Online surface code decoder with a superconducting circuit

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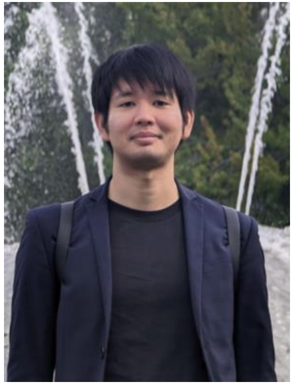
- Career
  - 2022.3: Ph.D. in Information Sci. and Tech. @ The University of Tokyo
    - Supervisors: Masaaki Kondo (Keio Univ., R-CCS), Hiroshi Nakamura
    - Thesis: **Online Quantum Error Correction Using a Superconducting Circuit**
  - 2022.5 to 2023.2: Guest researcher @ Technical University Munich
  - 2023.4 to Present: Postdoc @ RIKEN Center for Quantum Computing
- Research Subjects and Interests
  - Computer architecture
  - Fault-tolerant quantum computing
  - Cryogenic computing



@IEEE Quantum week 2023

Summary of this talk

- Decoding surface code is reduced to graph matching problem
- A practical decoder should be **accurate, fast, and scalable**
- For superconducting quantum computers, decoder also should be **power efficient** to be operated in **a cryogenic environment**
- Our solution: **online decoder** with **superconducting digital circuit**
- Our works on real-time decoding for FTQC
  - QECOOL: Online decoder with superconducting circuits (DAC'21, arXiv:2103.14209)
  - QULAIS: Extension of QECOOL for logical operation with lattice surgery (HPCA'22)
  - NEO-QEC: Extension of QECOOL/QULATIS with binarized NN for better accuracy (arXiv:2208.05758)

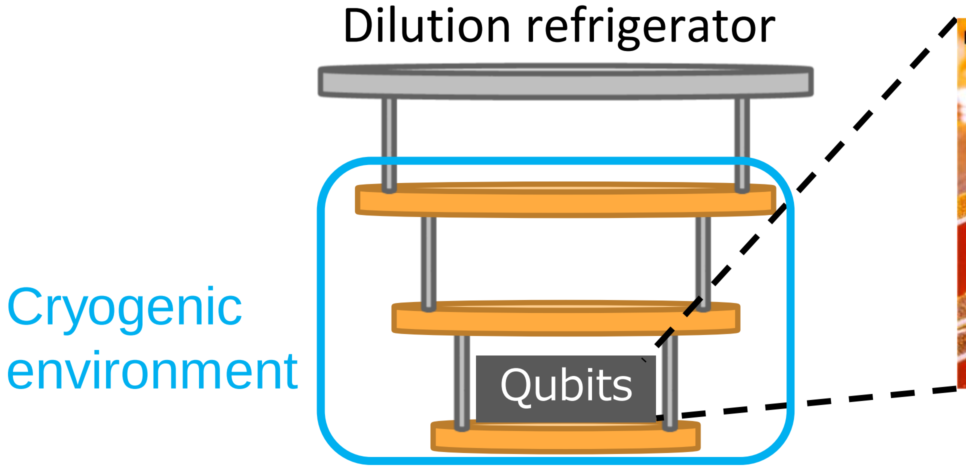
More detailed slide
from my RQC seminar

https://researchmap.jp/y-ueno/presentations/42717344

Outline

- Introduction
  - Superconducting quantum computer
  - Quantum error correction with surface code (SC)
- Requirements for a practical decoder
- QECOOL: online decoder with a superconducting circuit
- Conclusion and advanced works

Superconducting quantum computer (QC)



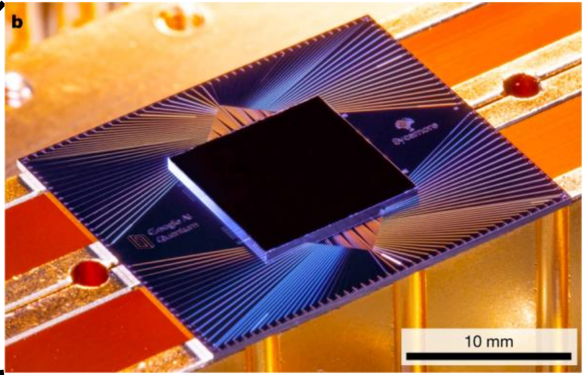


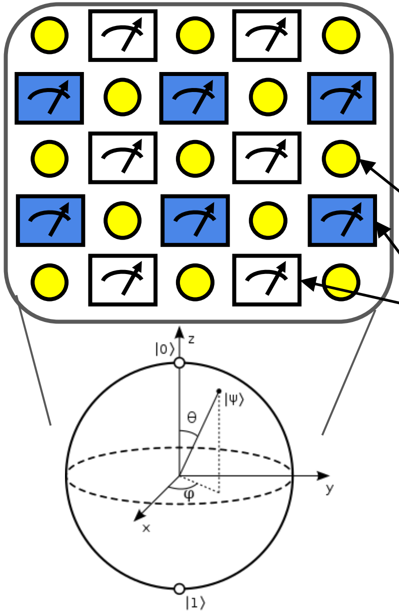
Figure from [1]

- Superconducting qubit: one of the most promising qubit implementation
  - Operate only at cryogenic environment (~20 mK)
- Qubits have very low error tolerance
  - **<u>Quantum error correction (QEC) code</u>**

[1] Frank Arute, Kunal Arya, Ryan Babbush, et al. Quantum supremacy using a programmable superconducting processor. Nature 574, 505–510 (2019).

