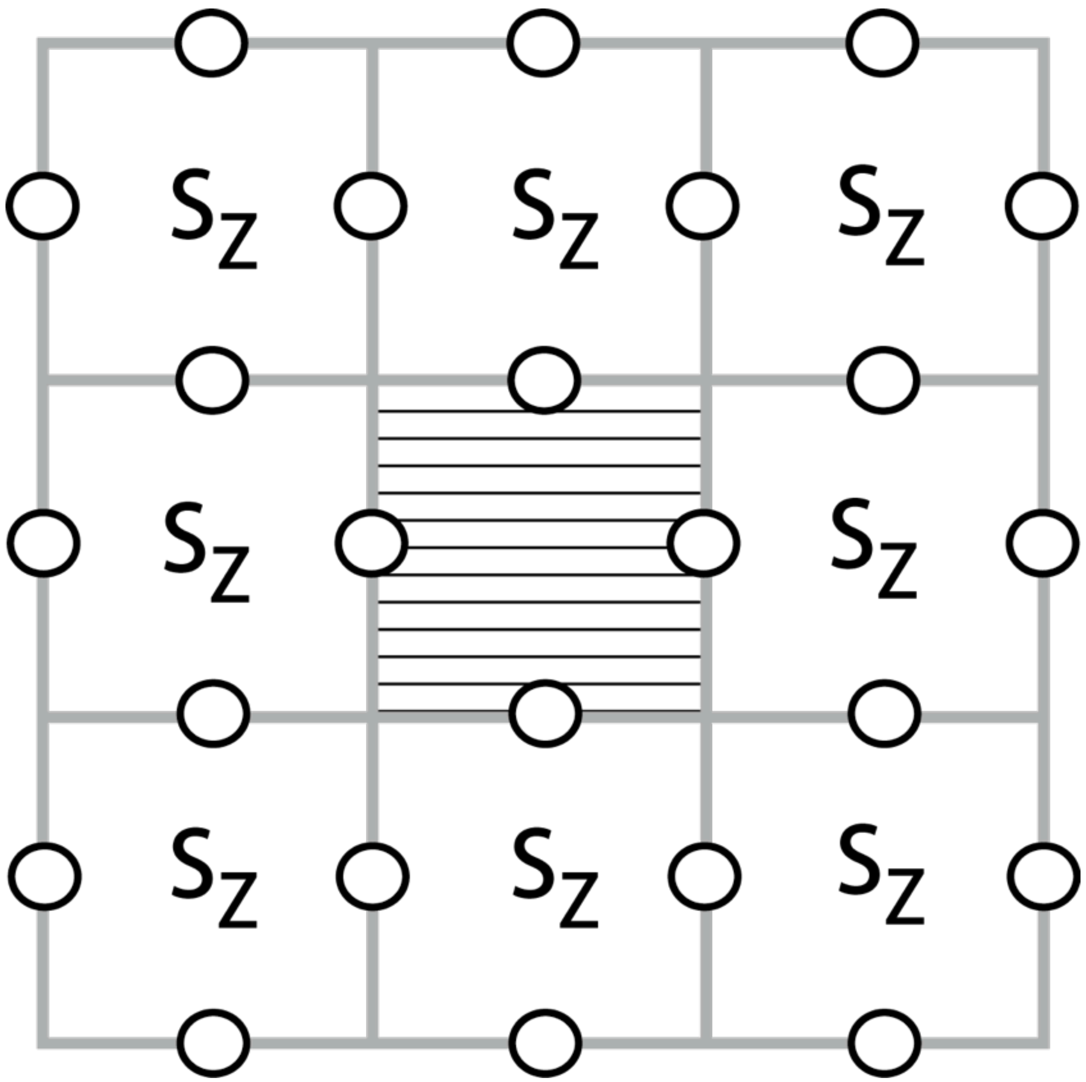
Simplest Example ~Encoding logical qubit~



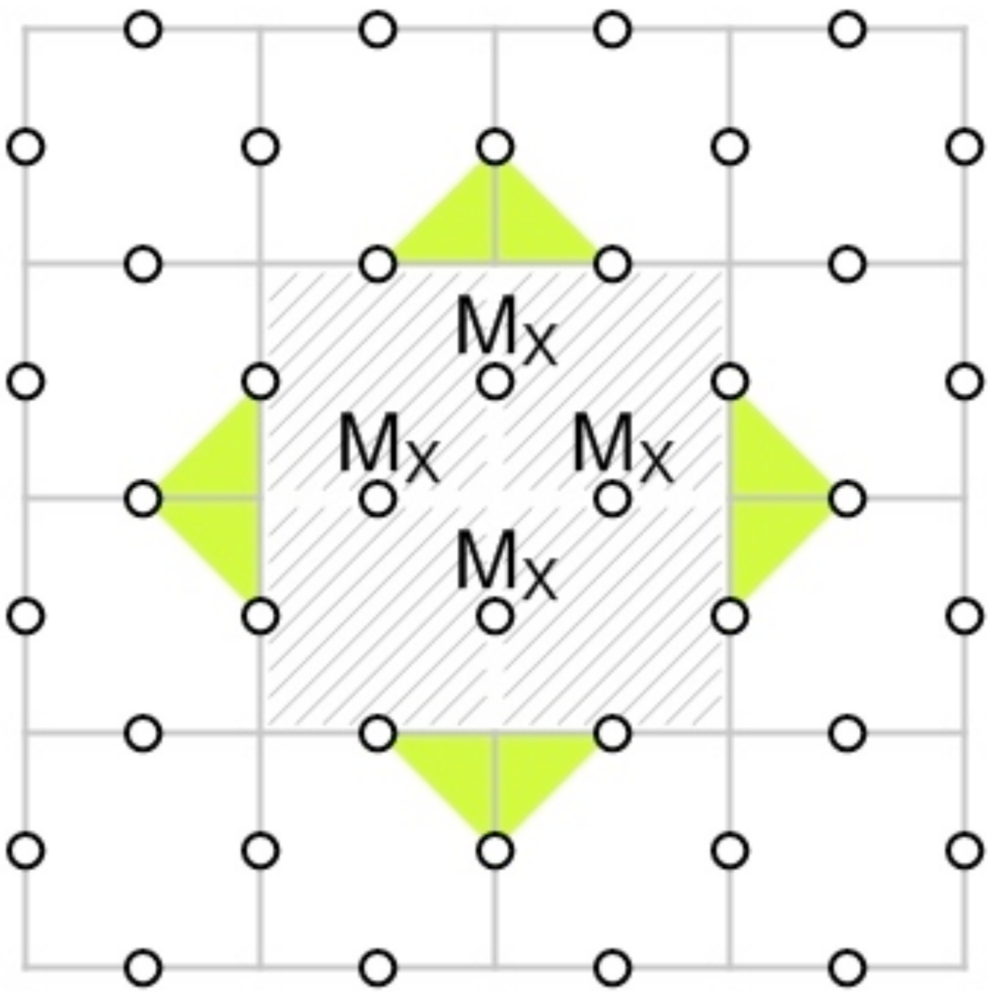
odd parity: 0
even parity: 1
It's logical 0 here.

Lattice holes as logical qubits



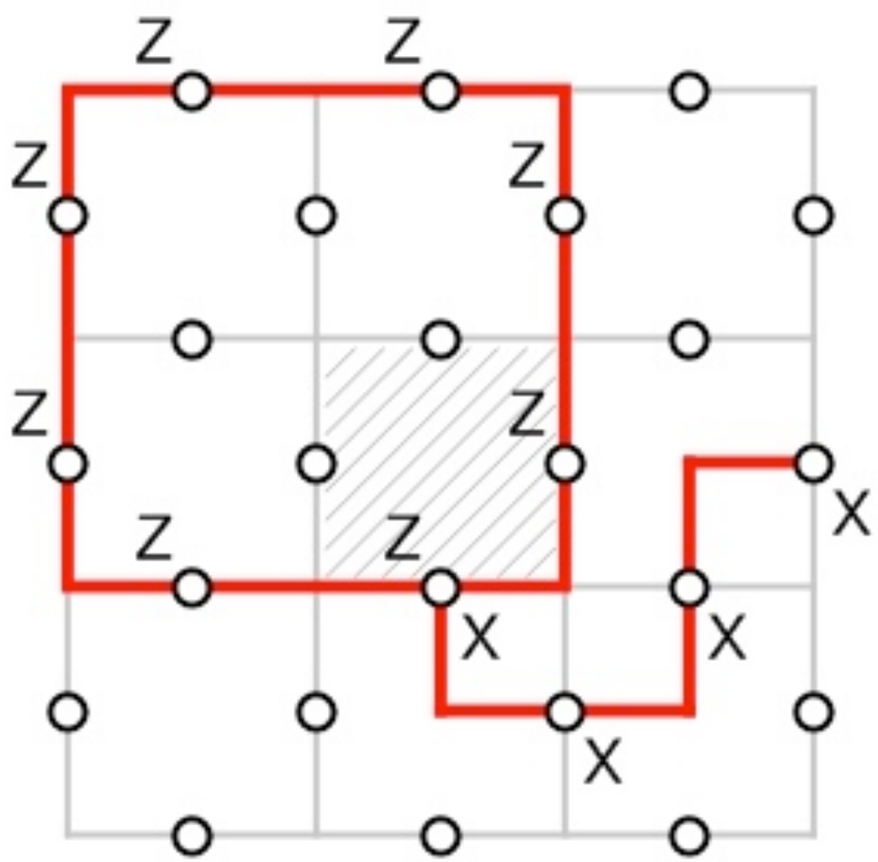
- Introduce degree of freedom by not measuring stabilizer (first, measure out any data qubits in the *interior* of the hole in X basis, to disentangle)
- Only one degree of freedom associated with arbitrary size hole
- Here, 24 lattice qubits, 9 Z stabilizers, 16 X stabilizers (but one *not independent*) = 24 independent stabilizers
- n.b.: Holes referred to as "defects" in most papers, I reserve that term for physically defective qubits

Larger holes

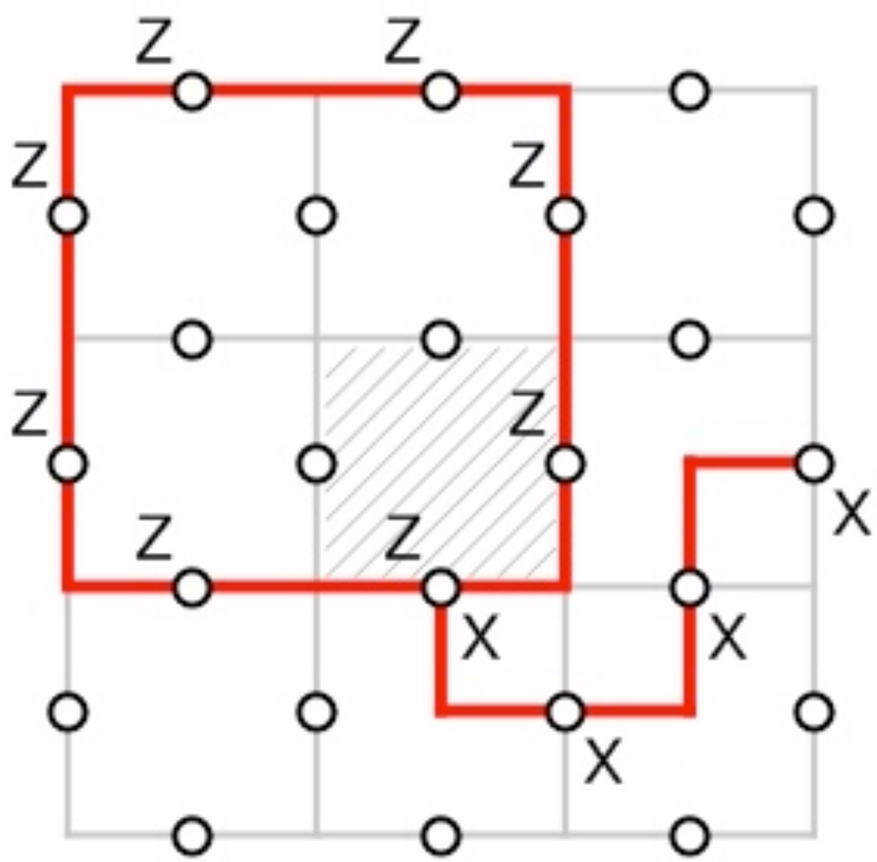


- Only one degree of freedom associated with arbitrary size hole
- Must correct three-term X stabilizers (green)
- Initialize to $|0_L\rangle$

Logical X and Z gates



Logical X and Z gates



- Degree of freedom can be operated on by chains and rings of single-qubit X and Z *on lattice qubits*

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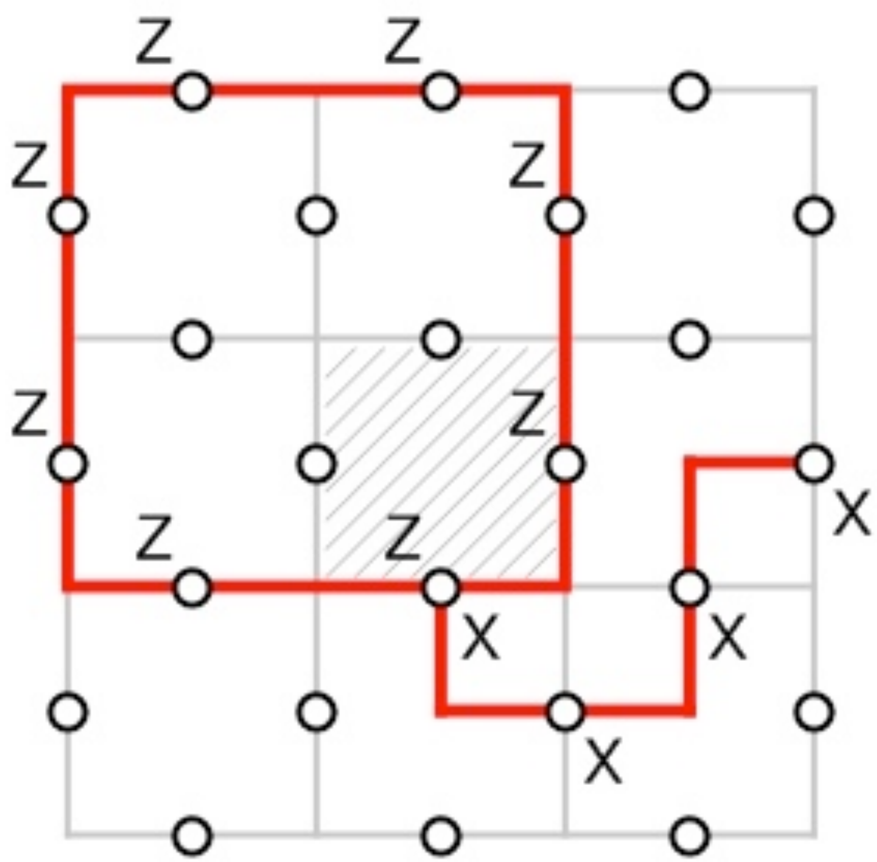
Logical X and Z gates



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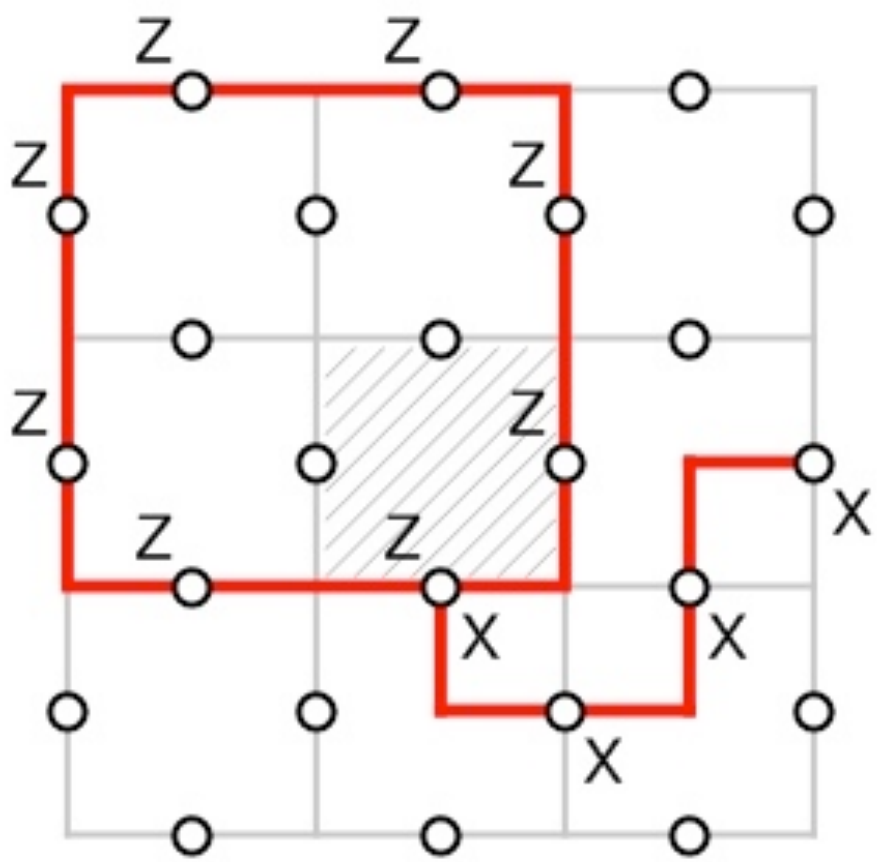
- Chain of X flips connecting hole to boundary gives X gate on logical qubit

Logical X and Z gates



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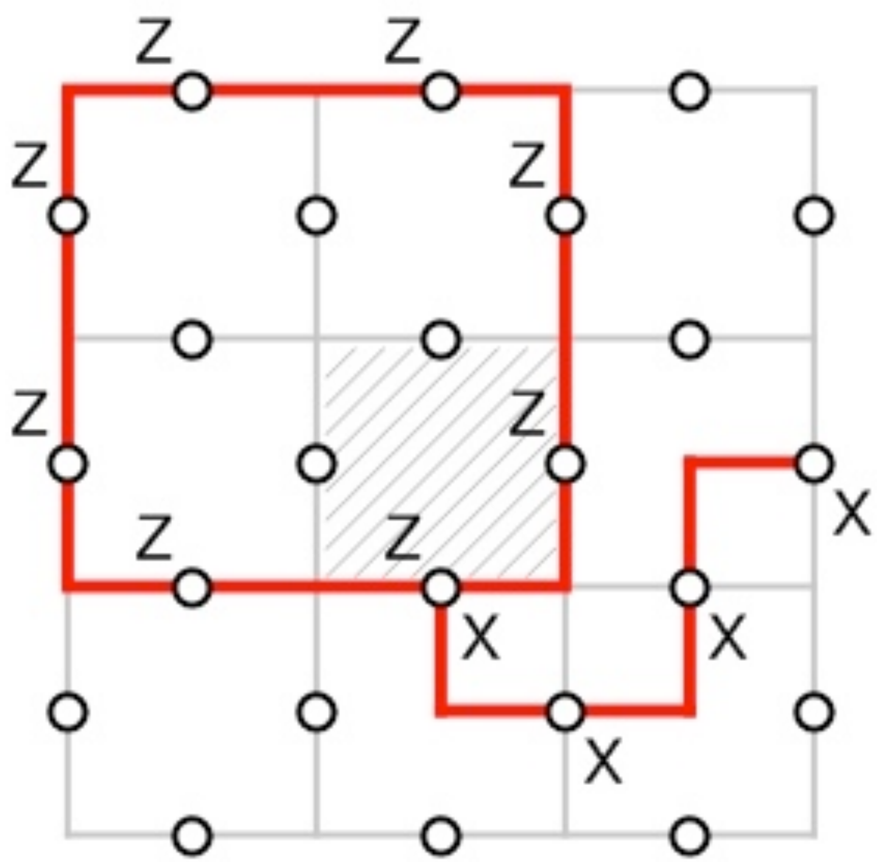
- Ring of Z flips *around* hole gives logical Z gate