Example of QEC code: Surface code (SC)

Surface code
(Code distance $d = 3$)



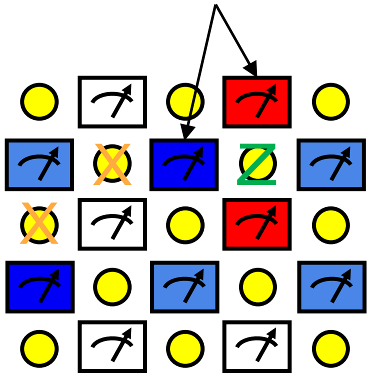
Data qubits

Ancilla qubits

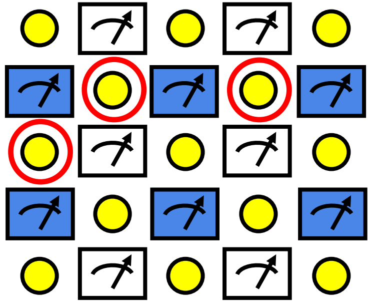
Logical qubit

Noise

Hot syndromes



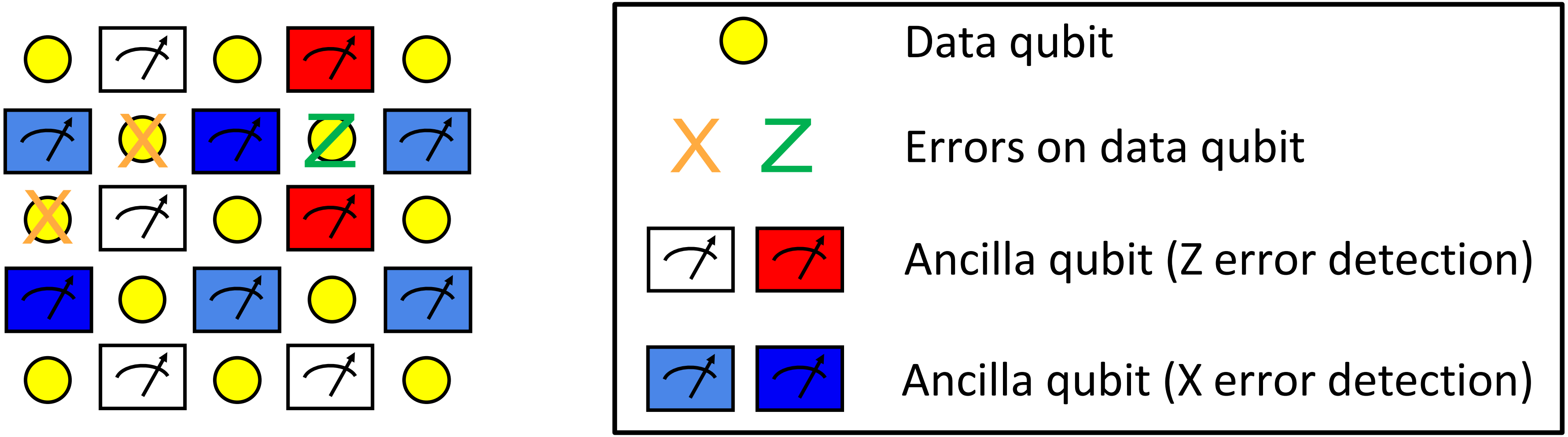
Decoding



Syndromes change according to errors

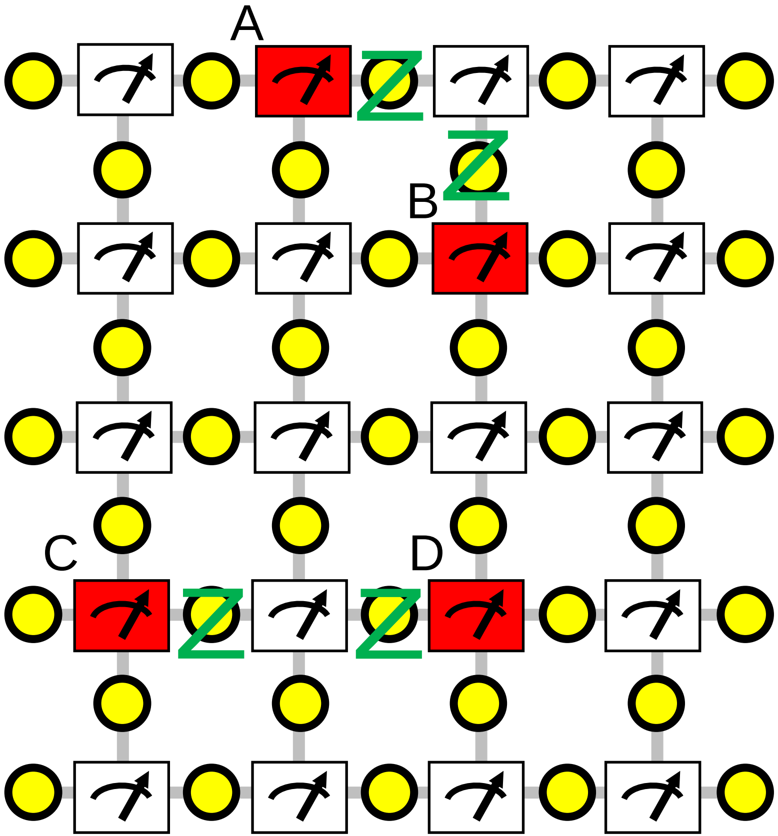
Decoding SC is specifying most likely errors from **hot syndromes**, and reduced to **graph matching problem**

Function of surface code



- Each ancilla qubit is used for error parity detection of neighboring data qubits
  - Endpoints of error chains are expected to be **hot syndromes**
- Errors on data qubit can be detected without direct measuring

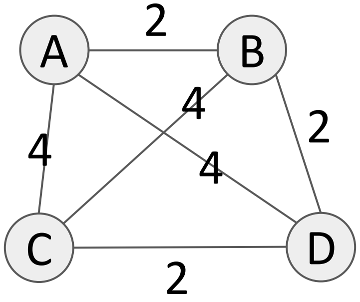
Decoding surface code



Assumption

- *X* and *Z* errors can be decoded independently
- Shorter error chains are likely to occur

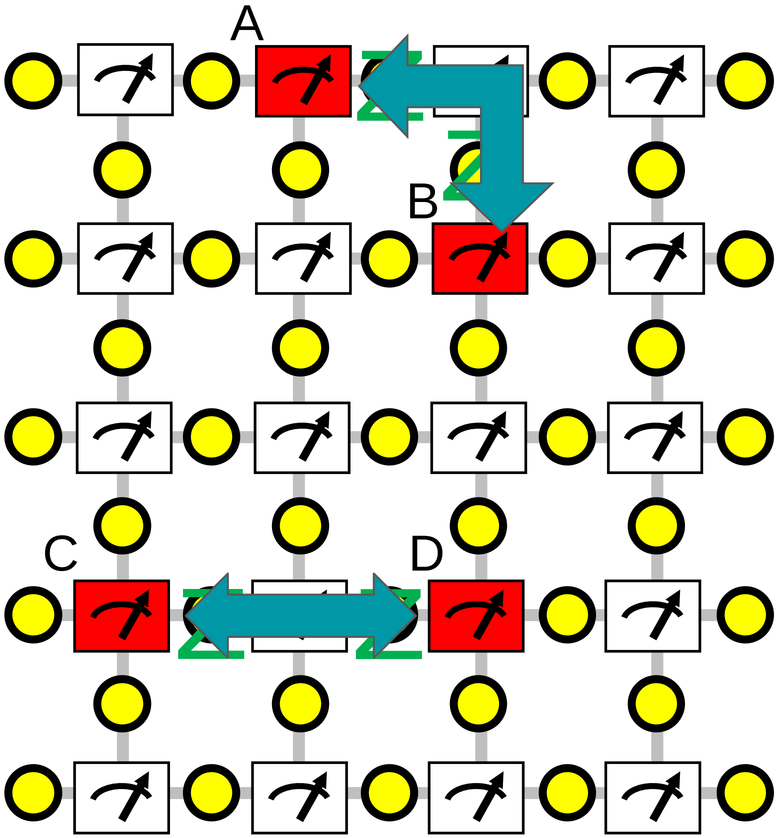
Minimum Weight Perfect Matching (MWPM)



V: Hot syndromes
W_e: Manhattan distance

Exact solution: **Blossom algorithm ($O(n^3)$)**

Decoding surface code



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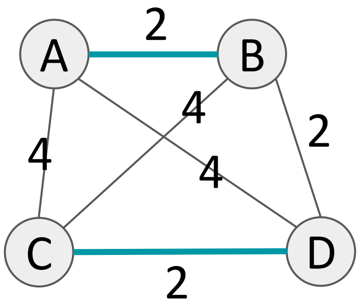
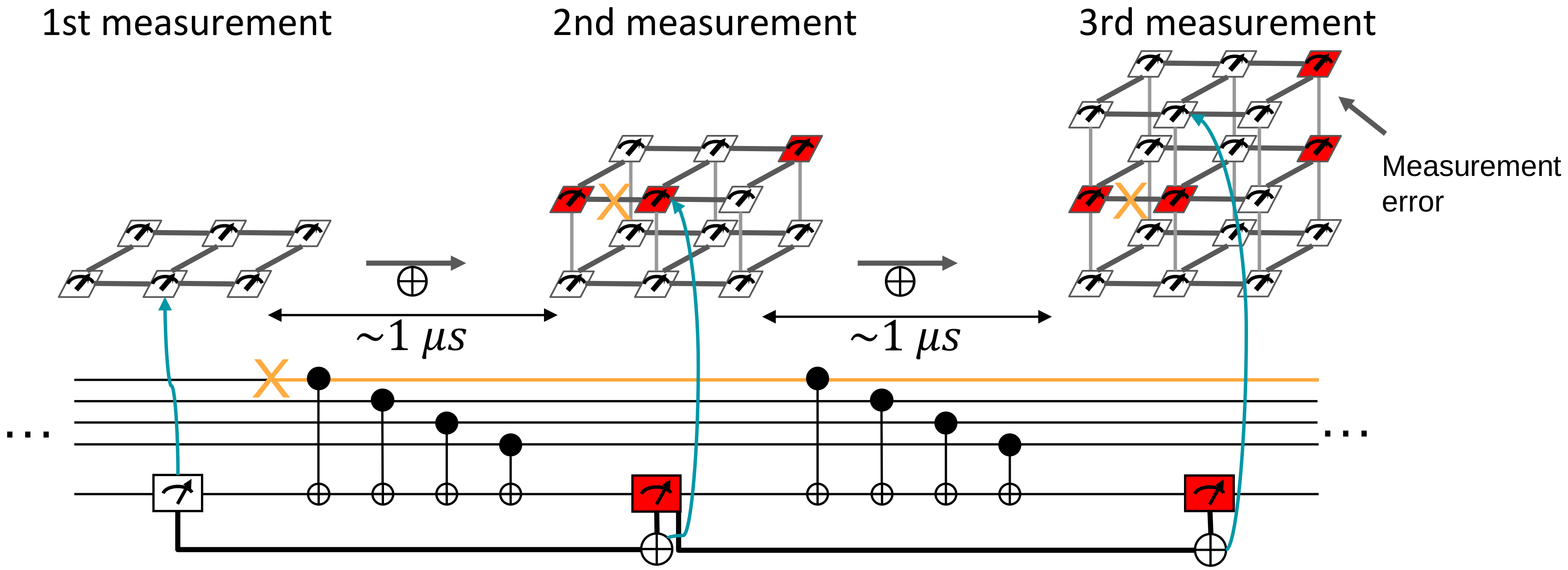
Minimum Weight Perfect Matching (MWPM)



V: Hot syndromes
W_e: Manhattan distance

Exact solution: **Blossom algorithm (O(n^3))**

Measurement error on ancilla qubit



- If ancilla qubit measurement is susceptible to read errors, multiple measurement processes are required
  - For every new measurement, the new syndrome is **XORed** with the latest value

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Requirements for a practical decoder

Requirements

1. Power consumption
   - Decoder must operate in **a cryogenic environment** with limited power budget
2. Latency
   - Slow decoding leads to **accumulation of errors** and **slow quantum computation**
3. Scalability
   - Decoder must protect not only single qubit but also **logical operations**
4. Accuracy
   - Decoder must have a **high error threshold**