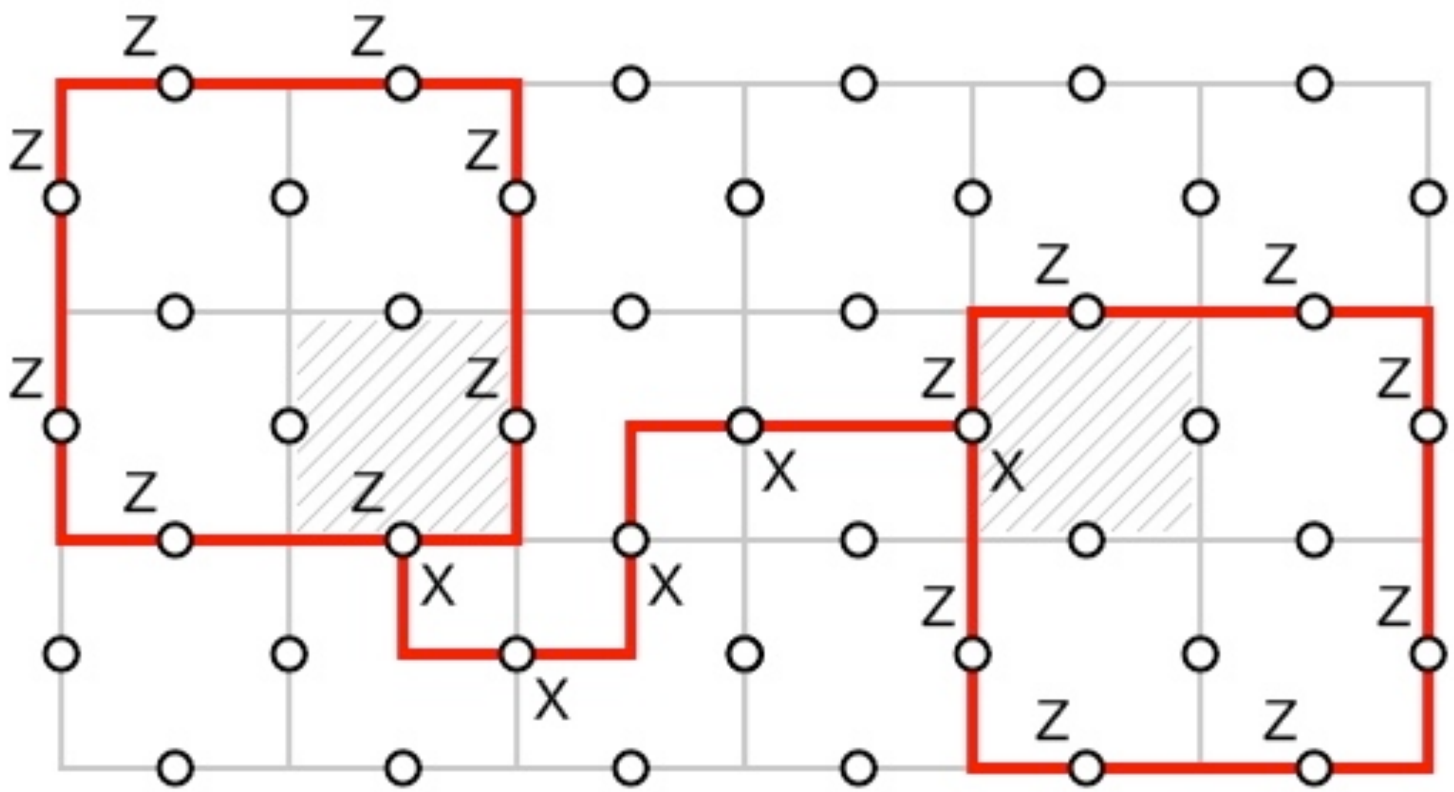
Aqua : Advancing Quantum Architecture

Logical X and Z gates



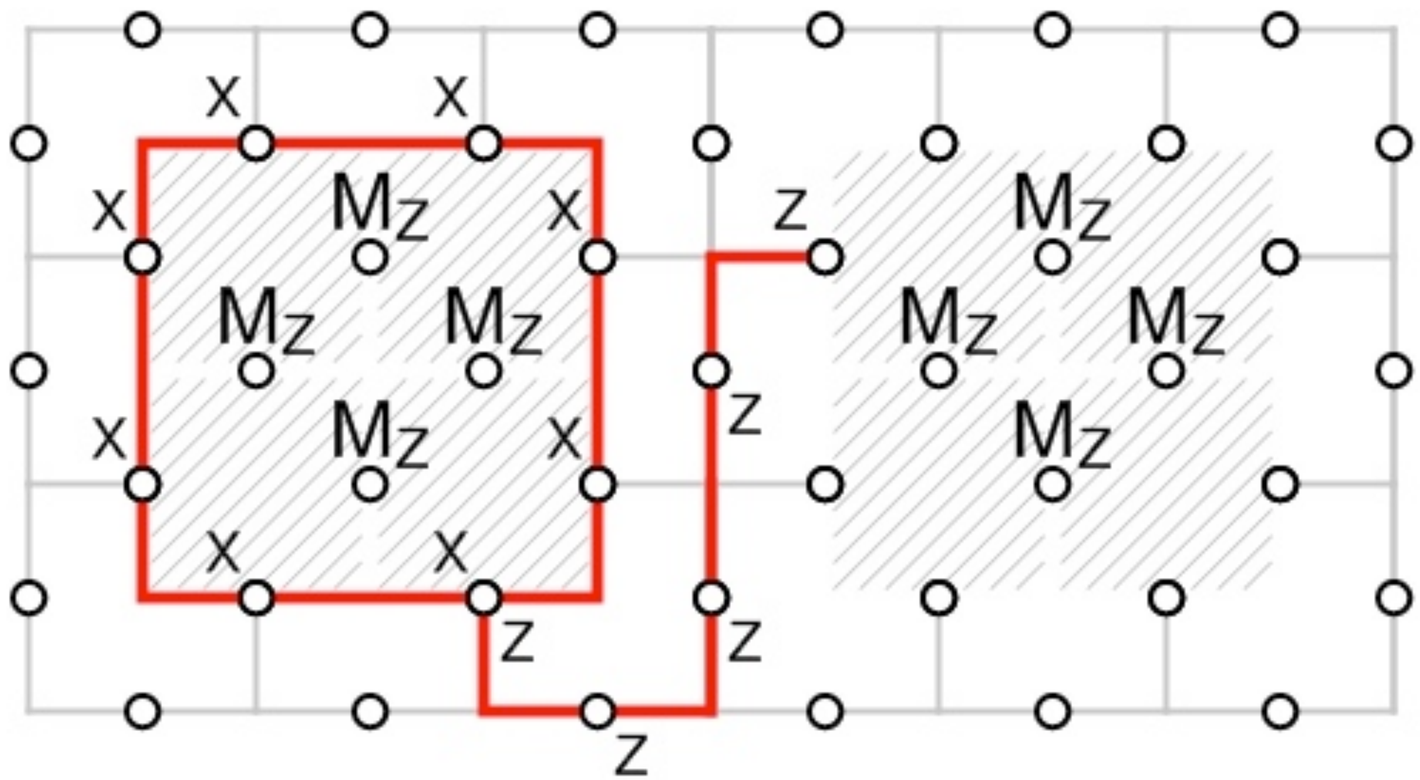
- Degree of freedom can be operated on by chains and rings of single-qubit X and Z *on lattice qubits*
- Chain of X flips connecting hole to boundary gives X gate on logical qubit
- Ring of Z flips *around* hole gives logical Z gate
- n.b.: This can be *any* ring around the hole or *any* chain connecting hole to lattice edge

Pairing up holes



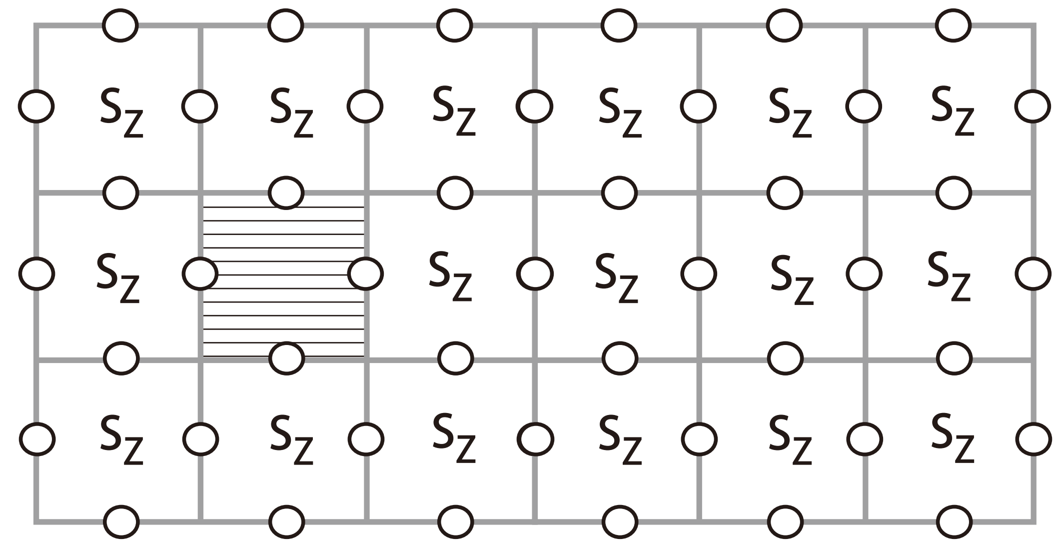
- Better to use a pair of defects to represent one qubit
  - No need to connect operators to boundary
  - Easier to move qubit around computer
- Independent adjustment of X/Z error correction strength
- Terminology: **smooth qubit**
- Logical X gate chain connects the holes
- Logical Z gate circles *one* of the holes

Rough qubits (Dual lattice)

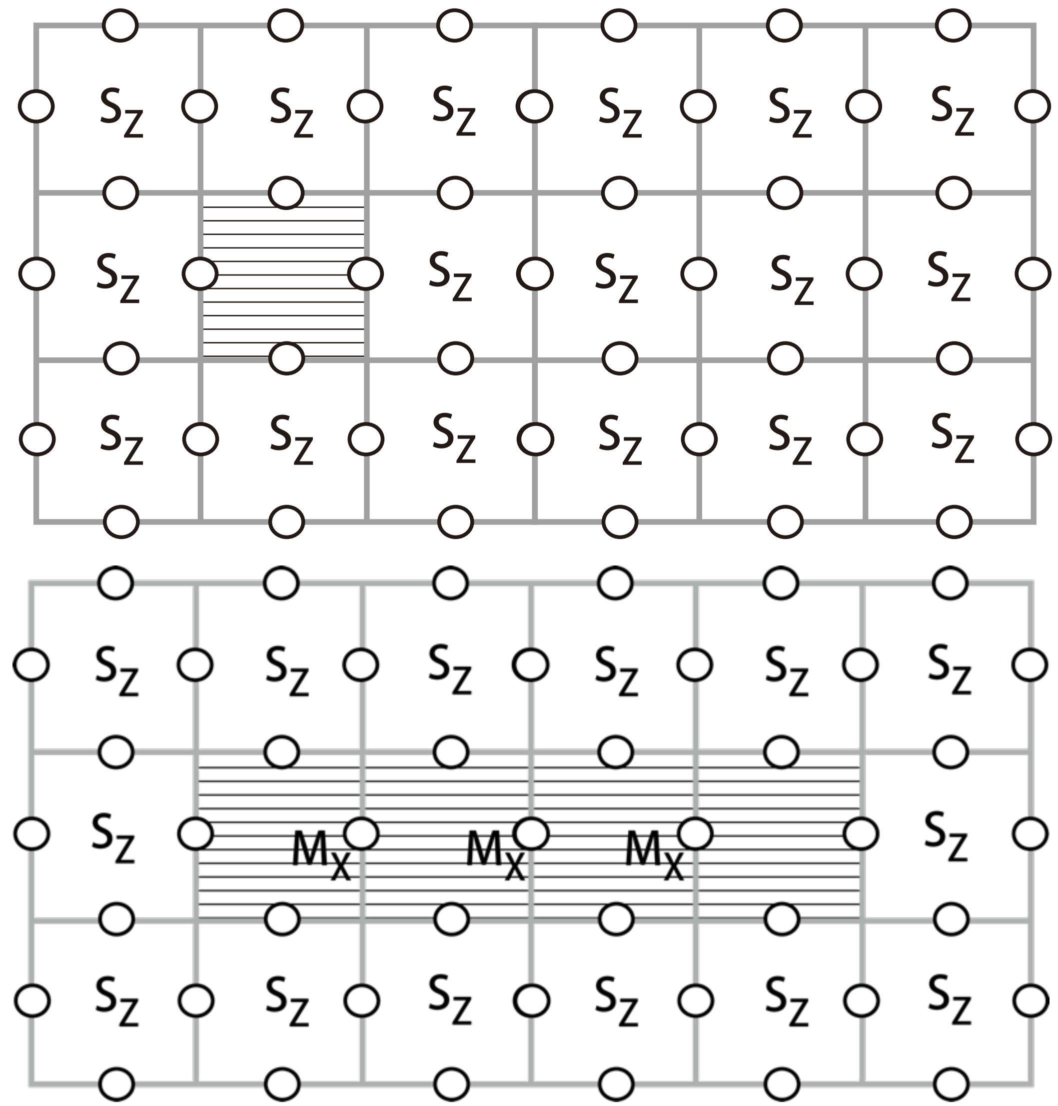


- Can make a different type of qubit
- X_L and Z_L reversed
- Primal and dual lattice

Moving holes



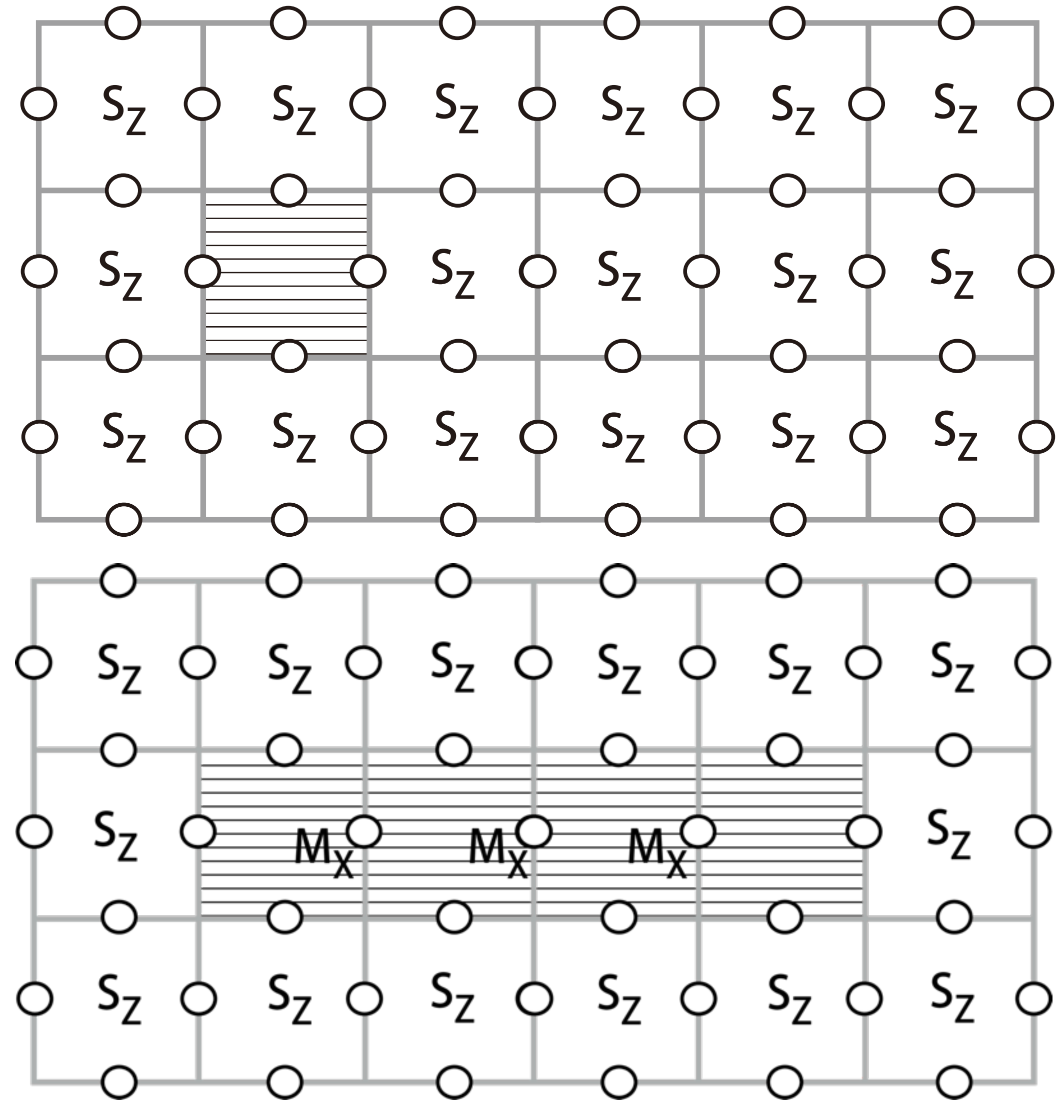
Moving holes



- First, expand hole using measurements and stop measuring stabilizers

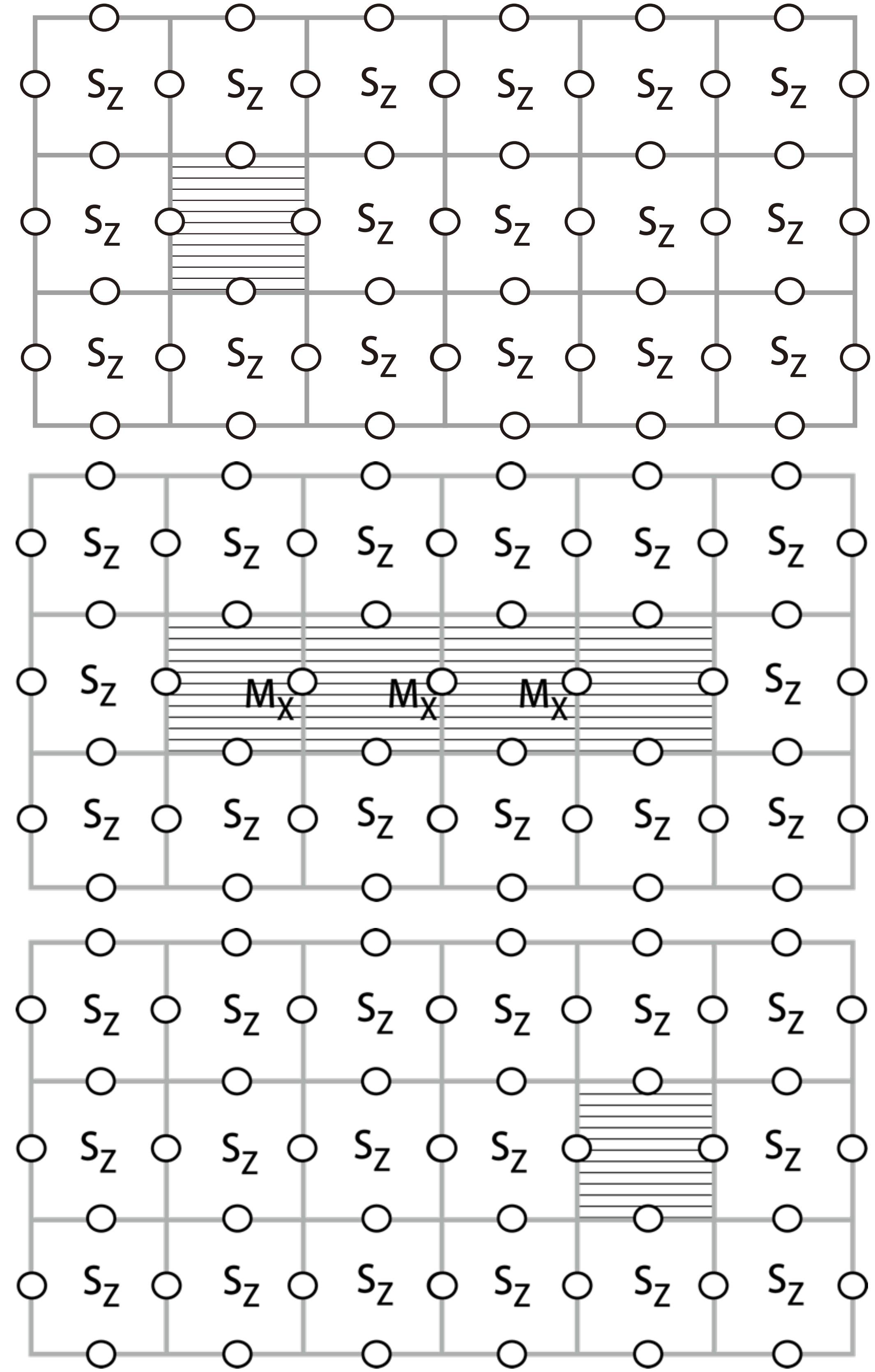
Moving holes

- First, expand hole using measurements and stop measuring stabilizers
- Fix up w/ bit flips (takes multiple rounds, depending on distance)