QULATIS, HPCA'22

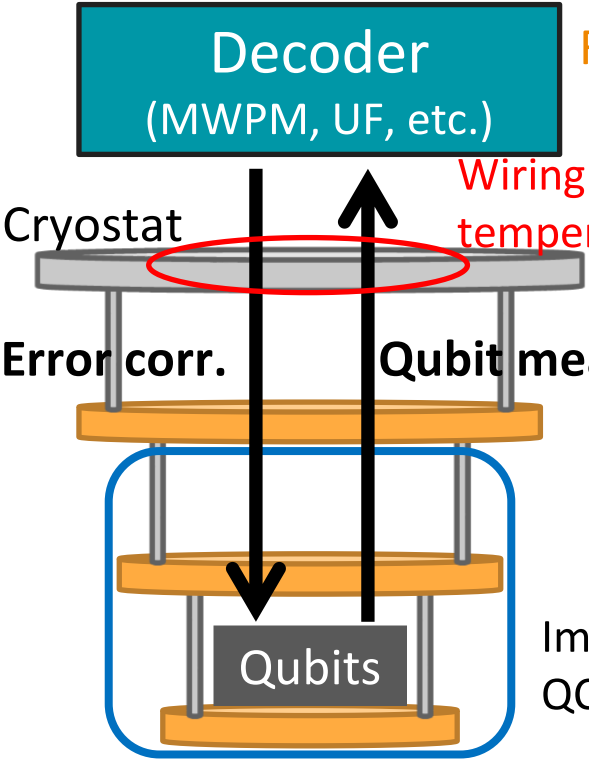
Our solutions

- Superconducting digital circuits
- Online-QEC manner
- Binarized neural network

NEO-QEC
arXiv:2022.05758

QEC architecture for superconducting QCs

Conventional architecture

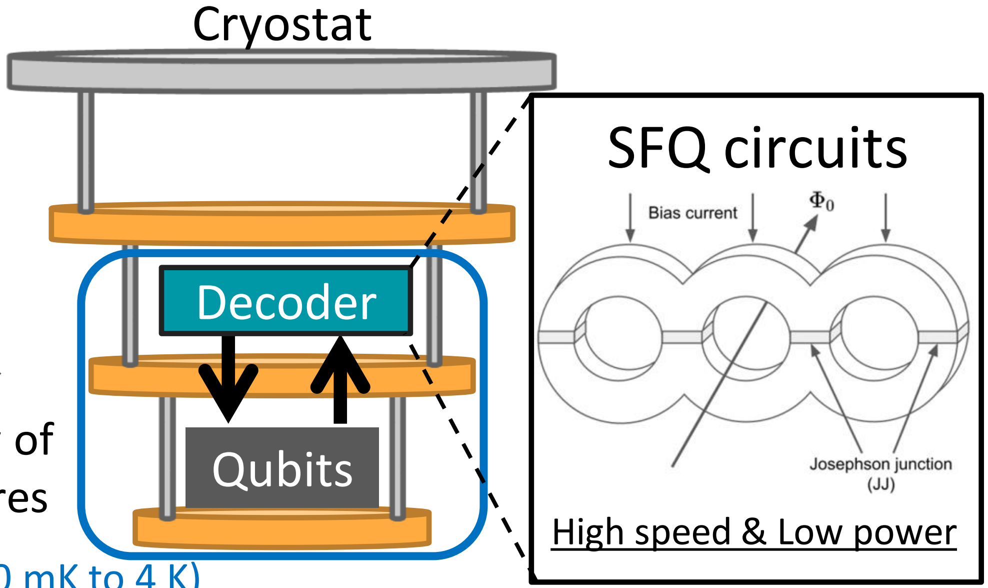


Room temperature
(300 K)

Wiring between different
temperature layers

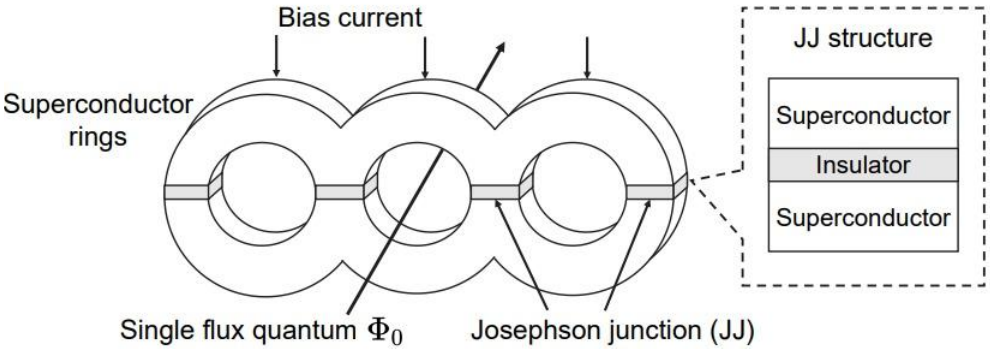
Proposed architecture

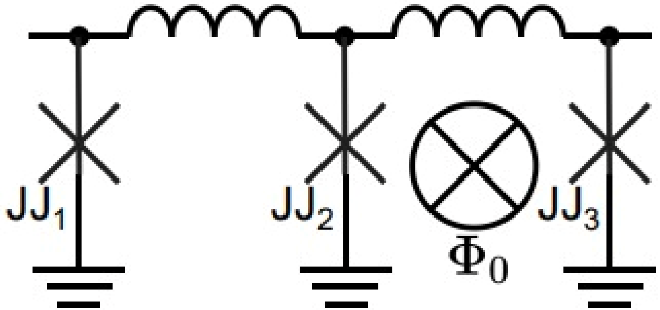
Improve scalability of
QC by reducing wires



Cryogenic environment (20 mK to 4 K)
Power budget ~ 1 W

Single flux quantum (SFQ) logic

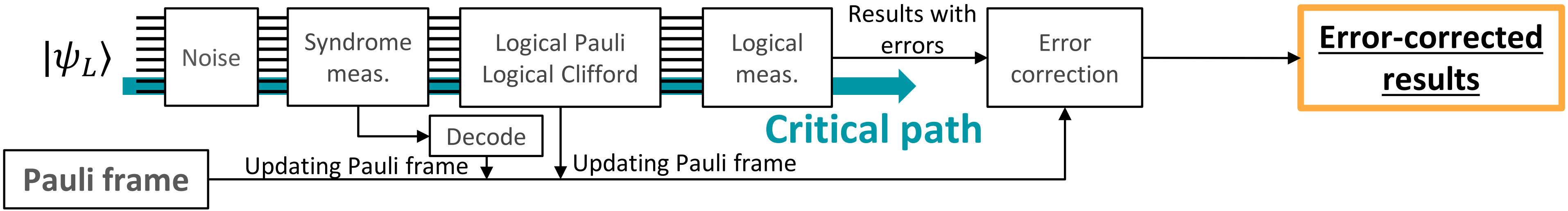




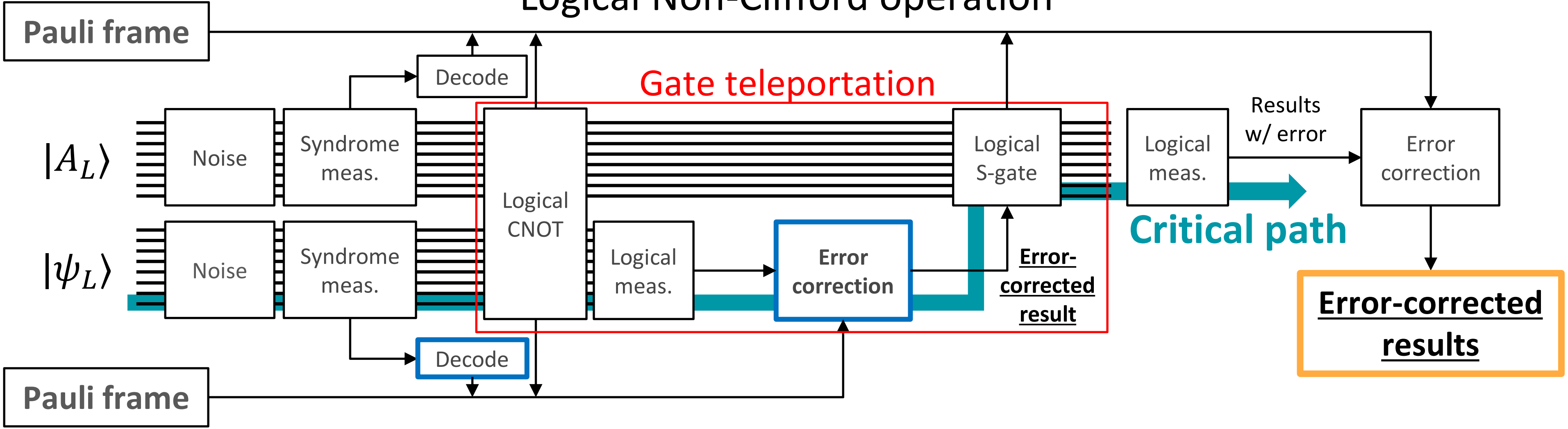
- Absence (presence) of flux quanta within the ring represents digital ‘0’ (‘1’)
- Operates only in a cryogenic environment (~ 4 K)
- High speed and low latency compared to CMOS circuits
- Limitation: Large amount of RAM is expensive
    - -> Conventional decoders such as MWPM are not implementable with SFQ

High-latency decoding slows down quantum computation

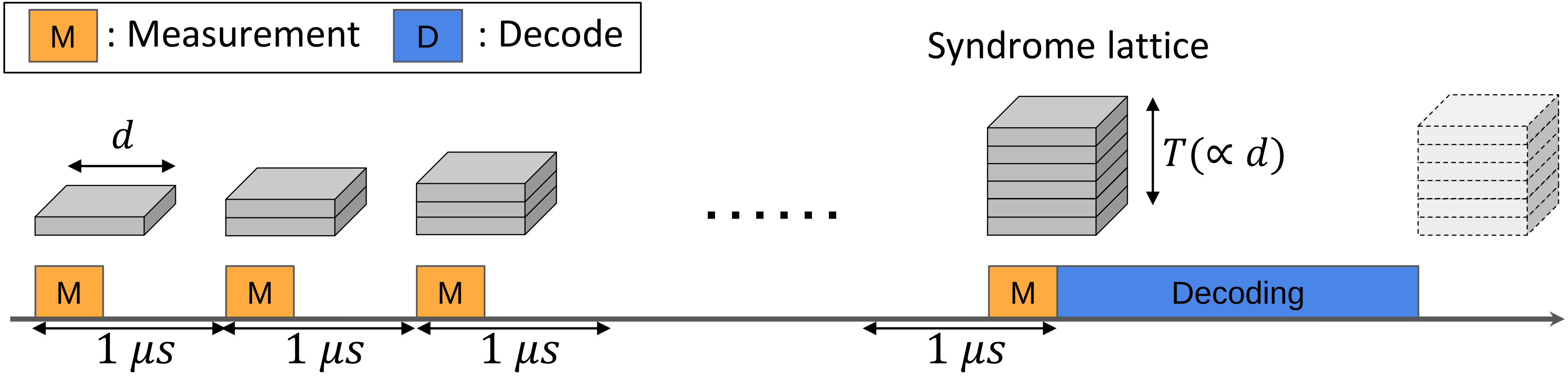
Logical Clifford operation



Logical Non-Clifford operation



Why is MWPM not practical?