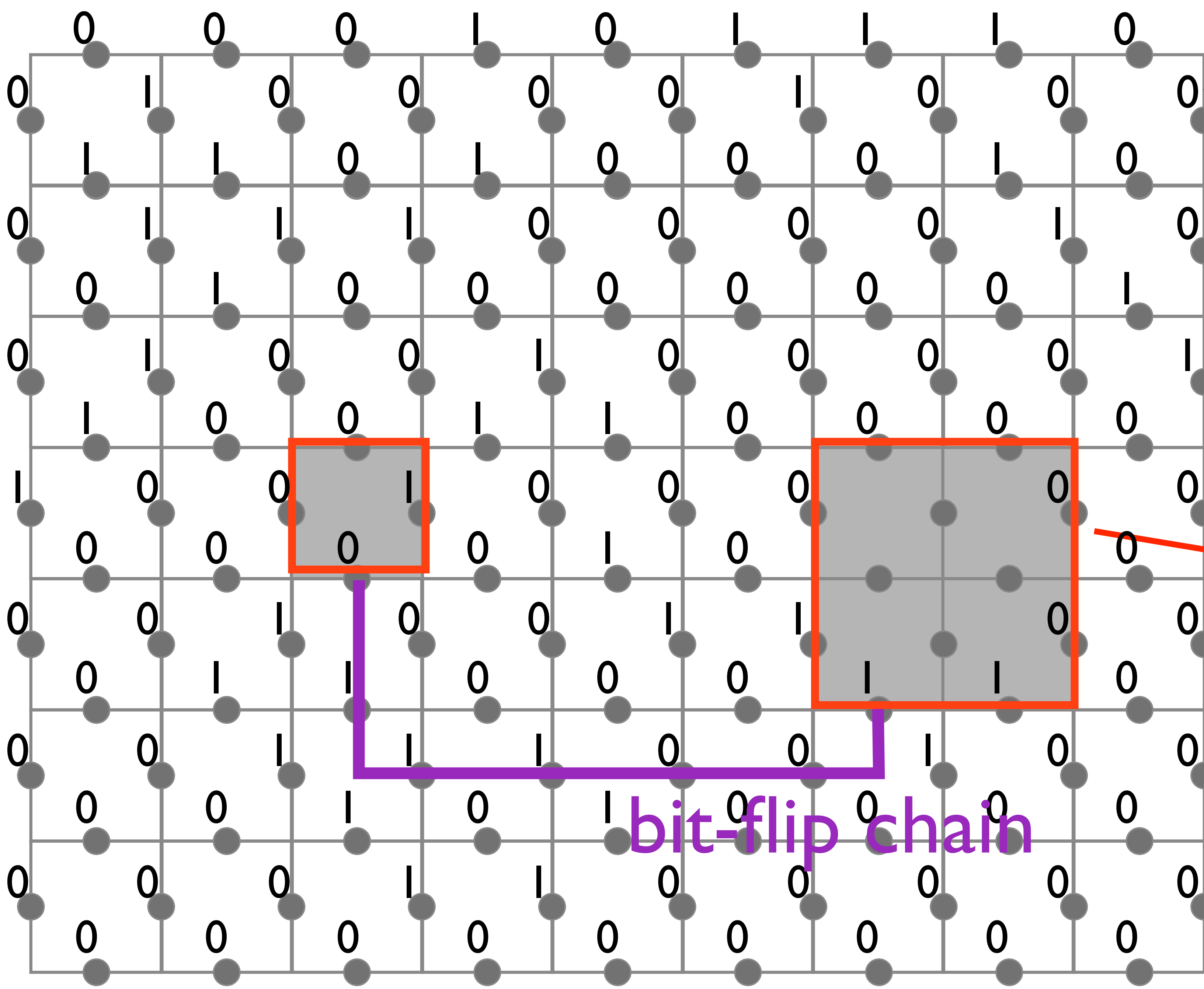


Moving holes

- First, expand hole using measurements and stop measuring stabilizers
- Fix up w/ bit flips (takes multiple rounds, depending on distance)
- Shrink hole to new location



Simplest Example
~NOT gate operation~



measured eigenvalue

data qubit

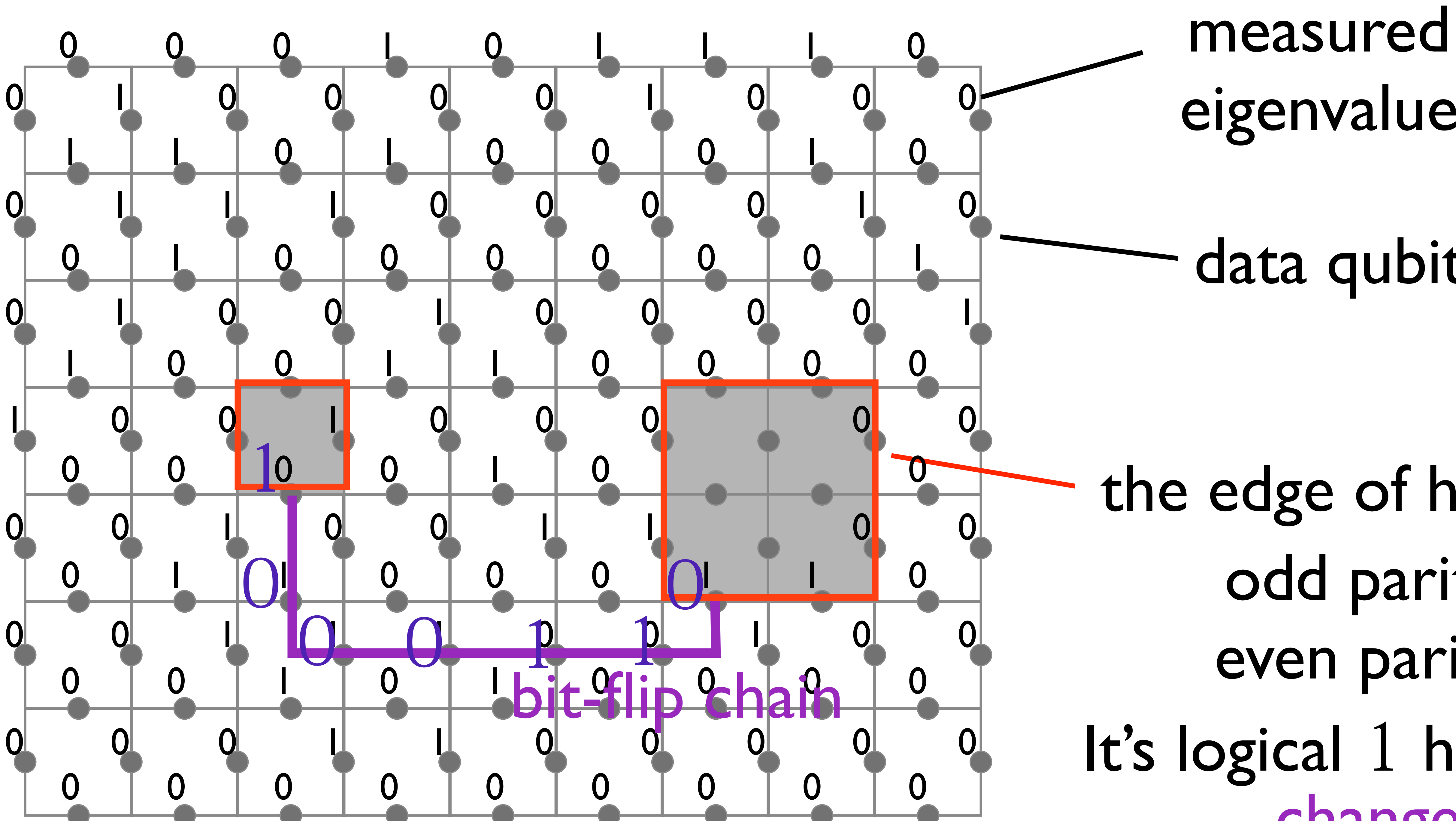
the edge of hole

odd parity: 0

even parity: 1

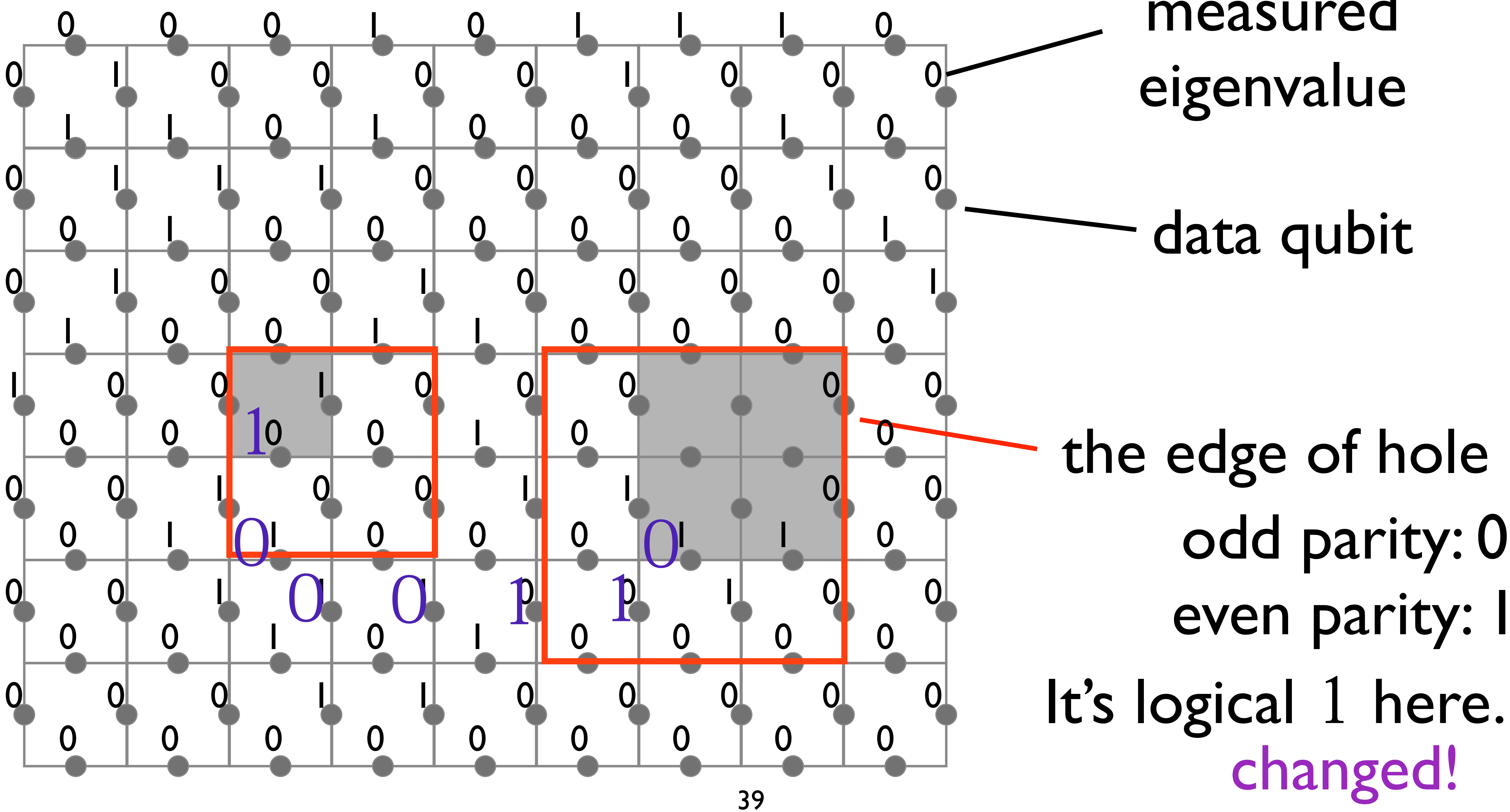
It's logical 0 here.

Simplest Example
~NOT gate operation~



odd parity: 0
even parity: 1
It's logical 1 here.
changed!

Simplest Example
~NOT gate operation~



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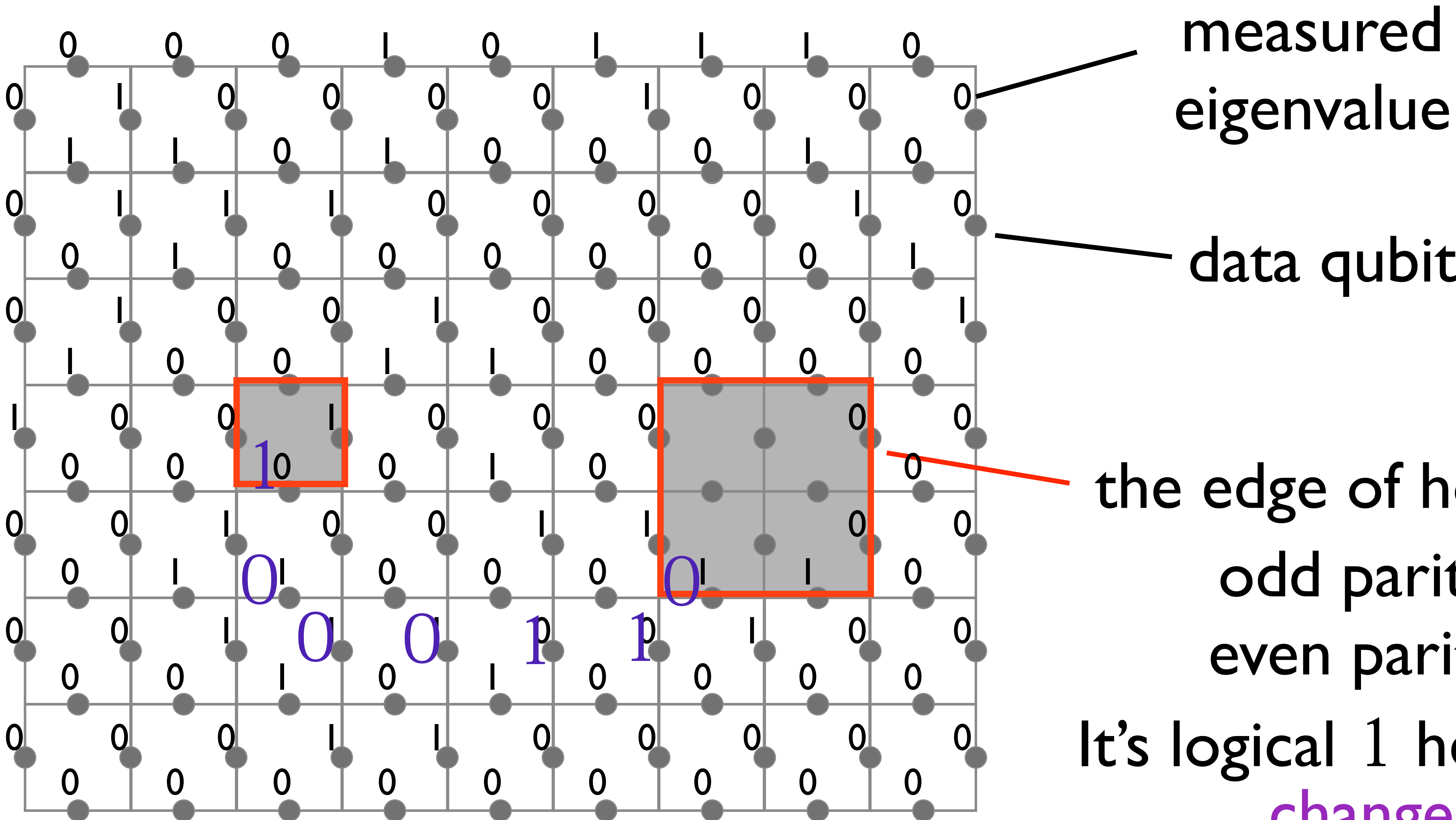

odd parity: 0

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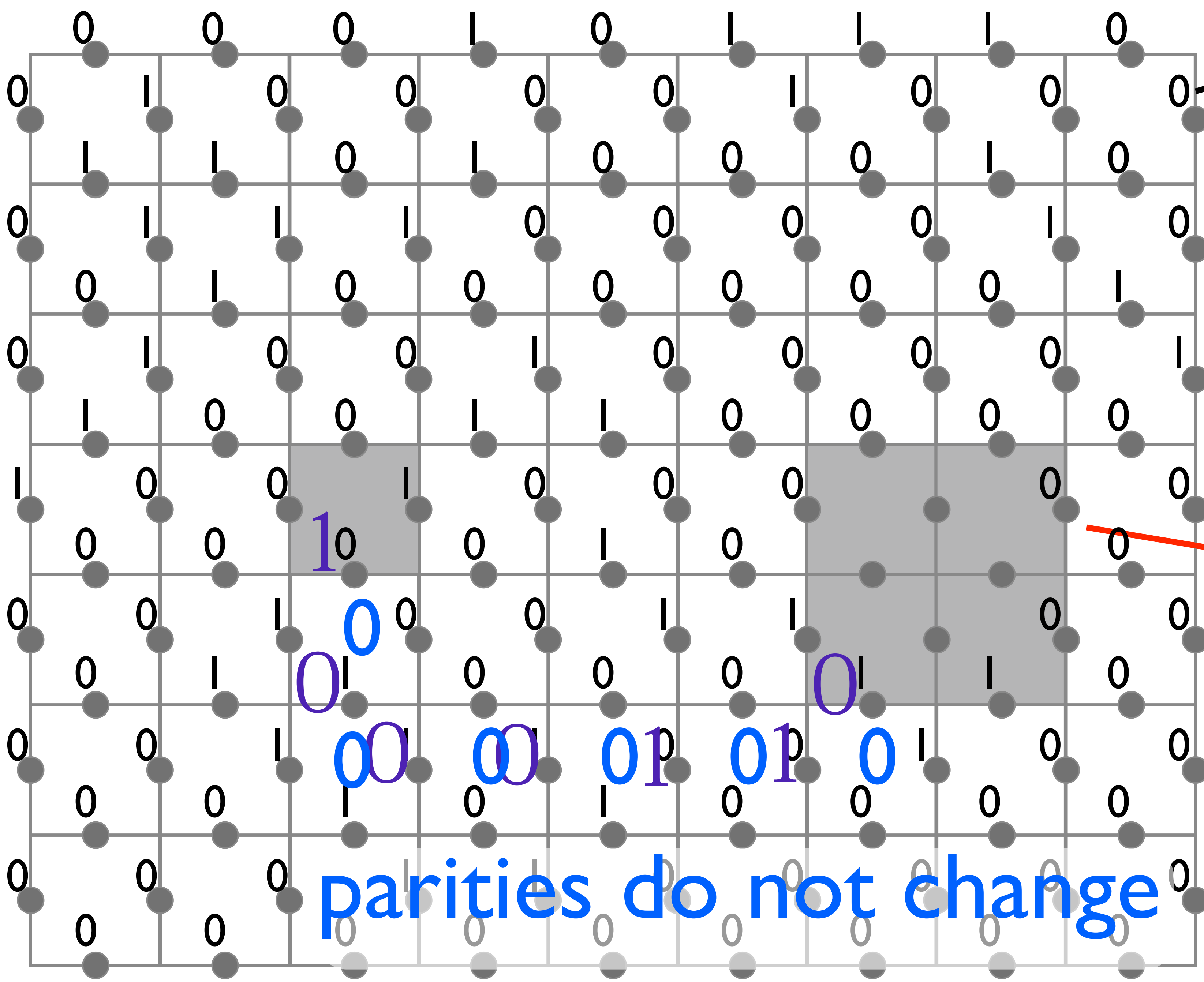
Simplest Example
~NOT gate operation~



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It's logical 1 here.

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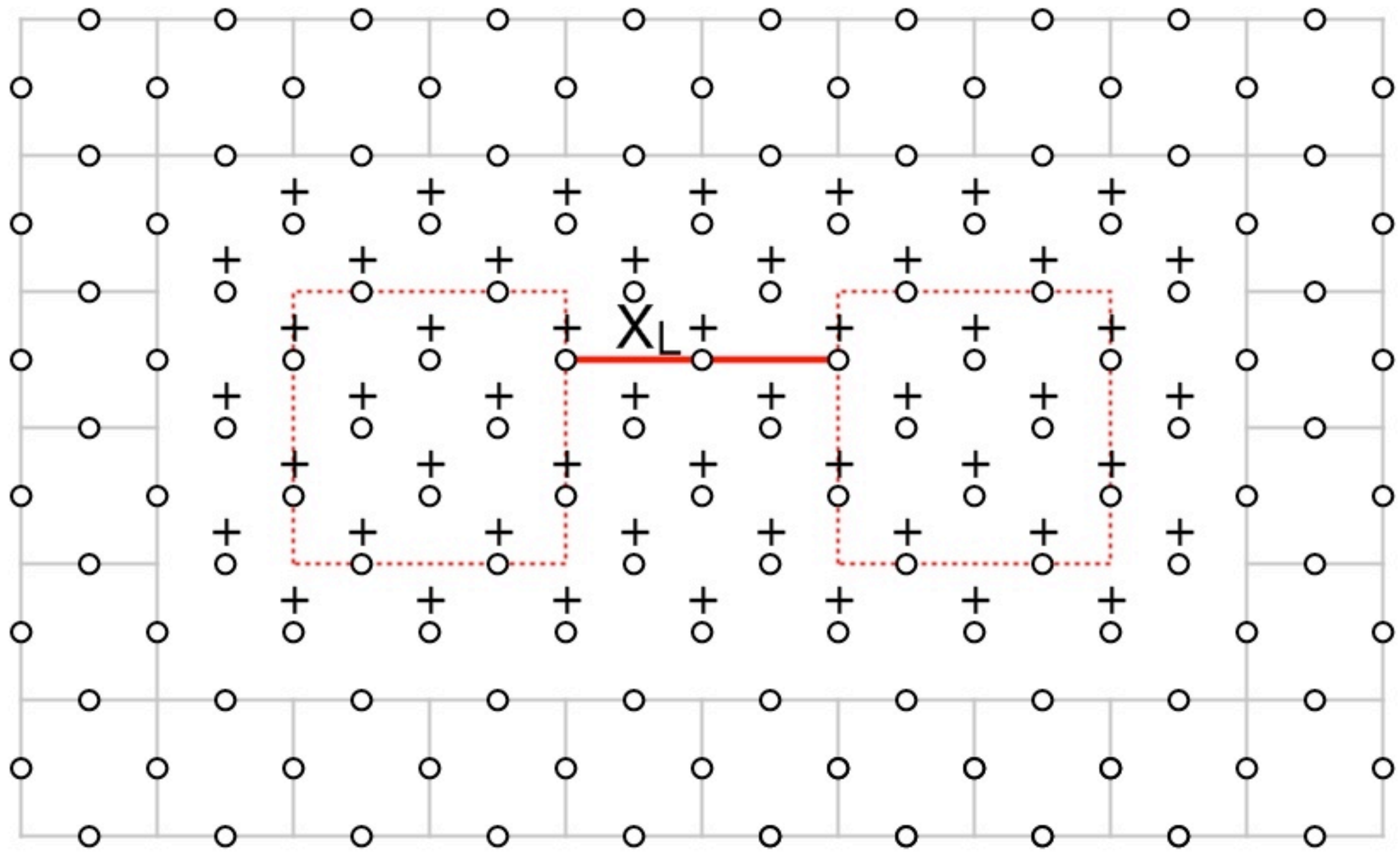
Initializing logical qubits



- Start with region of $|+\rangle$
- Smooth qubit in ±1 eigenstate of X_L
- Measure Z stabilizers

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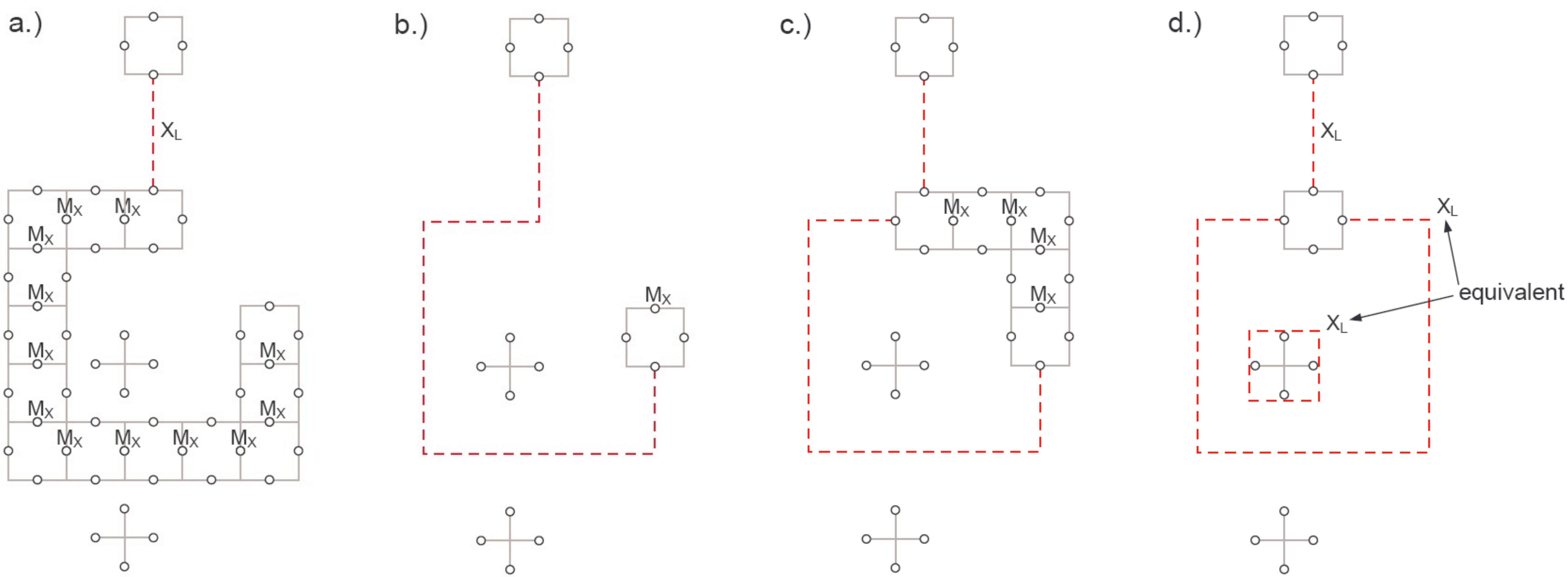
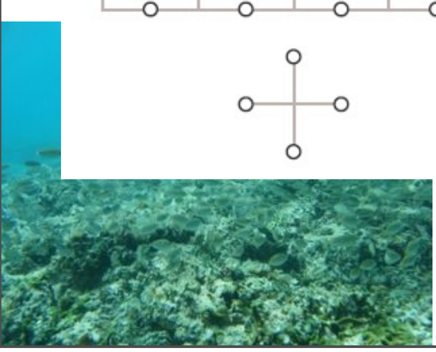
Braiding a CNOT

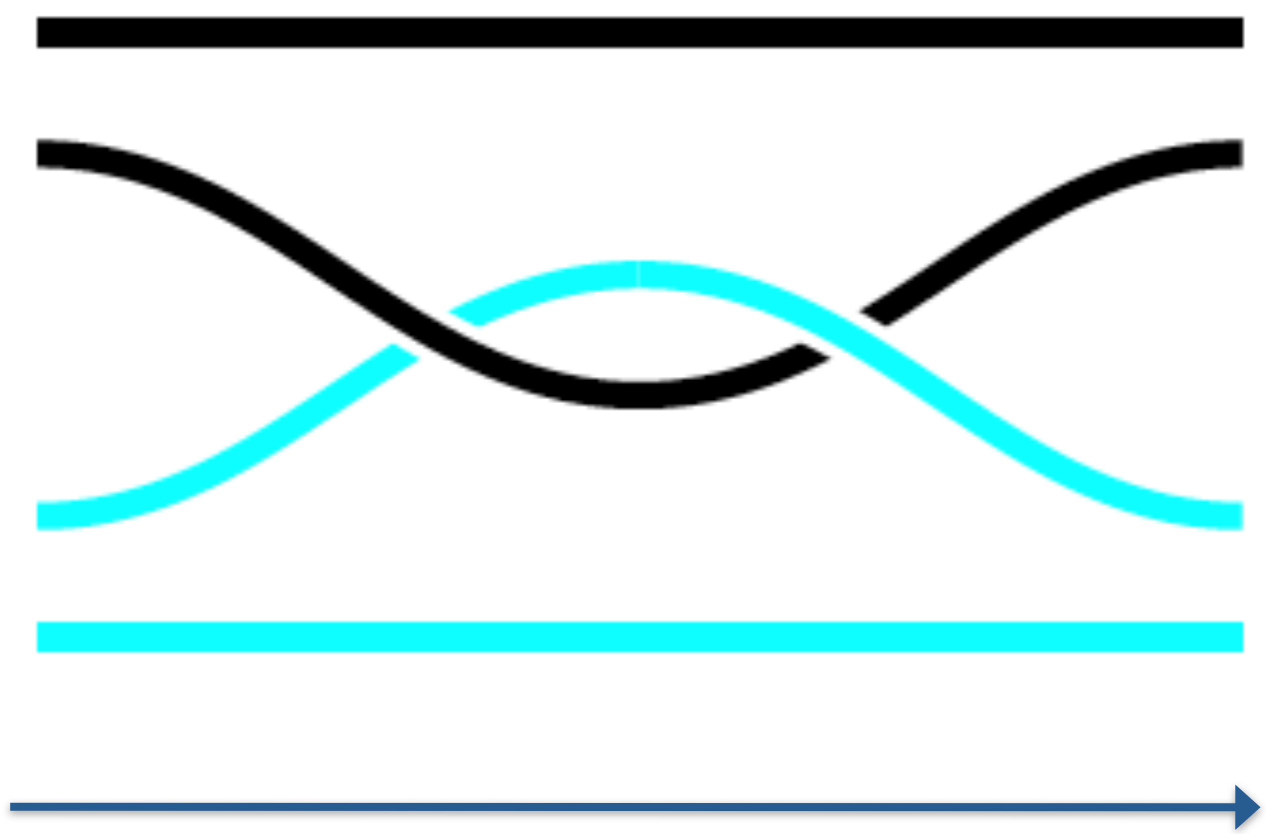
- Braiding smooth pair with rough pair gives CNOT

  (WHY? Stay tuned...)





Braiding: 2D+T Picture



} dual qubit.

(Rough holes)

} primal qubit.

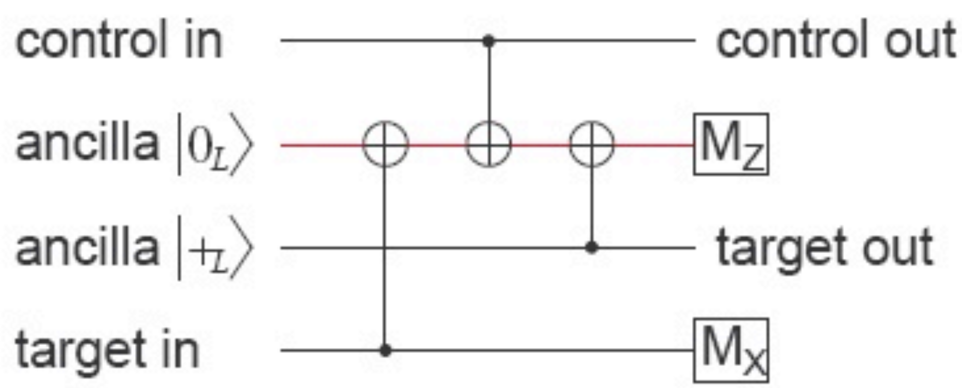
(Smooth holes)

Time

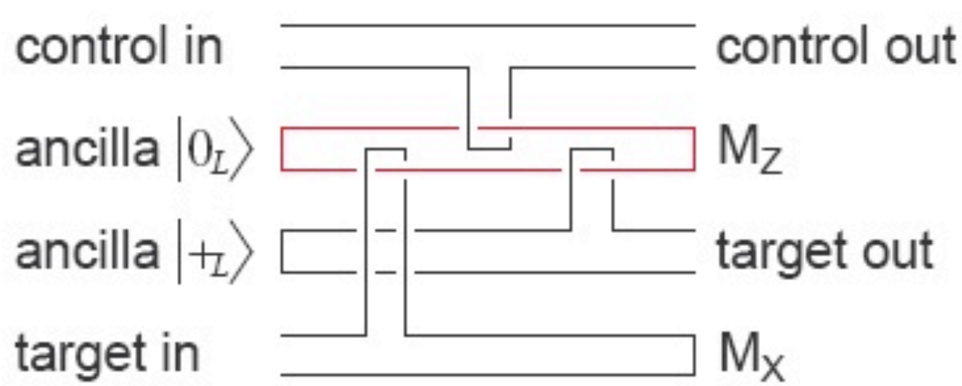
picture from Raussendorf et al., NJP 9, 2007

Smooth-smooth CNOT

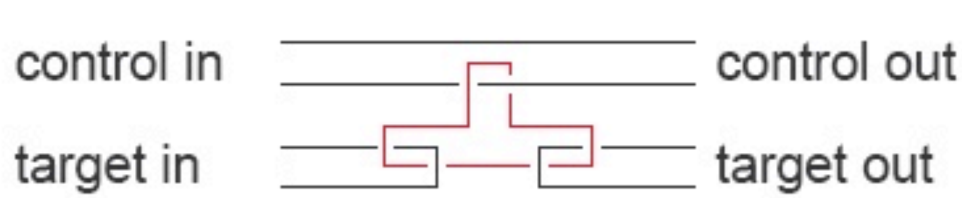
- Circuit is equivalent to CNOT followed by $(Z \otimes Z)^{M_X}$ followed by $(X_t)^{M_Z}$



- Circuit can be represented as a braiding of defects



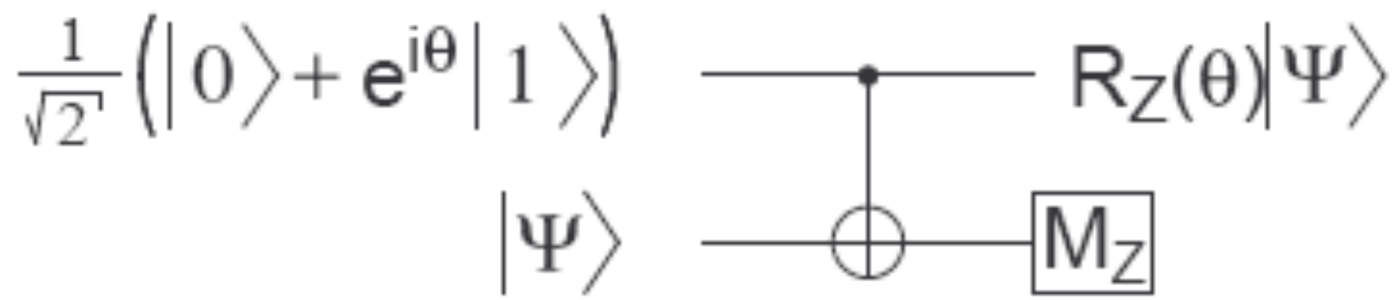
- Equivalent more compact braiding



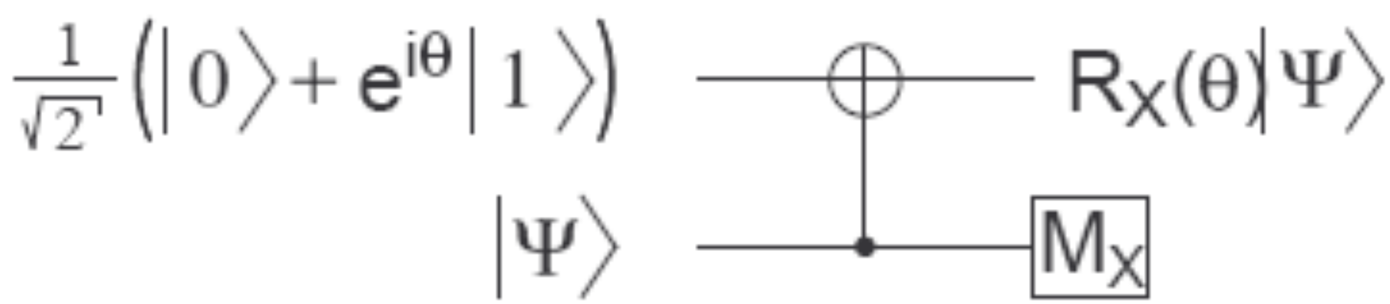
Non-Clifford gates

- We can prepare states $|0_L\rangle$, $|1_L\rangle$, $|+_L\rangle$ and $|-_L\rangle$
- We can perform gates X_L, Z_L, M_X, M_Z and CNOT
- Not universal without the following:

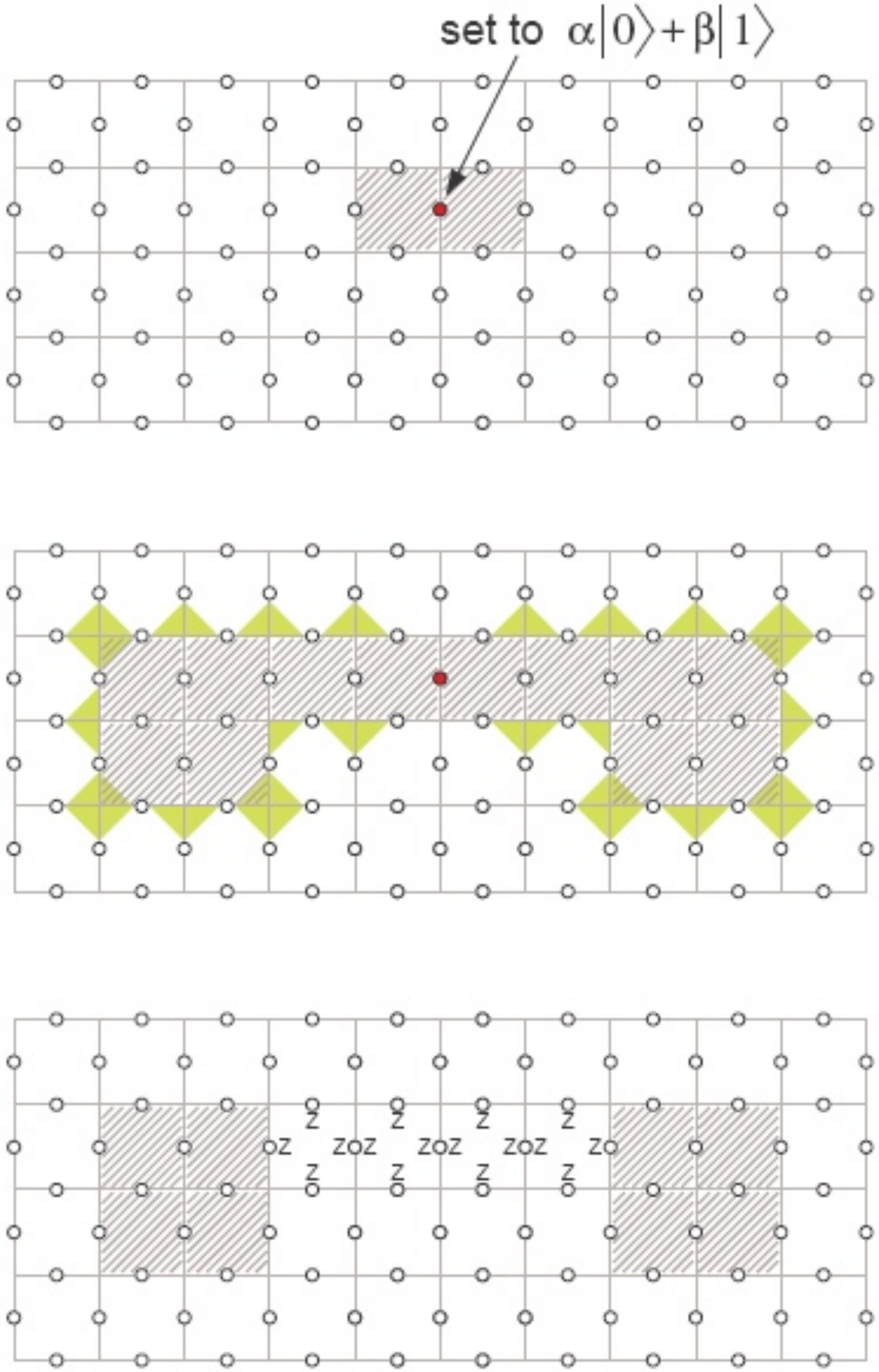
a.)



b.)



State injection

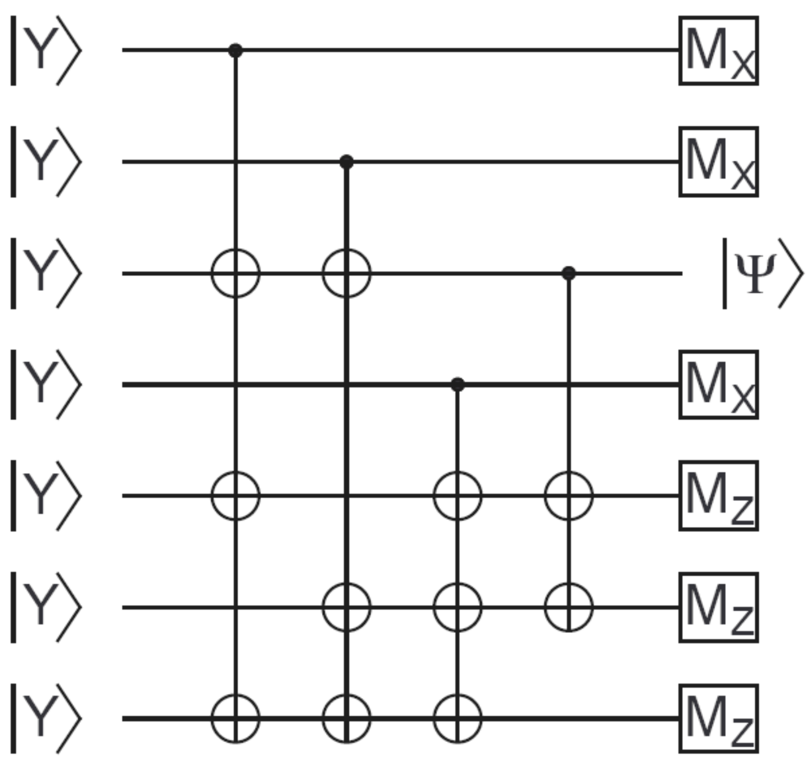


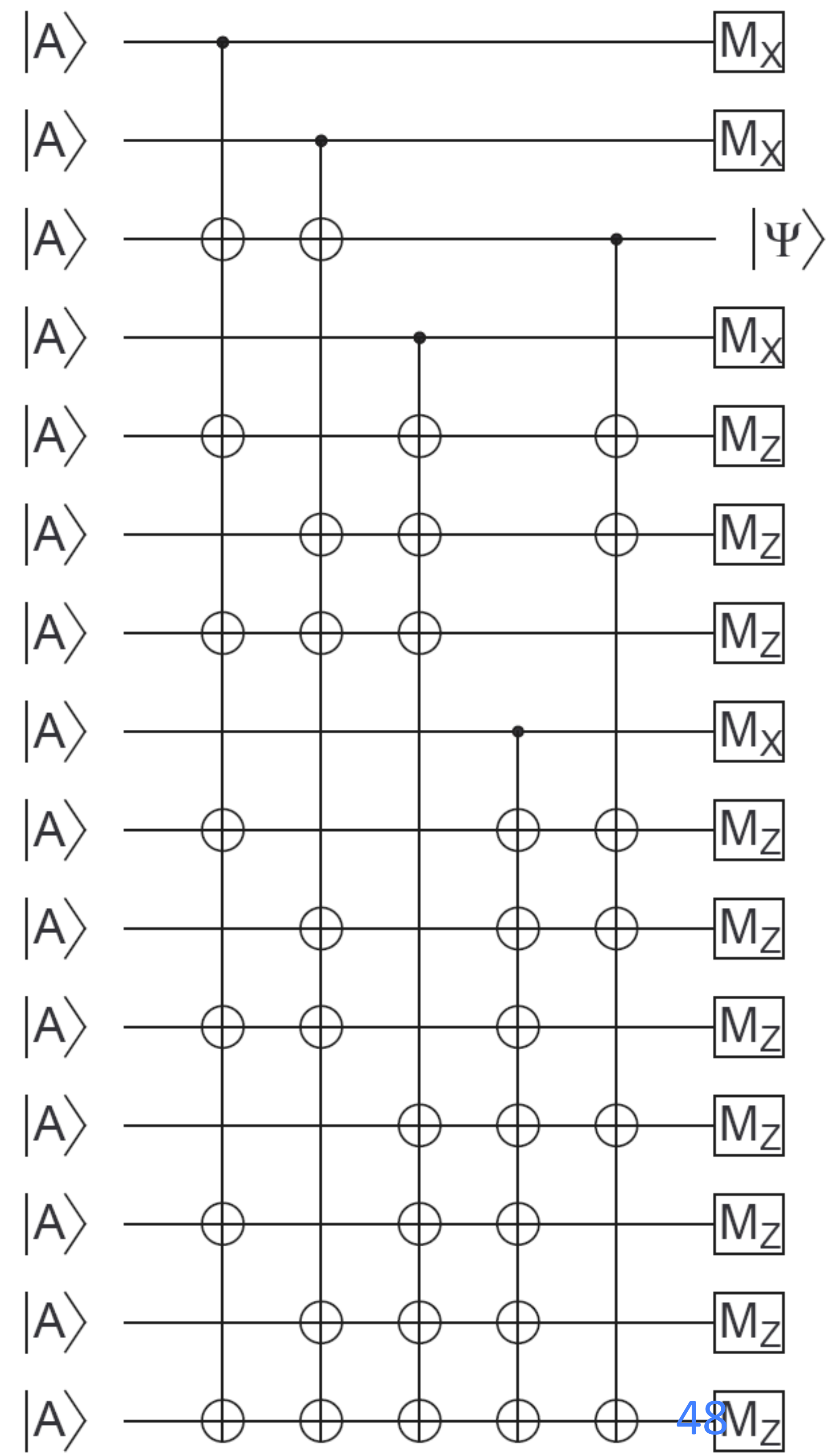
- Set a single qubit to desired state $\alpha|0\rangle + \beta|1\rangle$ (M_Z then rotate)
- Increase size of defects using X measurements
- Separate defects by measuring and correcting Z stabilizes
- Procedure is not fault-tolerant, restart if errors detected early
- Logical state will not be perfect $\alpha|0\rangle + \beta|1\rangle$, however...