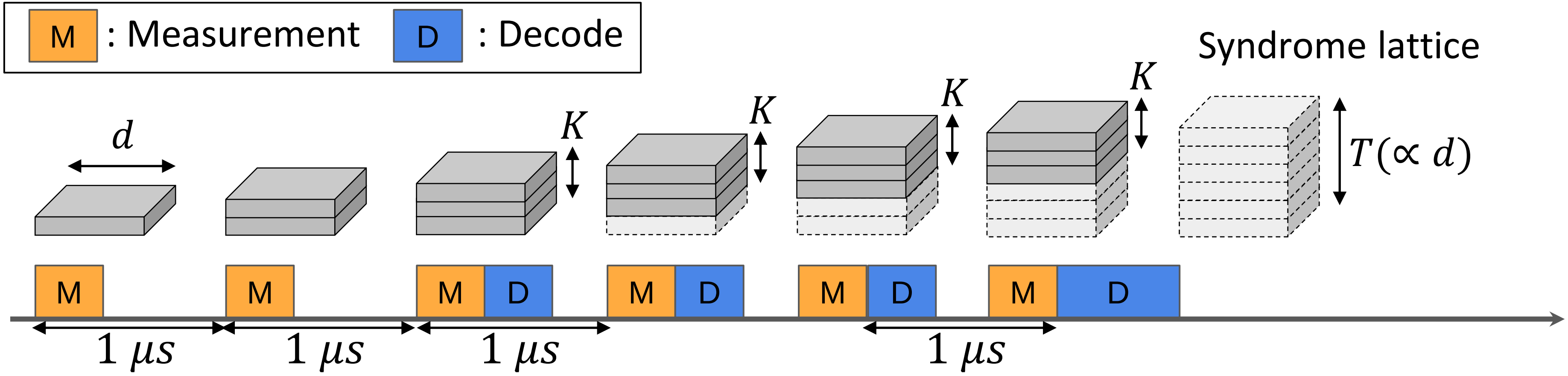


Measurement and decoding processes with the MWPM decoder

Batch-QEC manner

+ Accurate decoding
– Slow decoding
– $O(Td^2)$ bits of storage

Our solution: Online-QEC manner



Measurement and decoding processes with a practical decoder

Online-QEC manner

− Degradation of decoding accuracy

+ Fast decoding

+ $O(Kd^2)$ bits of storage

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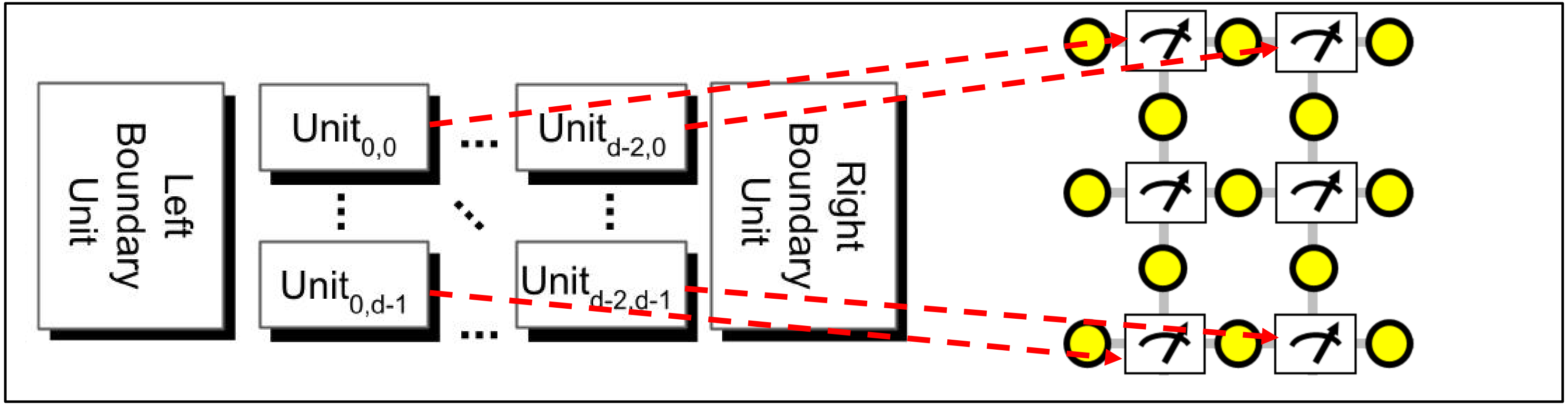
QECOOL

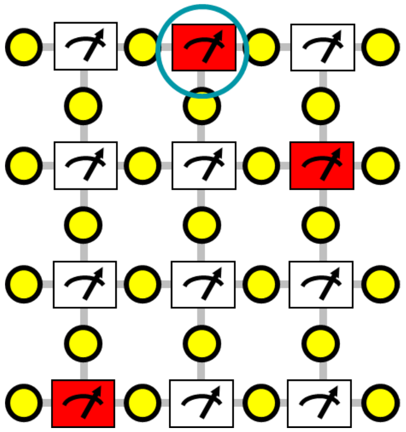


Architecture overview of QECOOL decoder

- Quantum Error COrrection by On-Line decoding algorithm
- **A distributed architecture** without large amount of RAM
  - Multiple processing elements (***Units***) corresponding one-to-one with ancilla qubits
  - Matching problems are solved by signal propagation among Units