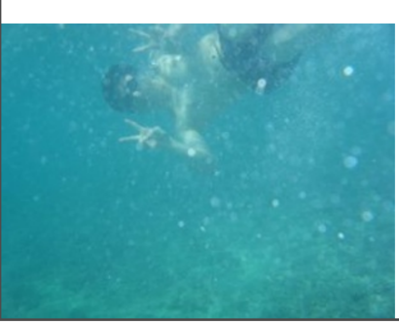
Aqua : Advancing Quantum Architecture

State distillation: “Singular factories”

- Two very special states exist $|Y\rangle = \frac{1}{\sqrt{2}}(|0\rangle + i|1\rangle)$ and $|A\rangle = \frac{1}{\sqrt{2}}(|0\rangle + e^{i\pi/4}|1\rangle)$
- These states can be “distilled”
- Imperfect $|Y\rangle$ and $|A\rangle$ states approach perfect versions exponentially quickly
- Probability of success asymptotically close to 1, though some byproduct operators needed







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Universality

- Adding these states:

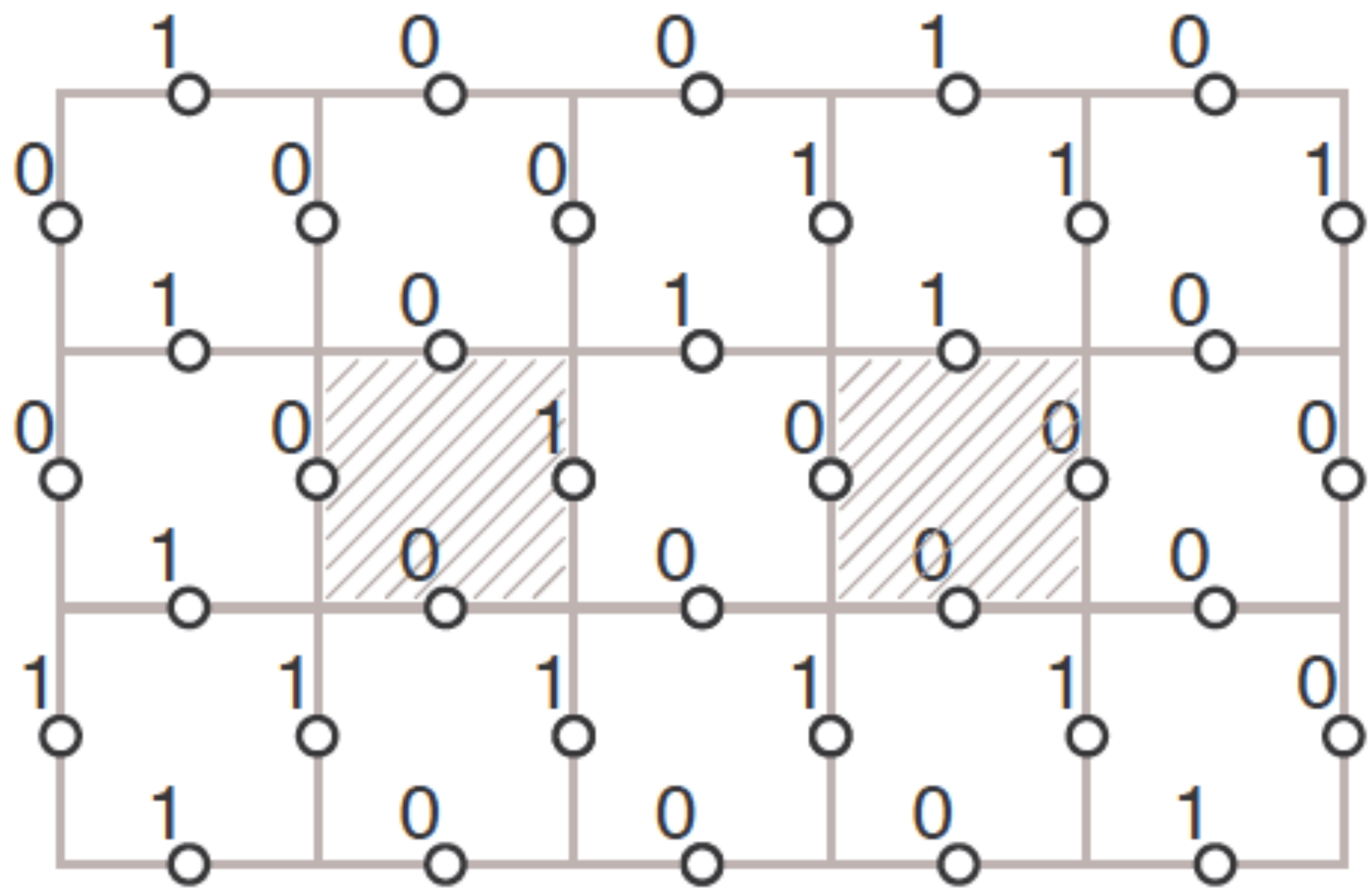
$$|Y\rangle := (|0\rangle + \mathrm{i}|1\rangle)/\sqrt{2}$$

$$|A\rangle := (|0\rangle + \mathrm{e}^{\mathrm{i}\pi/4}|1\rangle)/\sqrt{2}$$

gives us *probabilistic, heralded* universality

- Logical Toffoli gate consumes 7 $|Y\rangle$ and 4.5 $|A\rangle$ states (average)
- Distillation of enough states for *one* Toffoli gate ~1800 singular qubits + braidings (certain assumptions, not detailed here)

Measuring a Qubit



- Measure region in Z (or X) basis
- Every ring around either defect odd parity, state is 1
- Majority vote when not all same

CALTECH

CALIFORNIA INSTITUTE OF TECHNOLOGY 1891

USC Viterbi School of Engineering

USC UNIVERSITY OF SOUTHERN CALIFORNIA

KEIO UNIVERSITY 1858 CALAMVS GLADIO FORTIOR

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自己紹介

ISI
Information Sciences Institute
USC Viterbi School of Engineering

NOKIA
Connecting People

ASACA

ShibaSoku
high quality broadcast and video equipment

MOSIS

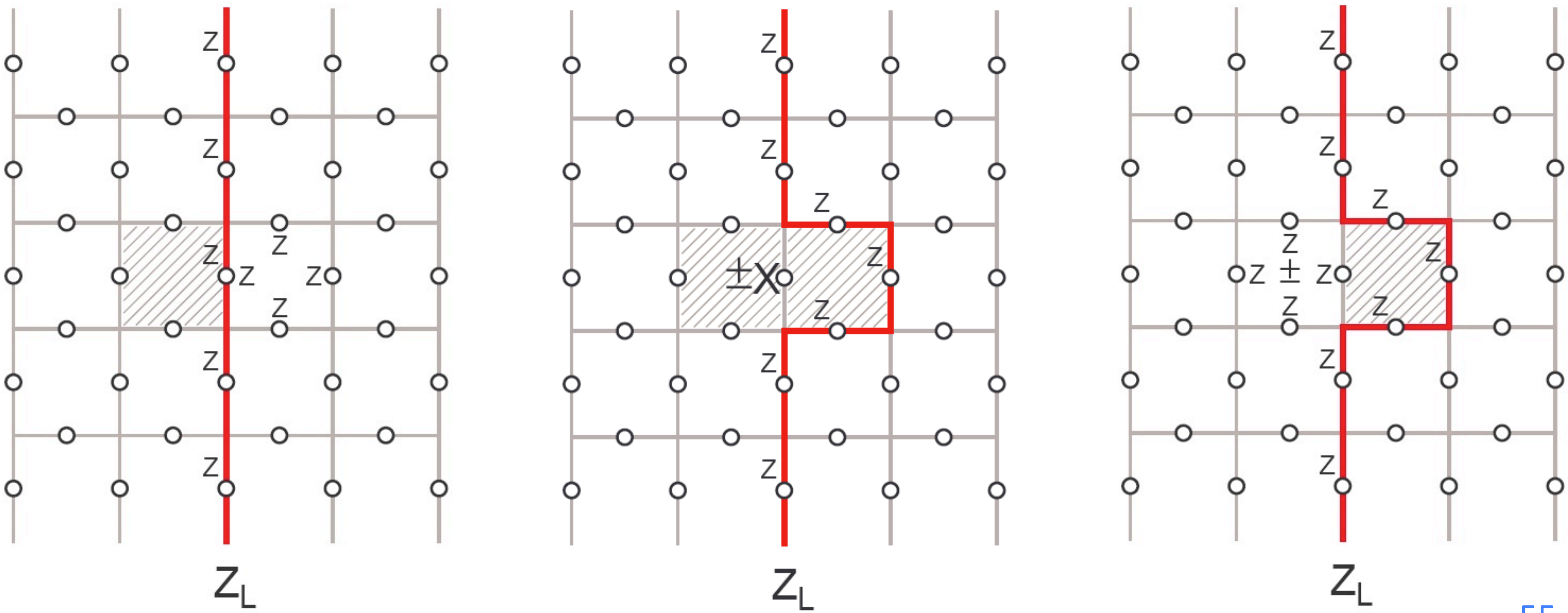
Quantum.

Theory

- Why braiding works
- Code distance
- Estimating logical error rate

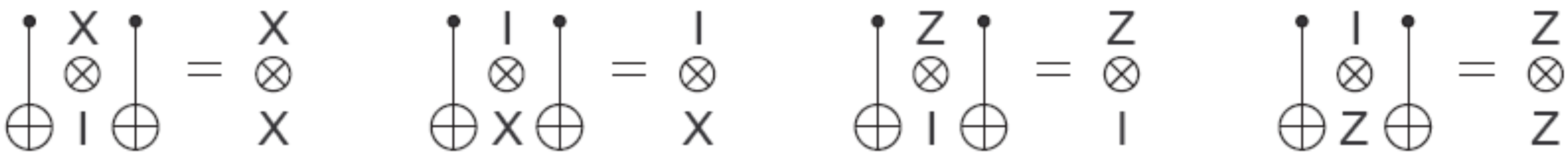
CNOT: moving defects

- Start with surface $|\Psi\rangle$ satisfying $Z_L|\Psi\rangle = |\Psi\rangle$ and Z_{face}
- Measure center qubit in the X basis to produce $|\Psi'\rangle$
- Surface $|\Psi'\rangle$ satisfies $Z_L Z_{\text{face}}|\Psi'\rangle = |\Psi'\rangle$ and $\pm X|\Psi'\rangle = |\Psi'\rangle$

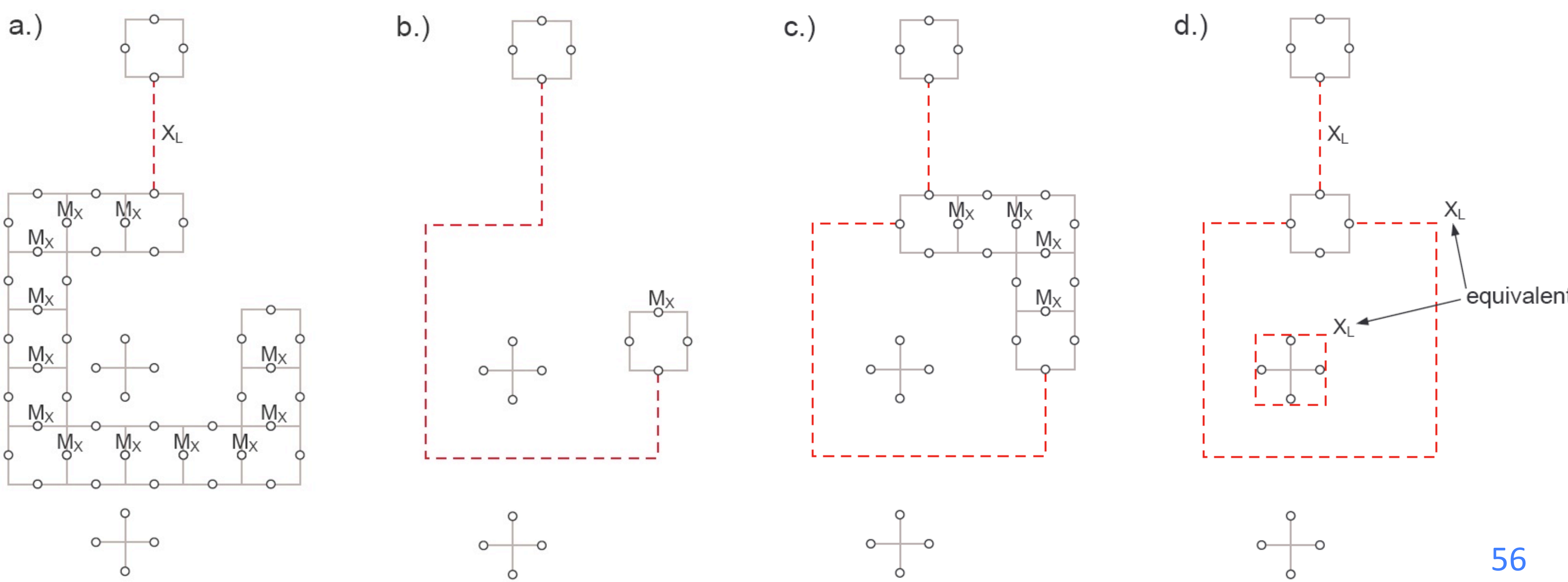


CNOT: $X \otimes I \rightarrow X \otimes X$

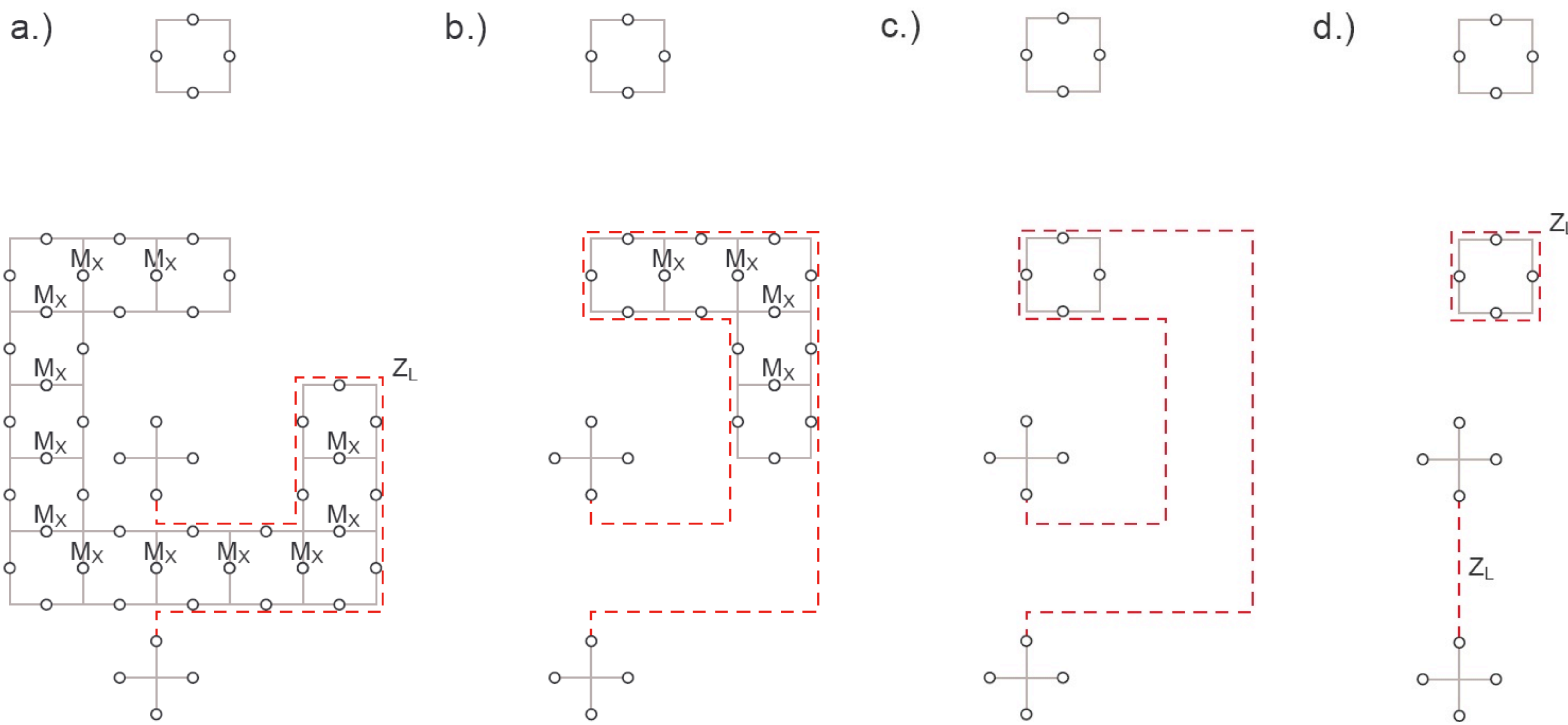
- If $M|\psi\rangle = |\psi\rangle$, then $U|\psi\rangle = UMU^{\dagger}U|\psi\rangle \Rightarrow M \rightarrow UMU^{\dagger}$
- CNOT manipulates stabilizers in the following manner:



- Need to show we can do this by braiding defects



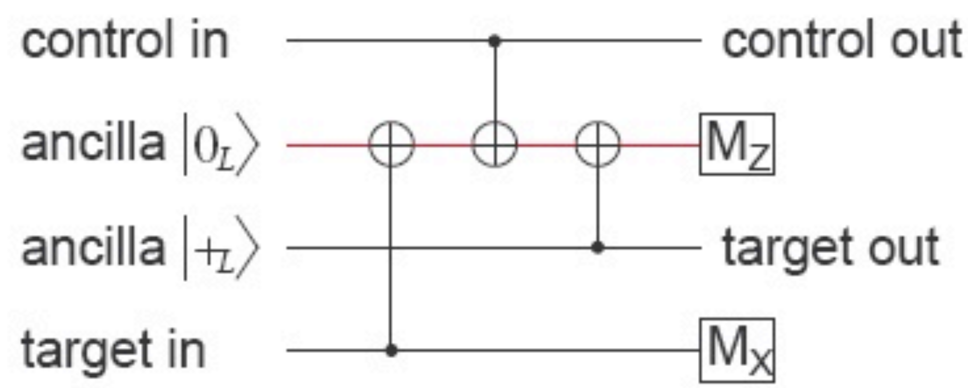
CNOT: $I \otimes Z \rightarrow Z \otimes Z$



- Mappings $I \otimes X \rightarrow I \otimes X$ and $Z \otimes I \rightarrow Z \otimes I$ also easy to show
- Defects can be interacted over arbitrary distances in almost constant time
- Still need CNOT between two smooth qubits

Smooth-smooth CNOT

- Circuit is equivalent to CNOT followed by $(Z \otimes Z)^{M_X}$ followed by $(X_t)^{M_Z}$



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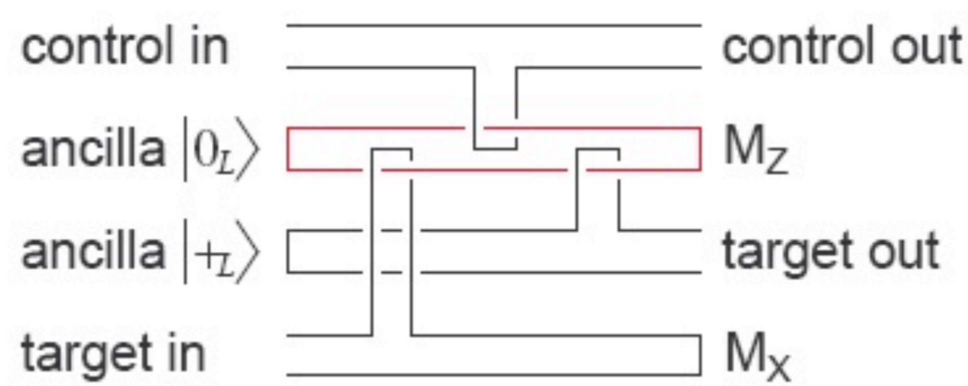

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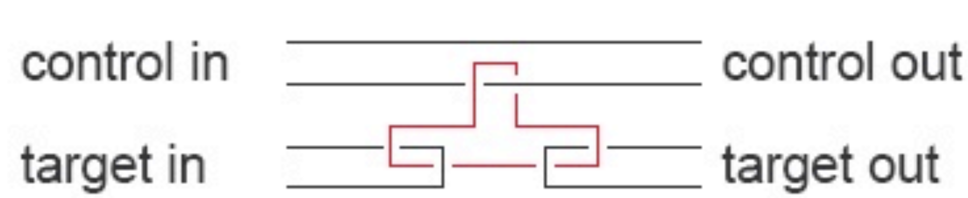

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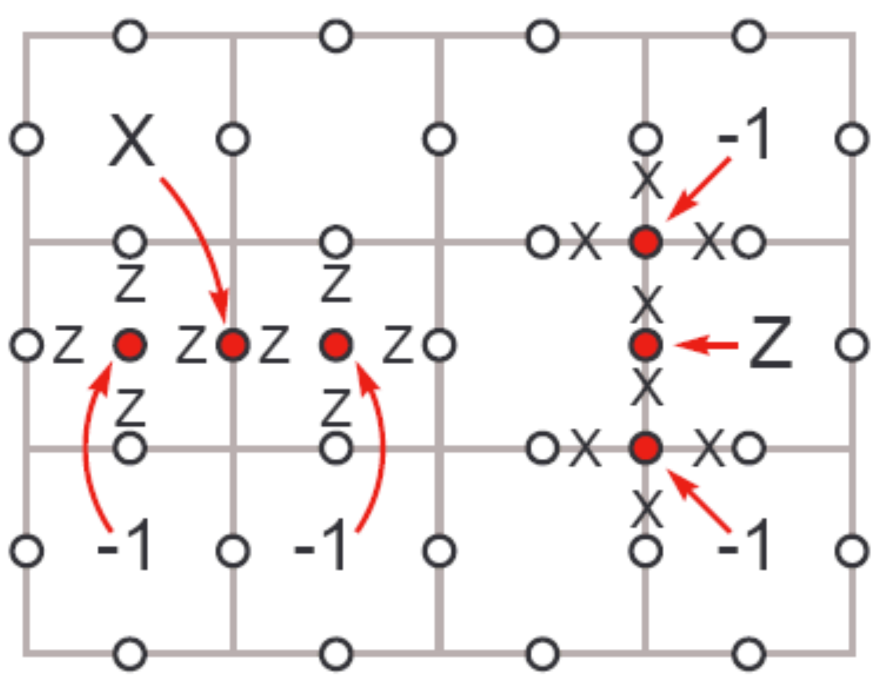
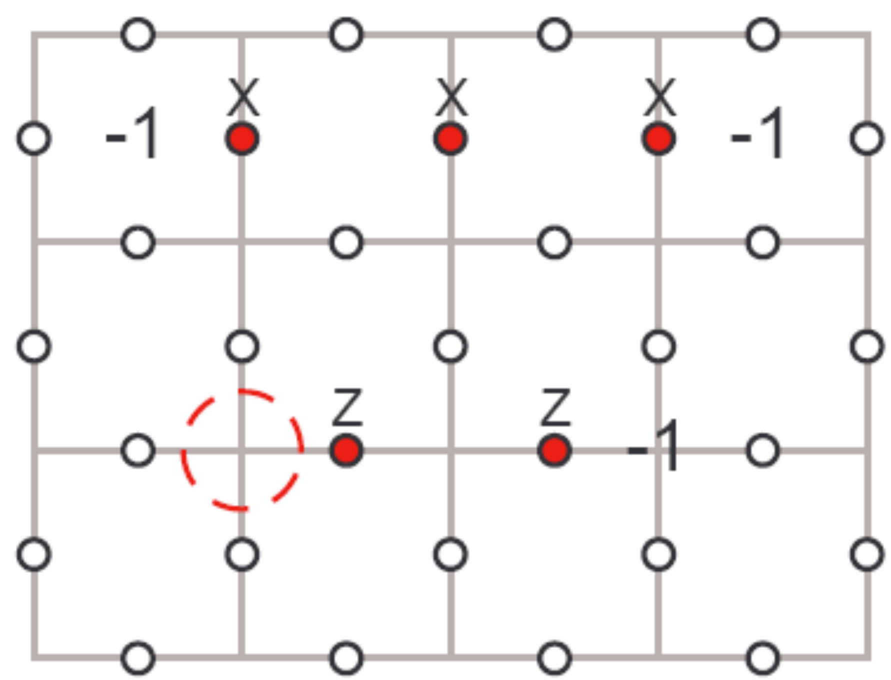
Error correction

- All error correction based on $XZ = -ZX$, eg:

$$Z_1 Z_2 Z_3 Z_4 |\psi\rangle = |\psi\rangle$$
$$Z_1 Z_2 Z_3 Z_4 X_1 |\psi\rangle = -X_1 Z_1 Z_2 Z_3 Z_4 |\psi\rangle = -X_1 |\psi\rangle$$

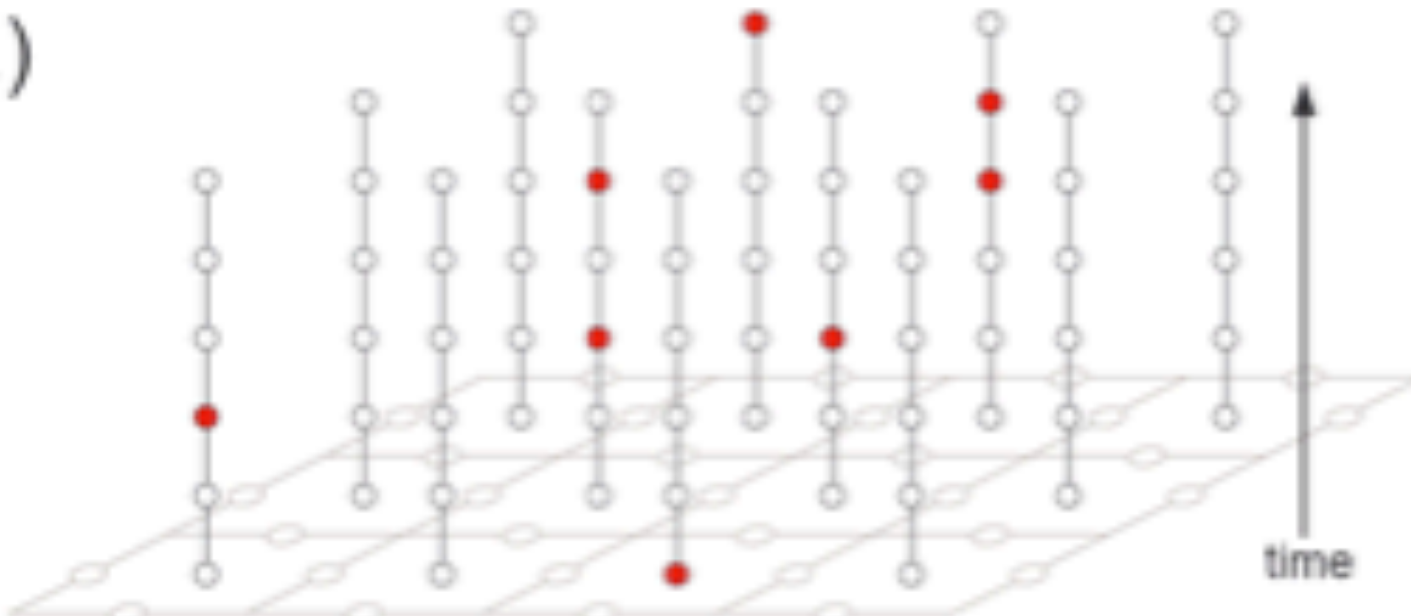




Need to carefully handle false syndromes and error chains

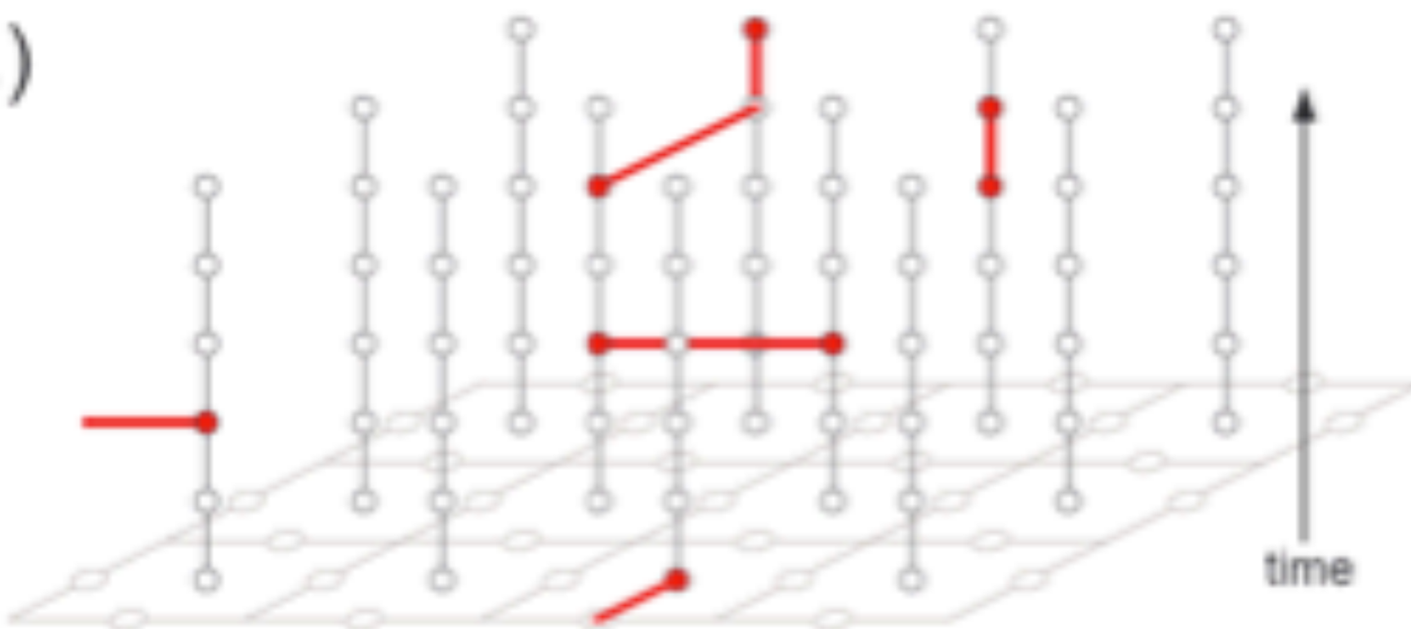
Error correction

a.)

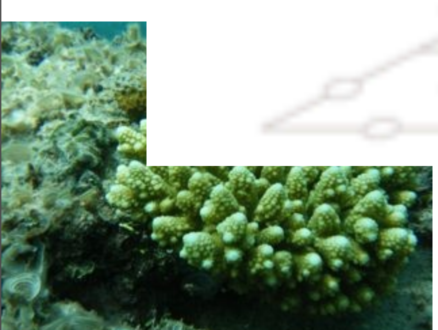


- Record time and position of changed syndromes

b.)

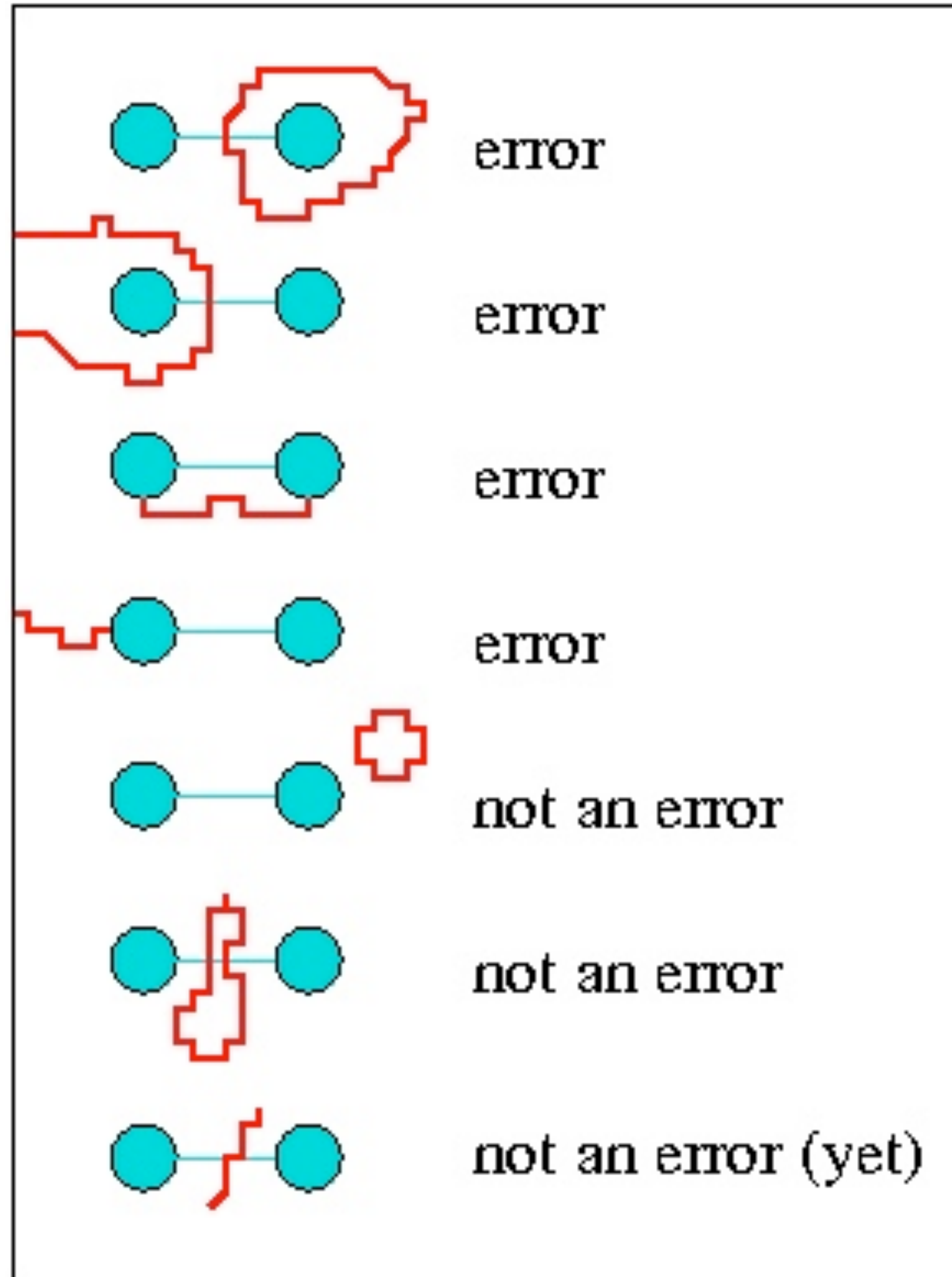


- Match closest pairs
- Apply corrective operations to spacelike edges
- Works *very* well, threshold error rate ~1%



Error Chains and Logical Gates

- Learn only endpoints of error chains
- Guess a path
- Usually (hopefully) results in meaningless loop
- Complete error chain (natural or mis-correct) results in logical X or Z gate



What is error correction?

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  - ➔ Goal of correction is to get back into code space

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  - ➔ Usually move to "closest" logical state

What is error correction?

- To protect against errors, encode a few logical states in larger physical Hilbert space
- Physical errors take the system *out of the code space*
  - ➔ Goal of correction is to get back into code space
- Some measure of "distance" from a legitimate code word (logical state)
  - ➔ Usually move to "closest" logical state
- More than halfway, you mis-correct
  - ➔ Mis-correct equivalent to accidentally executing a logical gate

Threshold

Threshold

- Executing error correction is itself a physical procedure

Threshold

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- EC can introduce errors

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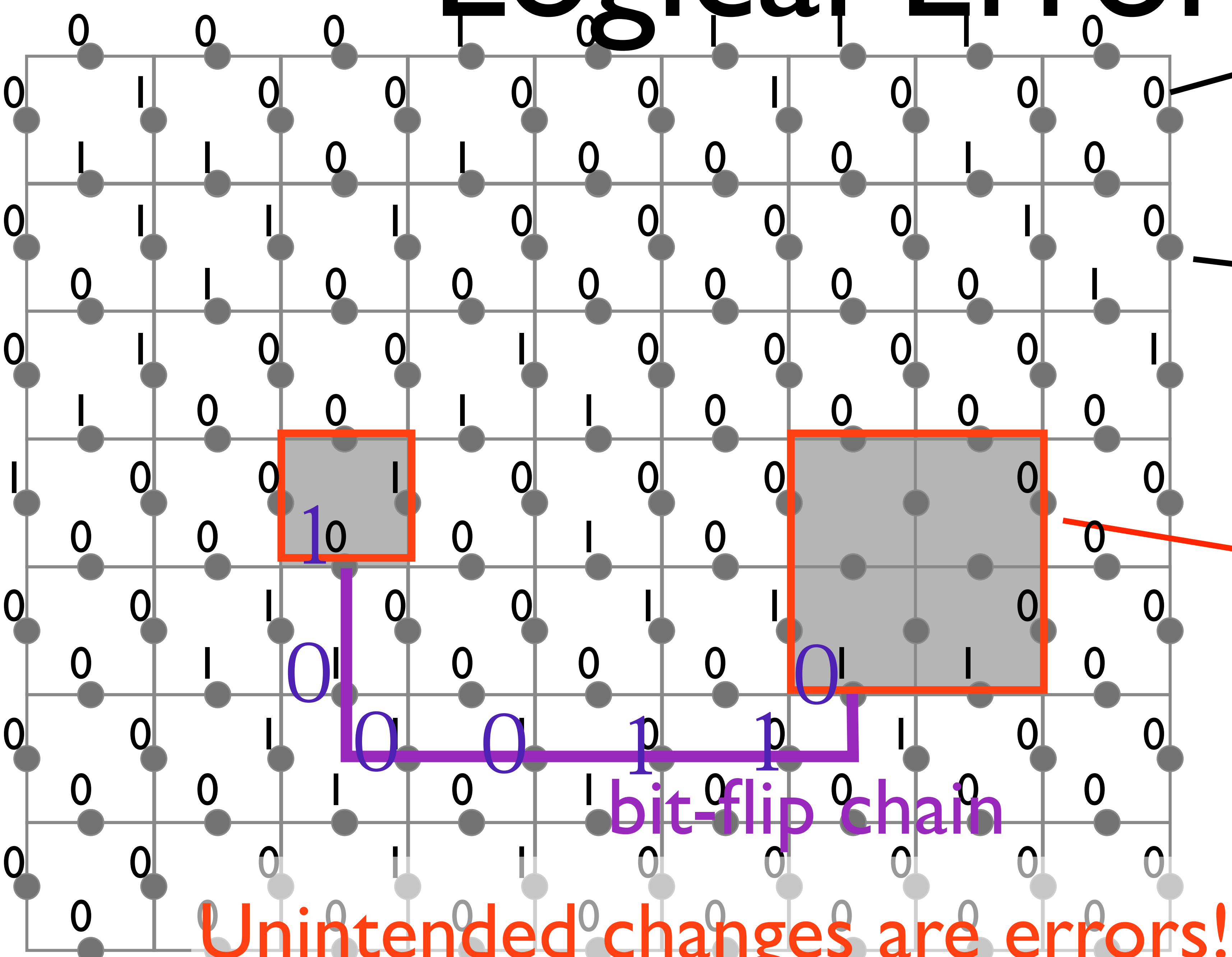
- EC can introduce errors
- *Threshold* is error level at which probability of logical error *declines* if you apply EC
- Most threshold analyses assume gate, memory, measurement errors same probability
- Generally must *beat* threshold by 1-2 orders of magnitude

Simplest Example ~Logical Error~



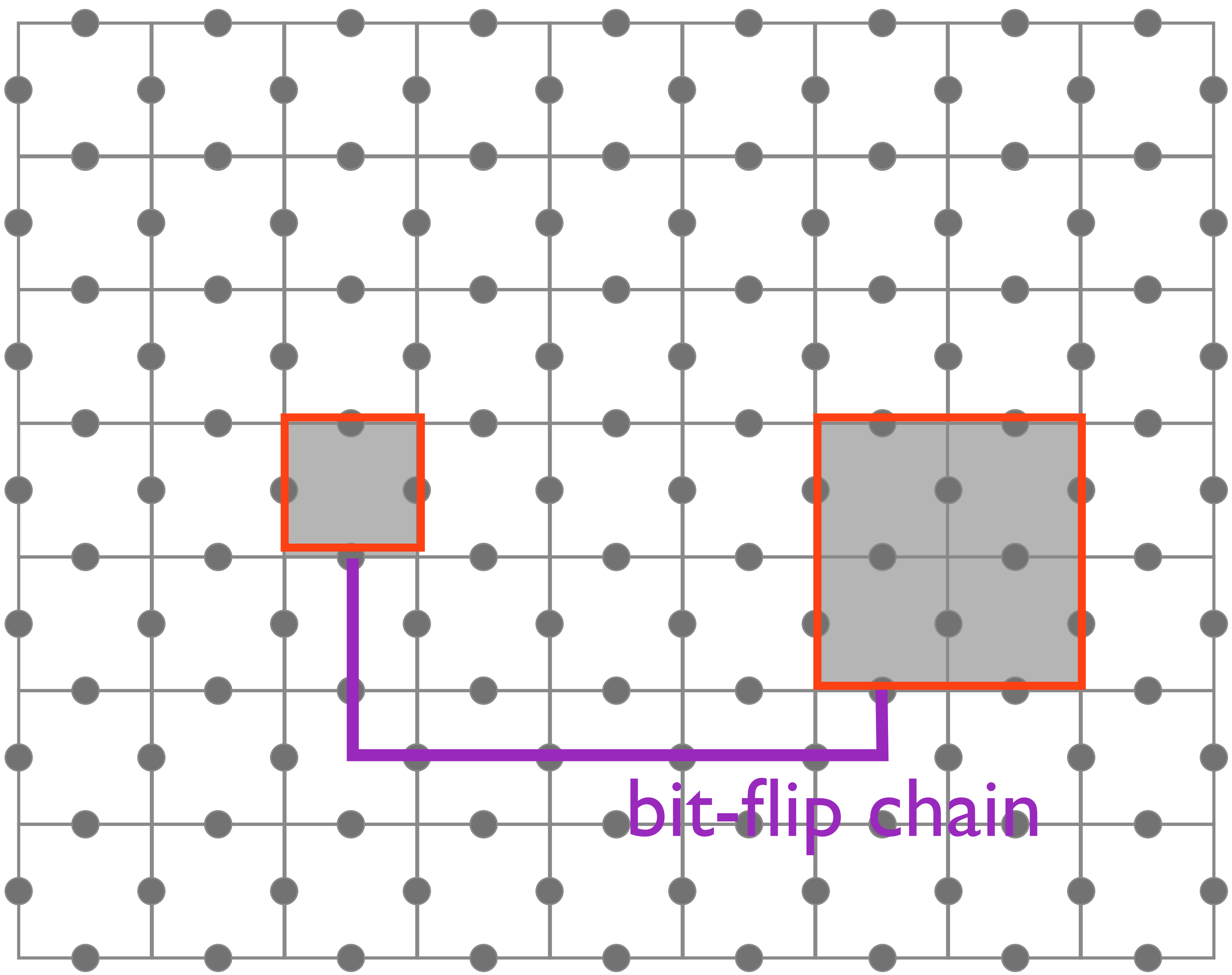
odd parity: 0

even parity: 1

It's logical 1 here.

changed!