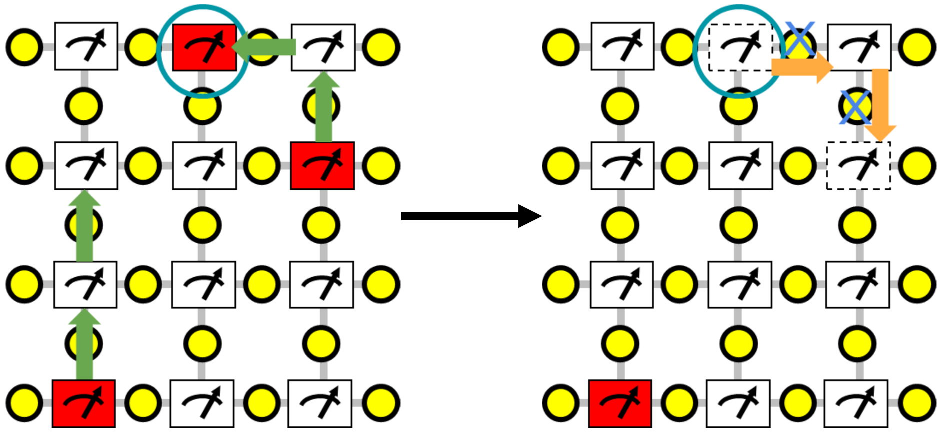
Overview of QECOOL algorithm

Step 1



Determine the starting point for finding a hot syndrome pair

Step 2

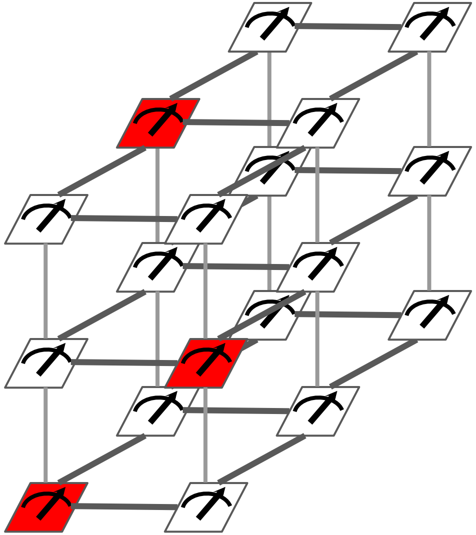


Perform **nearest neighbor search** using two types of signals among Units

Based on a **greedy graph matching algorithm**

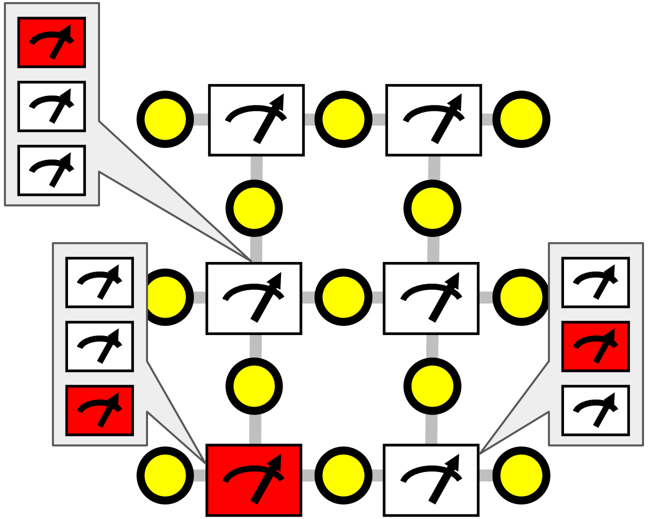
$O(n^2)$, approximation degree 1/2

Matching problem on a 3-D lattice



3-D syndrome lattice

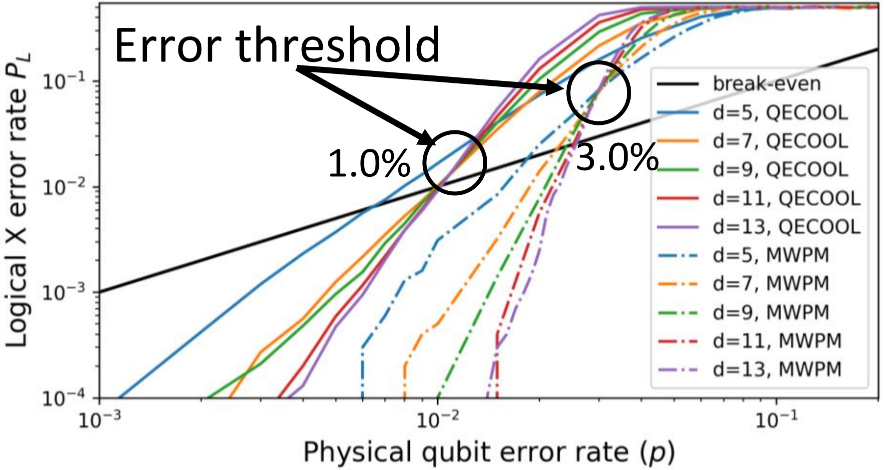
Map 3-D lattice to Units on 2-D grid

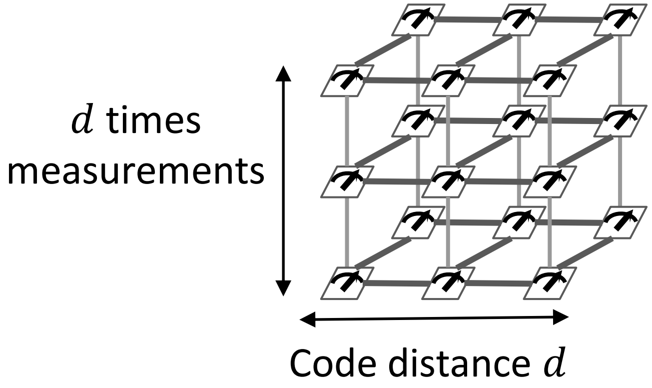


Units with $O(K)$ memory

- Each Unit has a $O(K)$ buffer to store multiple syndrome values
- Almost the same procedure as in case of 2-D lattice

Decoding performance of QECOOL





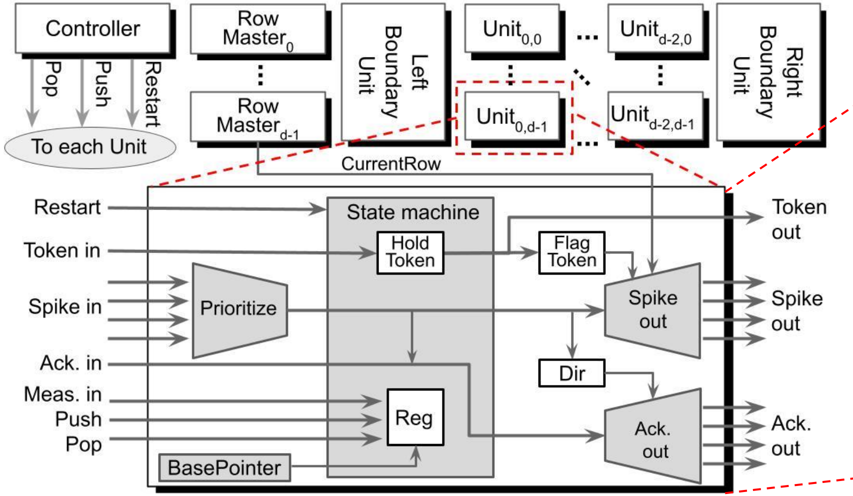
Target lattice shape

Experimental condition

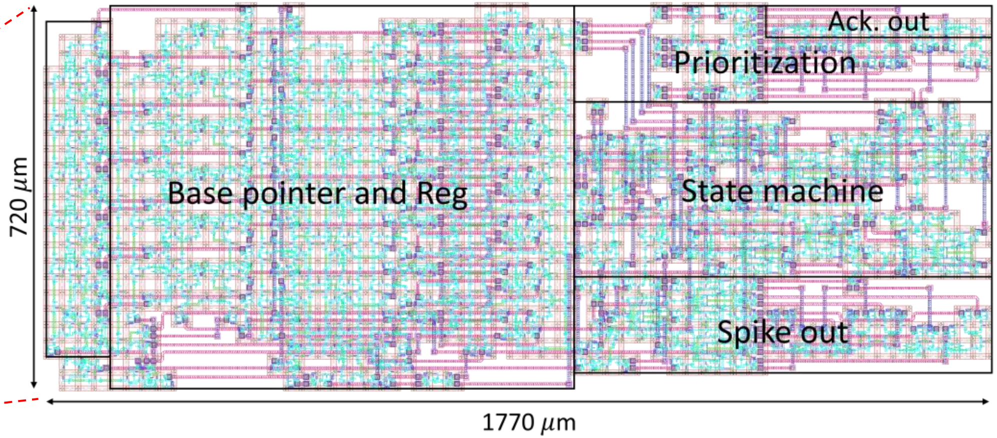
- Measurement process is performed **once every 1 μs**
- Each QECOOL Unit has a **7-bit** buffer to store syndrome values
- If buffer entry size is greater than $K = 3$, QECOOL is performed; otherwise, each Unit waits for measurement process
- MWPM operates with batch-QEC manner