Surface Code
~Code distance~



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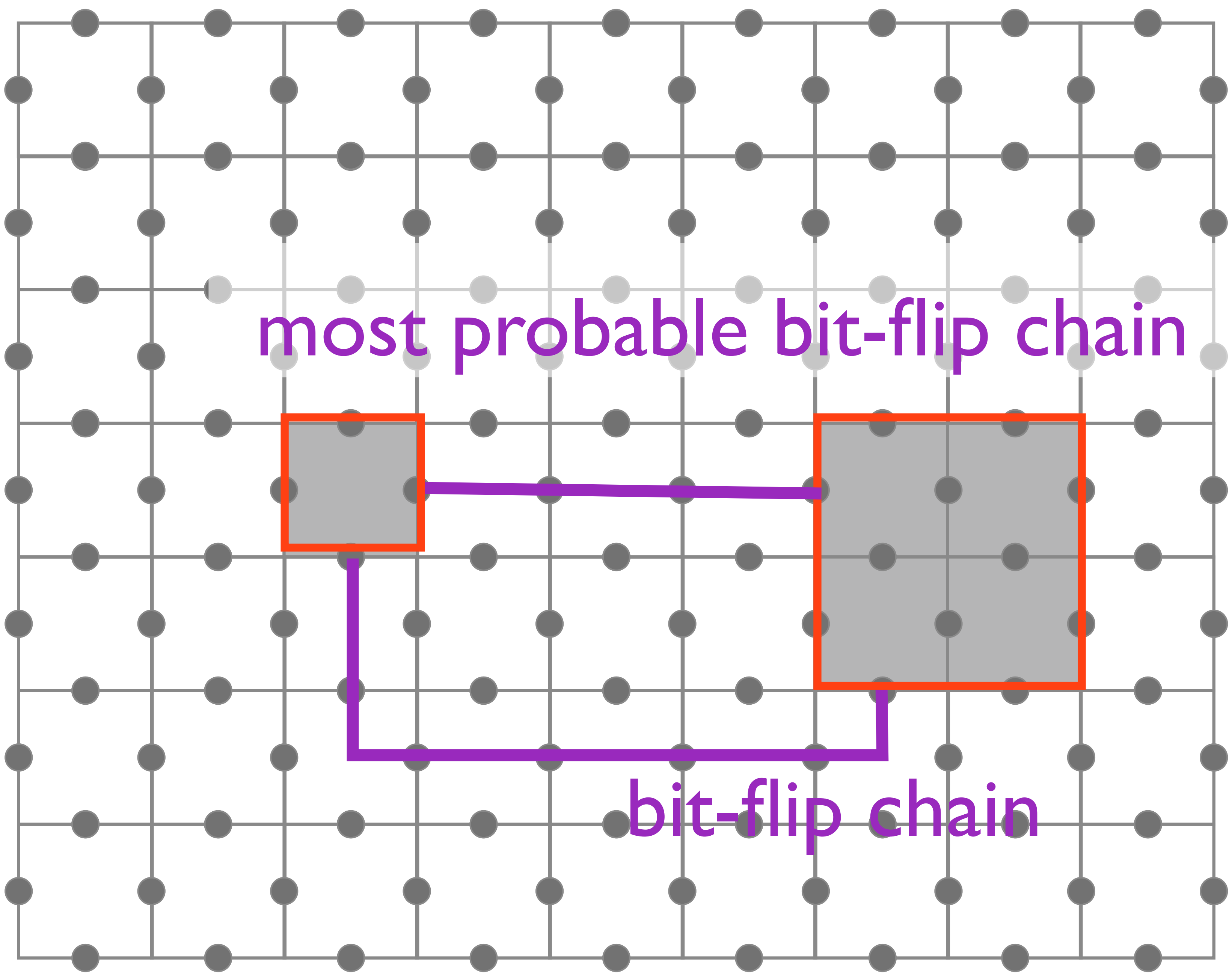

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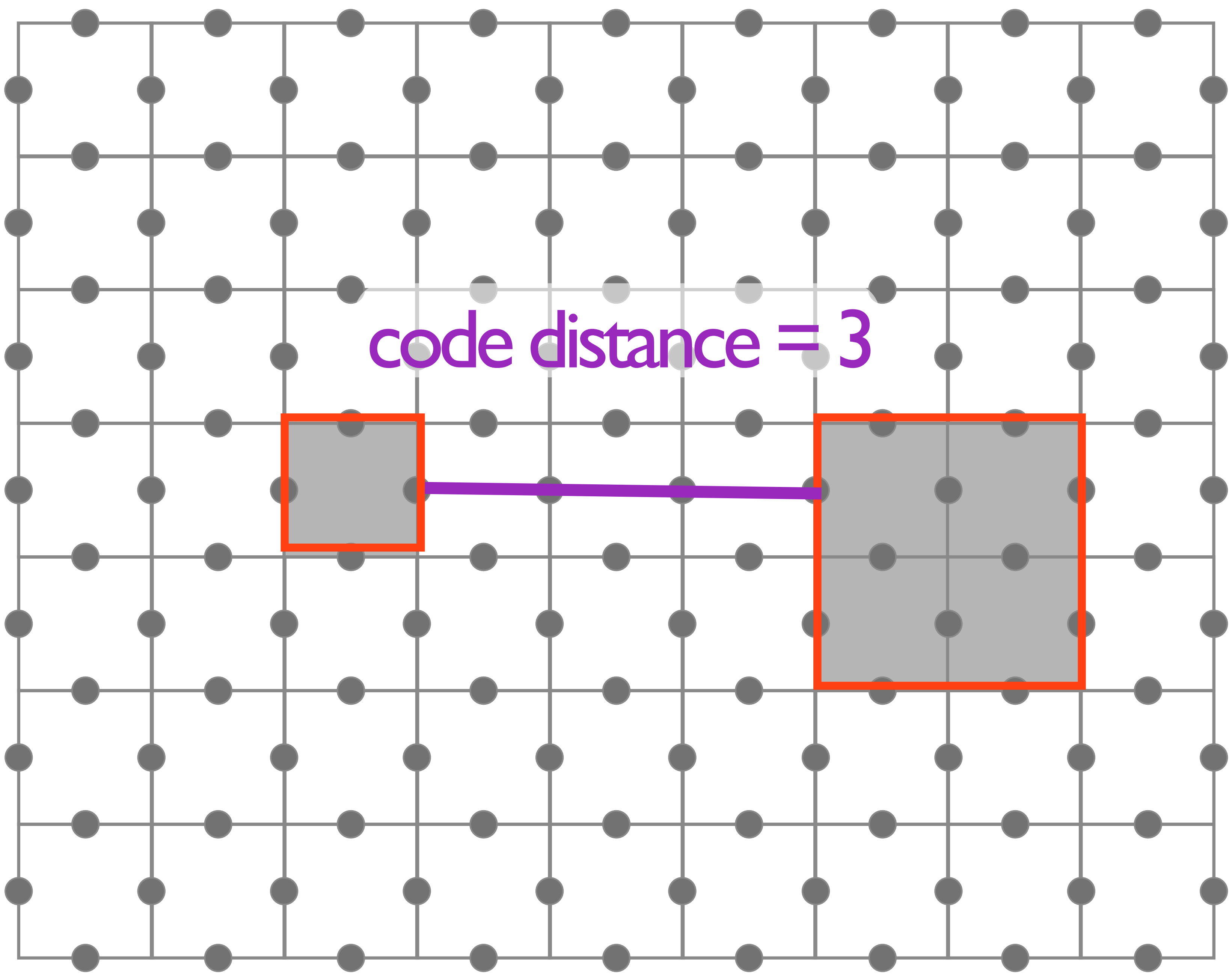

$$P_{logical\ memory\ error\ rate} = P_{physical\ memory\ error\ rate}{}^{4}$$

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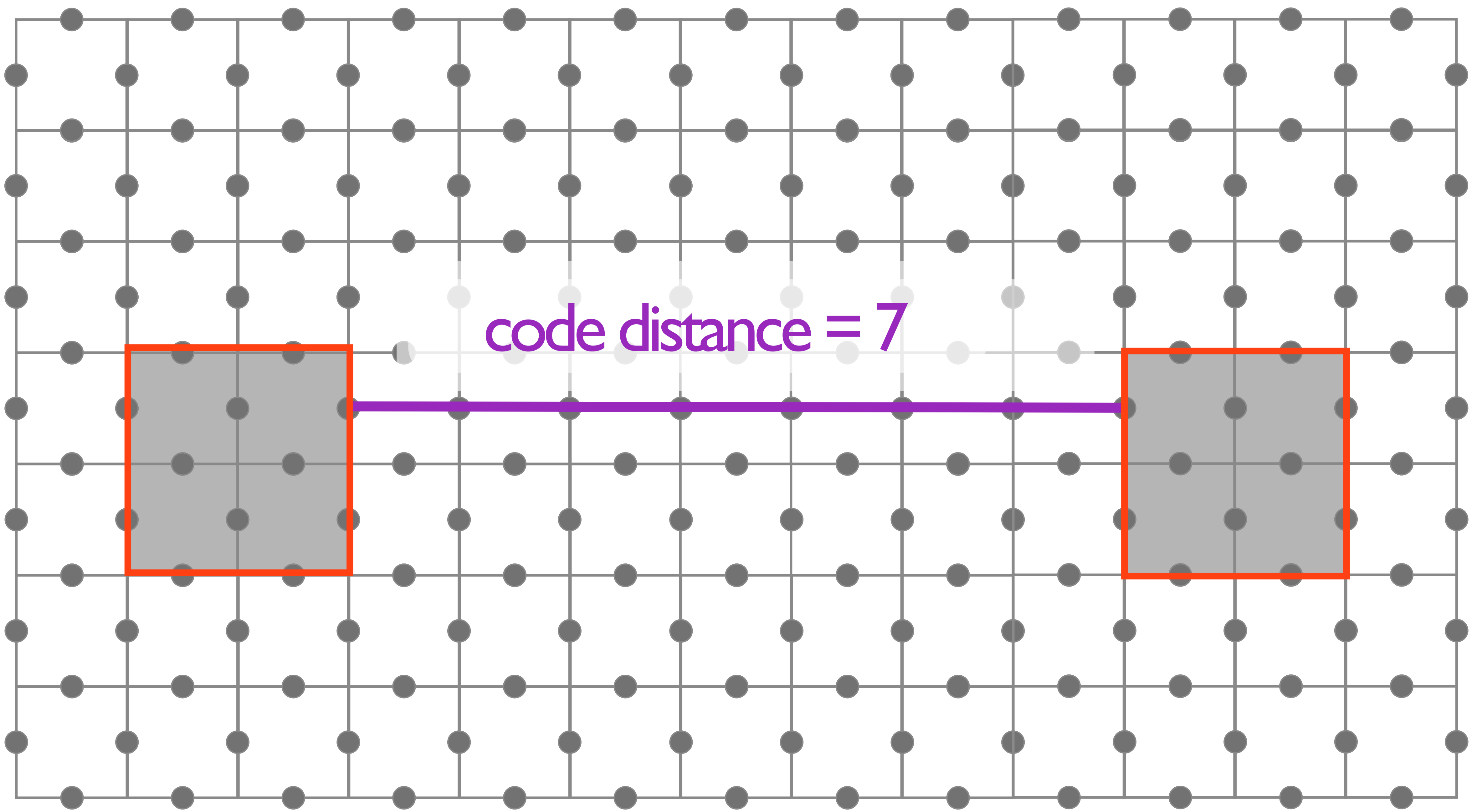
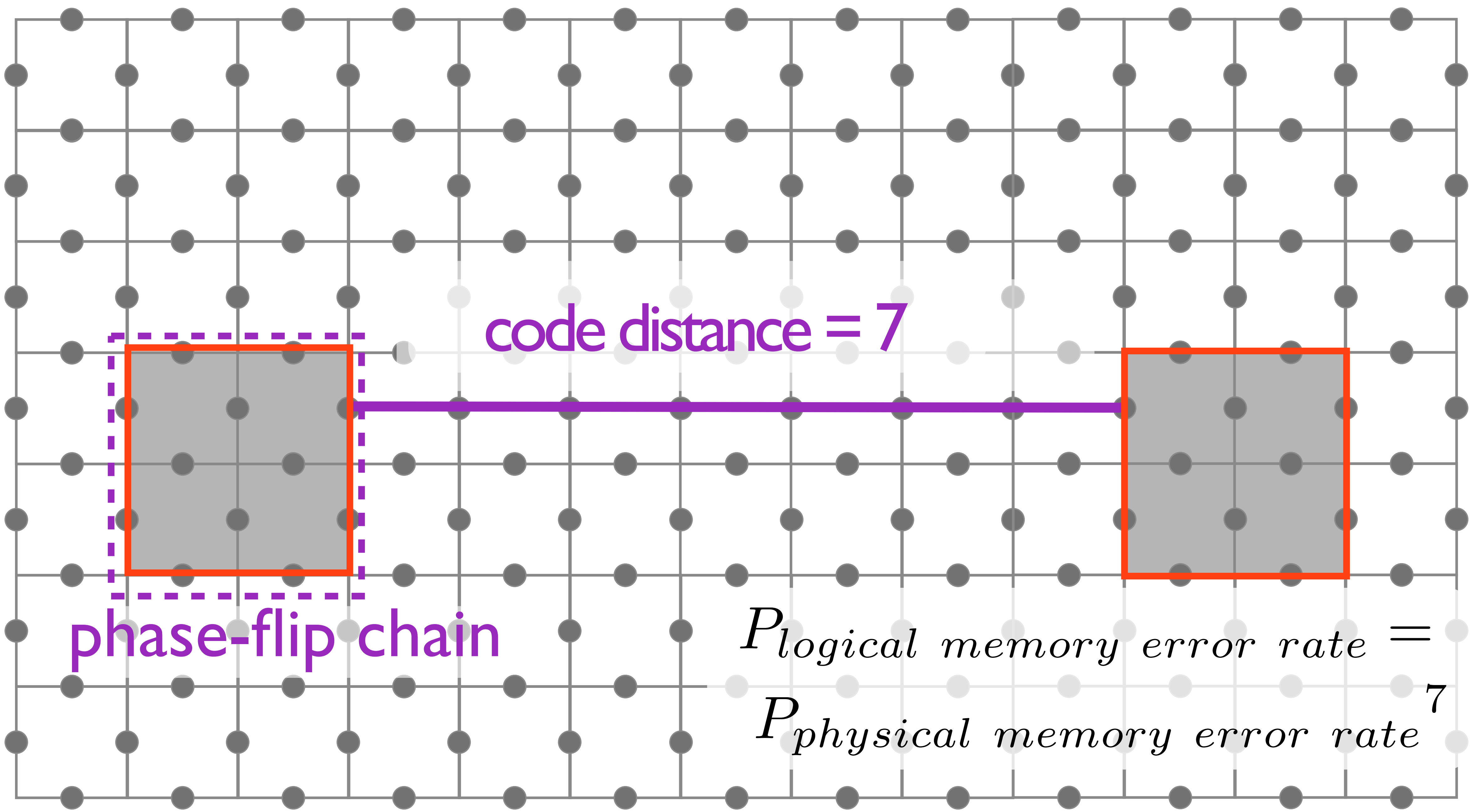
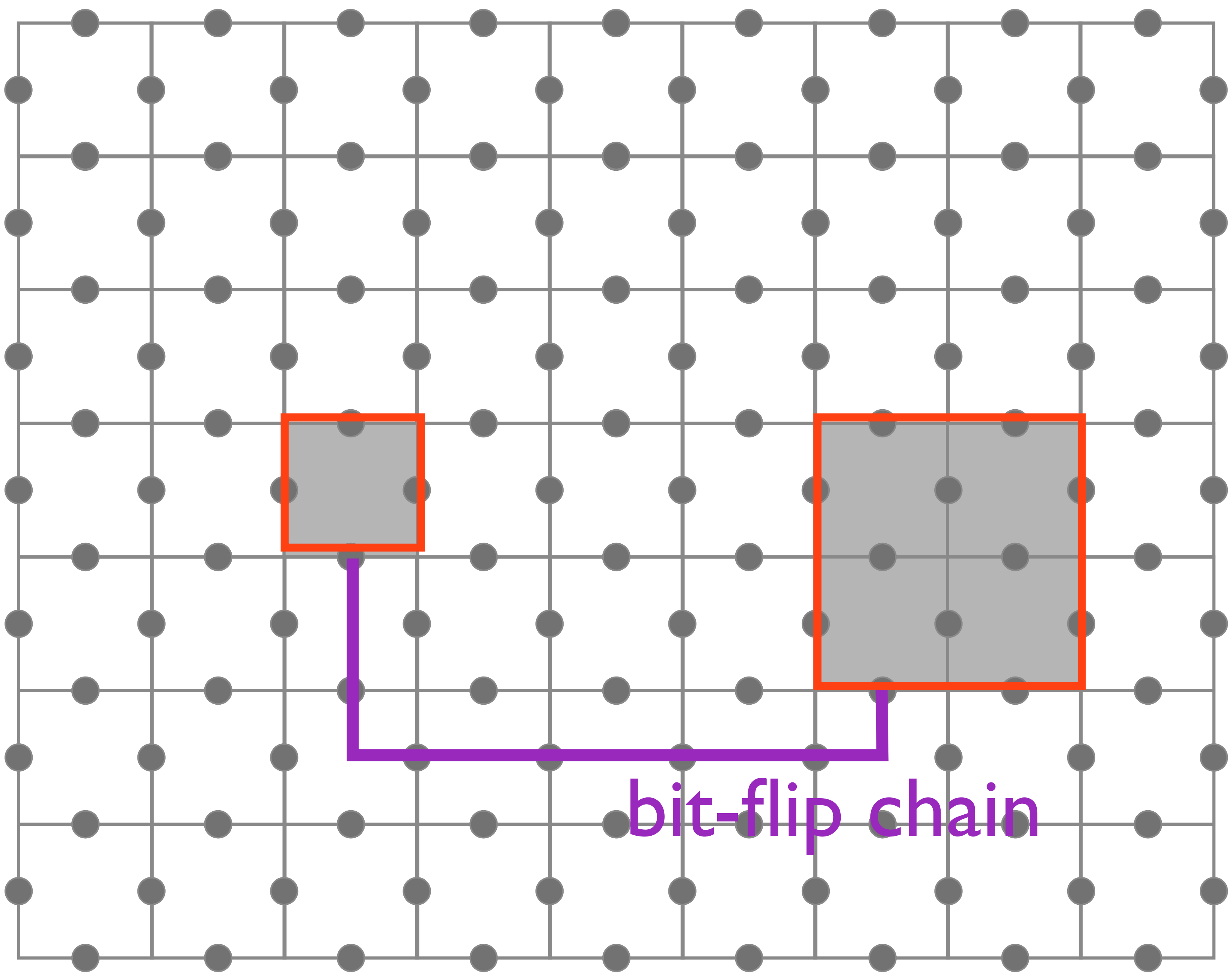


Surface Code
~Code distance~



$$P_{logical\ memory\ error\ rate} = P_{physical\ memory\ error\ rate}{}^{7}$$

Surface Code
~Code distance~



$$P_{logical\ gate\ error\ rate} = P_{physical\ gate\ error\ rate}{}^{7}$$

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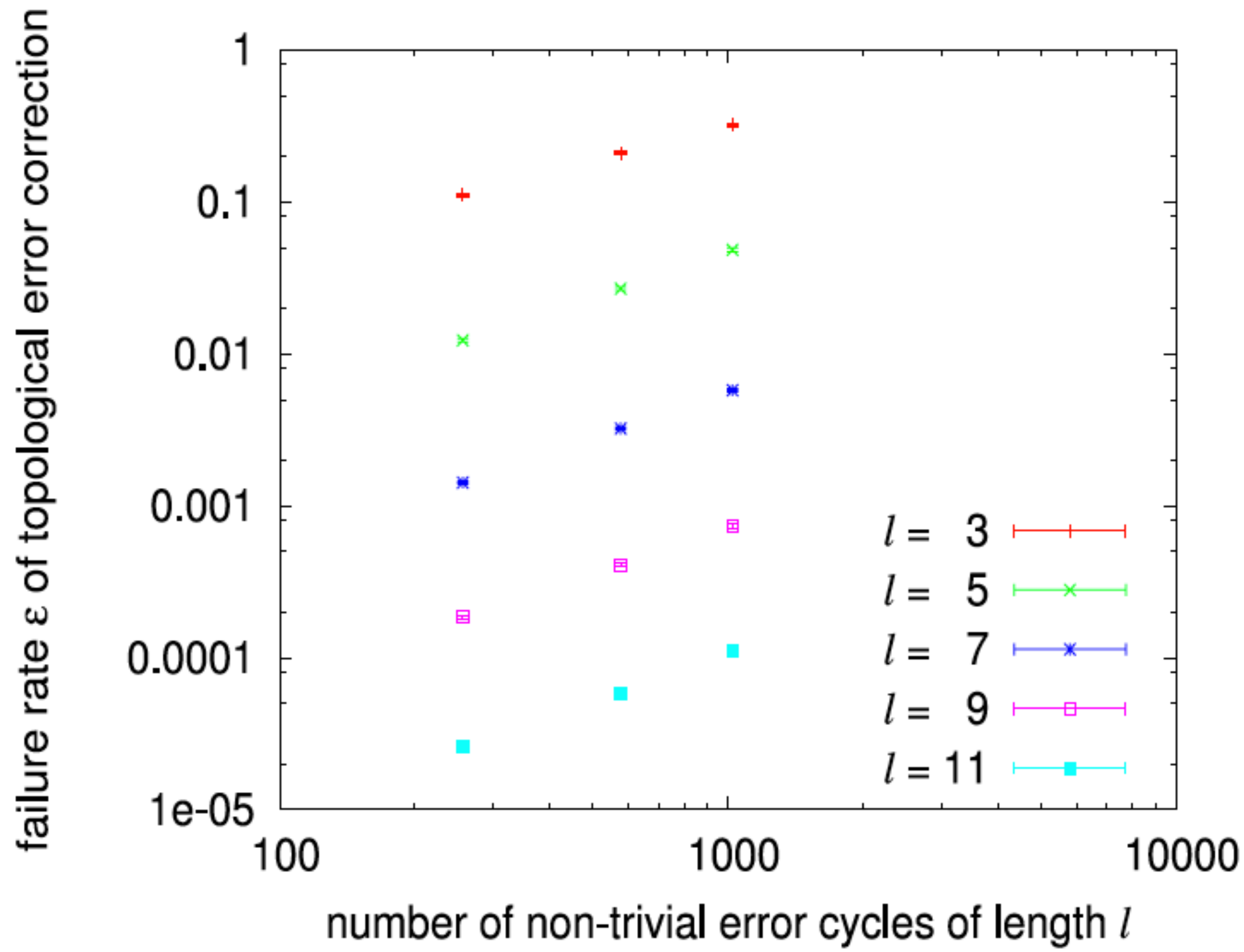
Exponential Suppression

- Classical simulation of small lattices
- Error rate

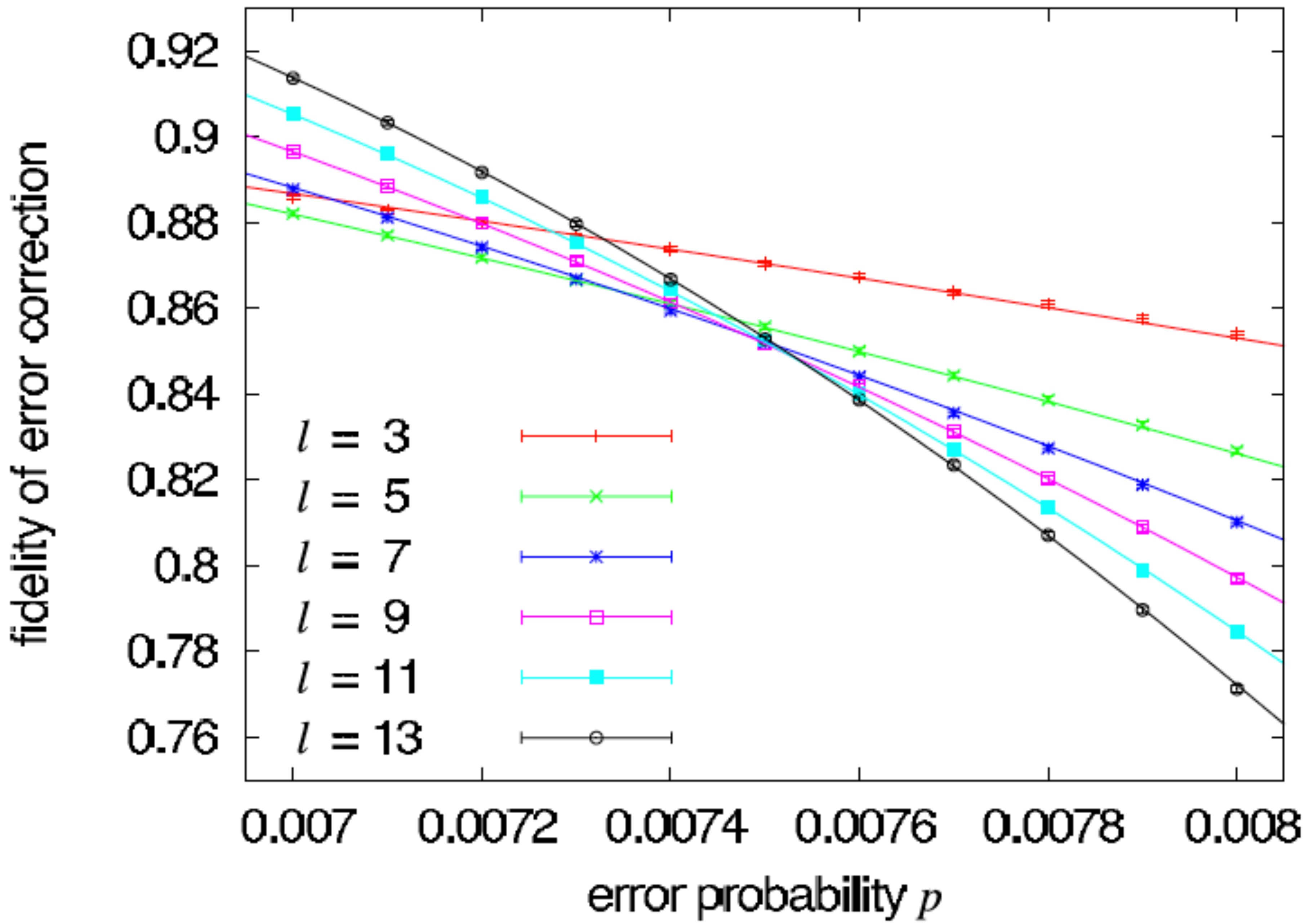
$$\epsilon_{\text{top}} \sim \exp(-\kappa(p)l)$$

- p = phy err rate
  K ~ 0.9
  l = min err chain length



- Still a polynomial correction needed
- Raussendorf et al., NJP 9, 2007

Threshold



- Gate = Memory = Meas errors = 0.75%
- Raussendorf et al., NJP 9, 2007

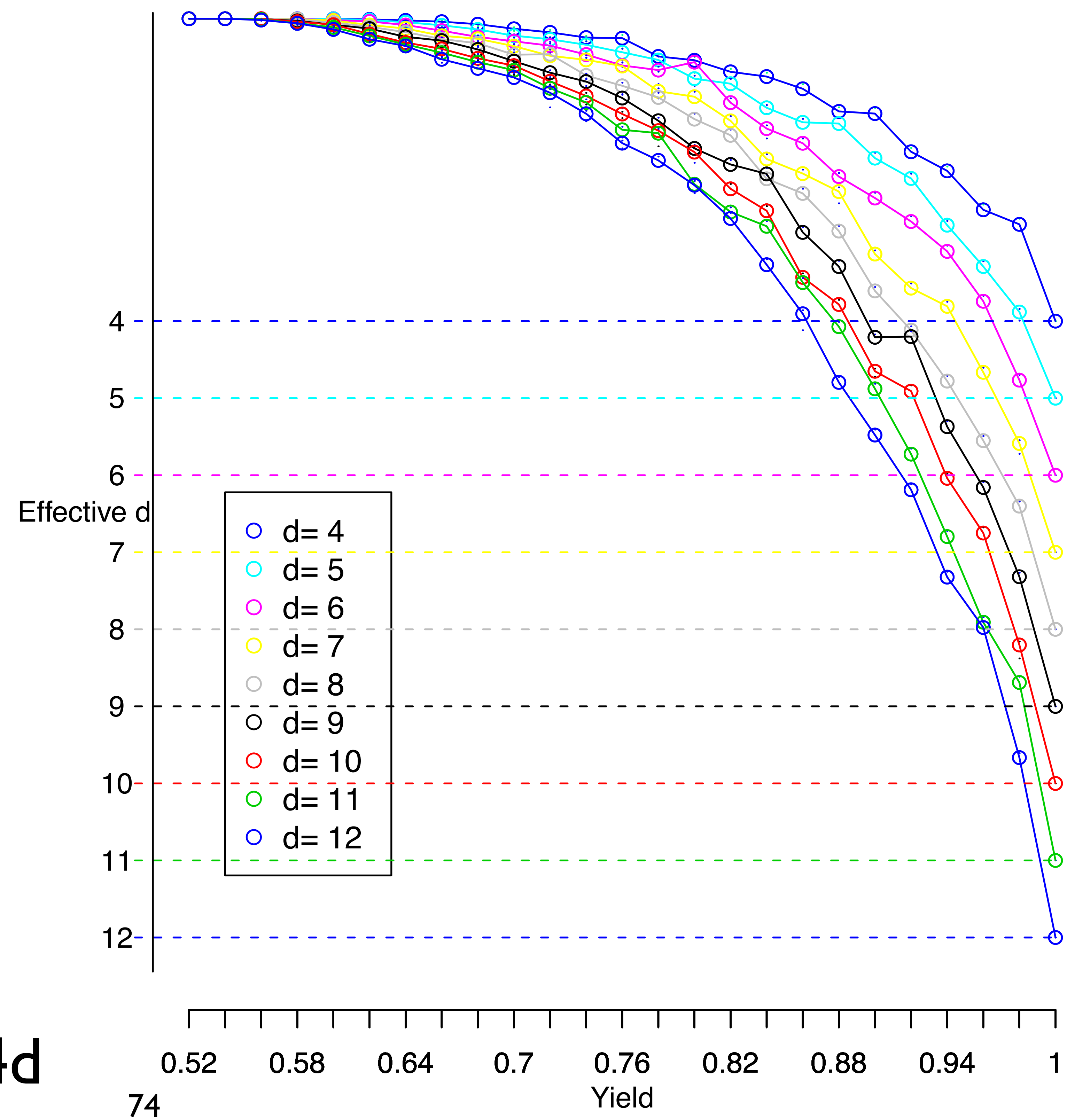
Advanced Topics

- 3-D version, talk to Simon
- Defective lattice
- Planar code
- Surface code communications
- Uses in distributed quantum computation

Defective lattice

Current estimate is that yield of 90% *halves* the effective code distance.

Nagayama *et al.*, in preparation



code distance = 4d

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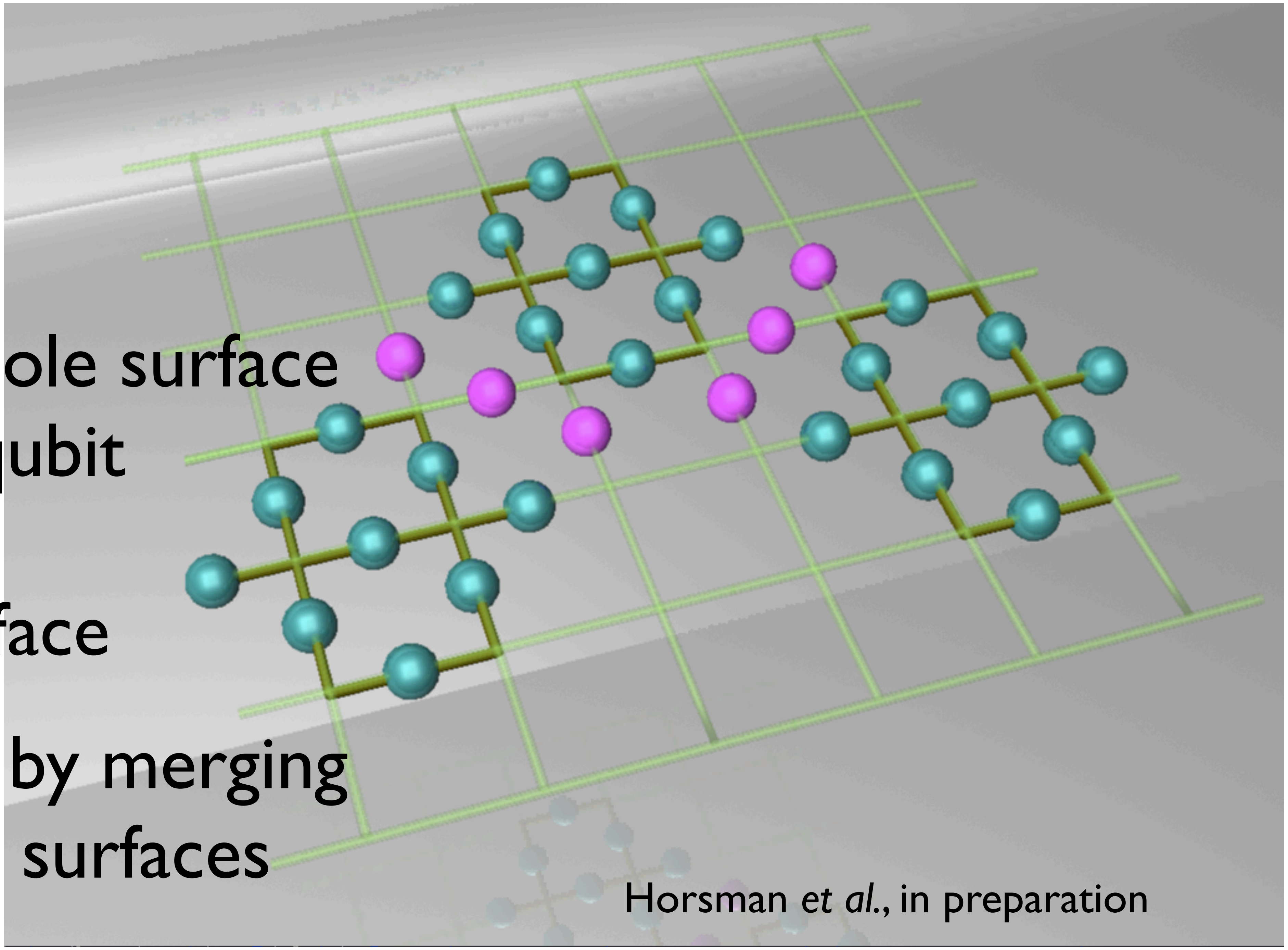
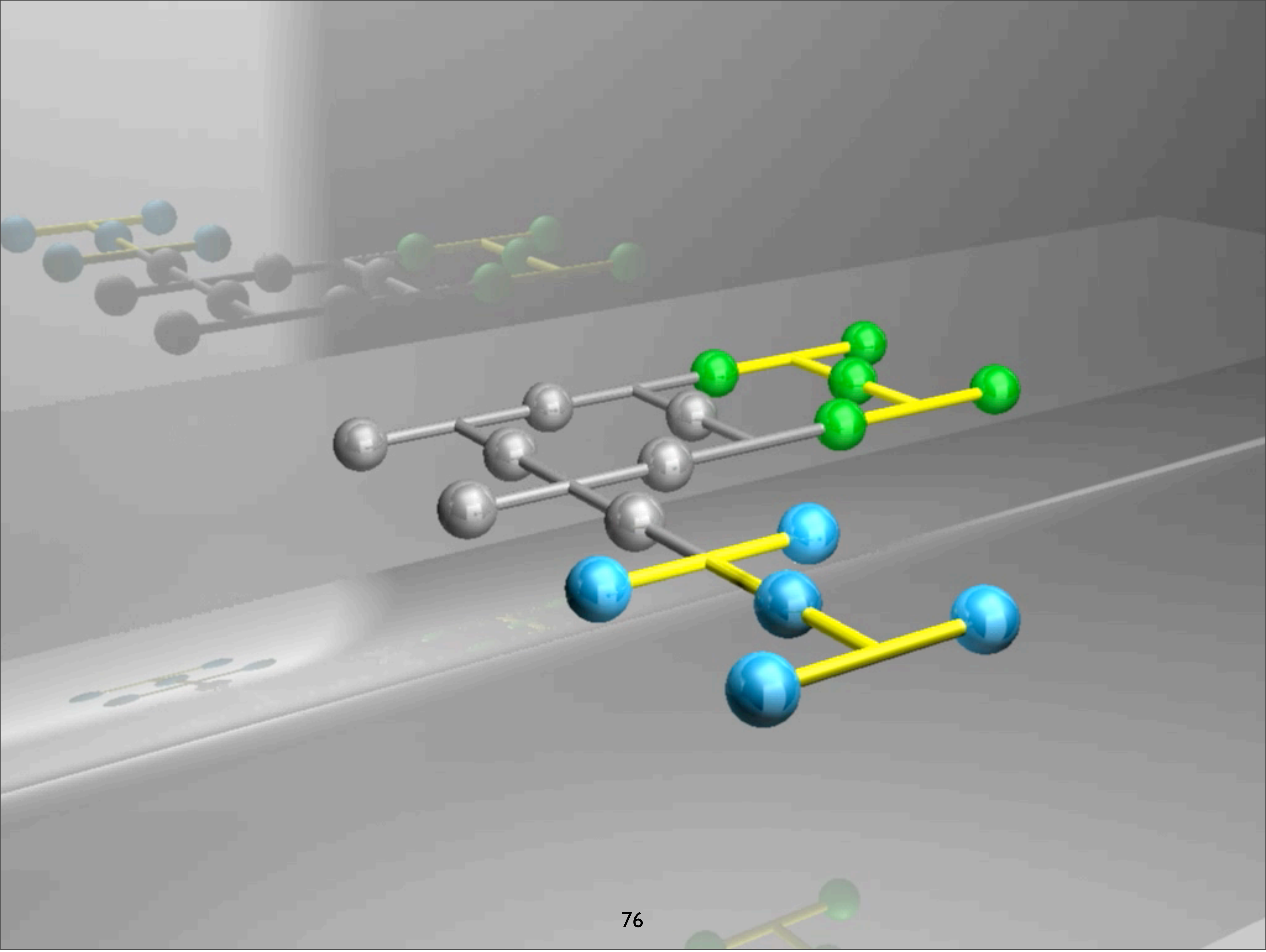
Planar Code



- Use one whole surface per logical qubit instead of holes in surface
- Gates done by merging and splitting surfaces
- Useful for small-scale experiments



Surface Code Strengths

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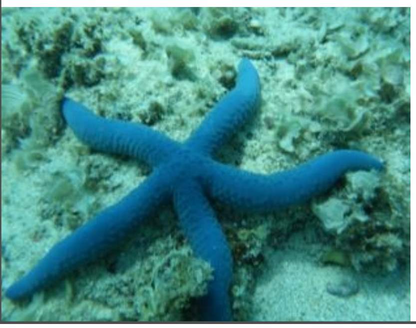
- Simple, 2-D or 3-D nearest-neighbor-only operation (physical feasibility high!)



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  - –software-assigned resources
  - –easy movement of logical qubits

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  - –easy movement of logical qubits
- Supporting classical processing achievable

Key References

- clearest explanation:
  Fowler *et al.*, PRA 80, 052312 (2009)
  (source of many of the figures)
- detailed paper:
  Raussendorf *et al.*, NJP 9, 199 (2007)
- cryptic seminal paper:
  Raussendorf and Harrington, PRL 98, 190504 (2007)
- Surface code communication:
  Fowler *et al.*, PRL 104, 180503 (2010)
- Defects in the surface code:
  Stace *et al.*, PRL 102, 200501 (2009)

8 Hours of Lecture on Surface Code

- http://aqua.sfc.wide.ad.jp/Publications.html

Preview: What kind of system can run surface code effectively?

- Billions of qubits
- GHz physical gates
- Millisecond memory lifetimes
- Error rate ~0.1%
- ~1 year to factor 2048-bit number
- Stay tuned...