- Threshold value: QECOOL p=0.01, MWPM p=0.03

SFQ implementation of QECOOL decoder



Architecture overview of QECOOL decoder



SFQ layout of QECOOL Unit

JJs: 3177	Area: 1.274 mm^2	Latency: 215 ps	Power cons.: **2.78 μW**

Total power consumption of per distance-9 logical qubit

$$9 \times 8 \times 2 \times 2.78_{[\mu W]} \approx \boxed{400\ \mu W}$$

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Conclusion and advanced works

- Online decoding of surface code in a cryogenic environment is necessary for a scalable superconducting quantum computer
- QECOOL is power-efficient enough to operate in a cryogenic env.
- Next step is supporting logical operations of the universal quantum gate set $\{H, \mathrm{CNOT}, T\}$
    - **QULAIS**: Extension of QECOOL for logical operation with lattice surgery (HPCA'22)
- Accuracy of QECOOL is lower than MWPM due to its greedy and online nature
    - **NEO-QEC**: Extension of QECOOL/QULATIS with binarized NN for better accuracy (arXiv:2208.05758)

More detailed slide
from my RQC seminar
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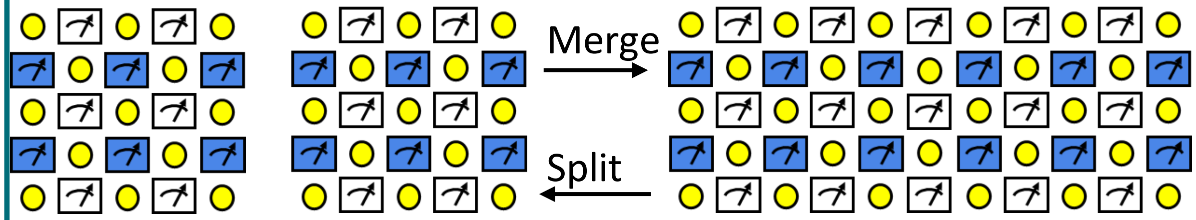
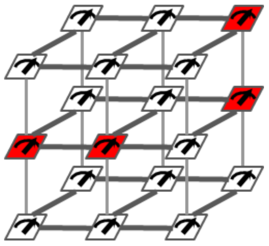
QULATIS: QEC methodology towards lattice surgery

Lattice surgery

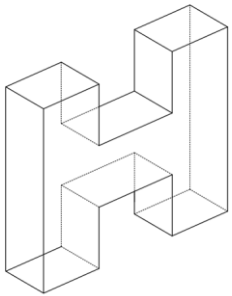


Framework to perform logical operations
with SC-based QEC

Target lattice shape



Single logical qubit
(QECOOL)

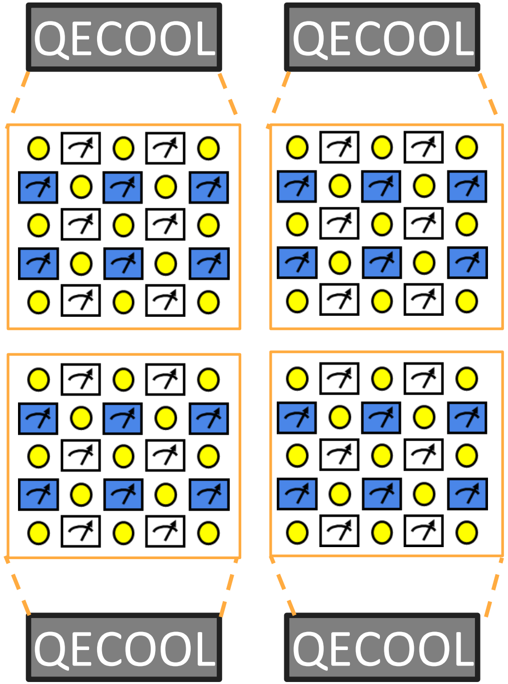


Lattice surgery
QULATIS

- Extension of QECOOL for decoding of lattice surgery
  - Supporting logical operations of the universal quantum gate set $\{H, \text{CNOT}, T\}$
- SFQ circuit design of QULATIS decoder is
  suitable for **online decoding in a cryogenic environment**

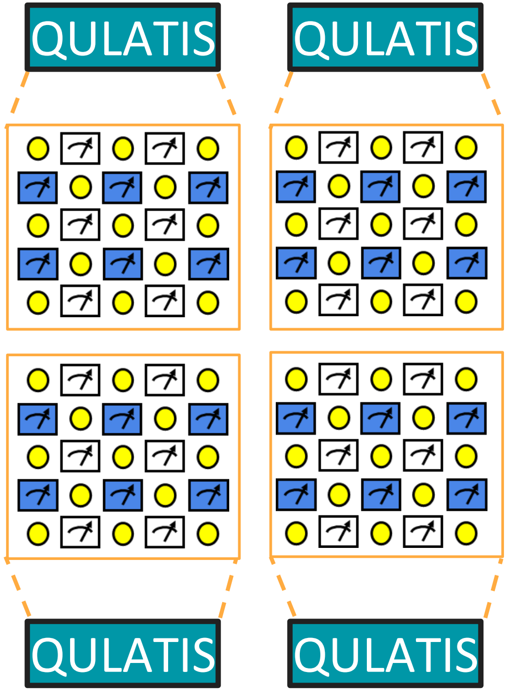
Brief summary of QECOOL and QULATIS decoders

QECOOL decoders



QECOOL decoders decode each logical qubits independently

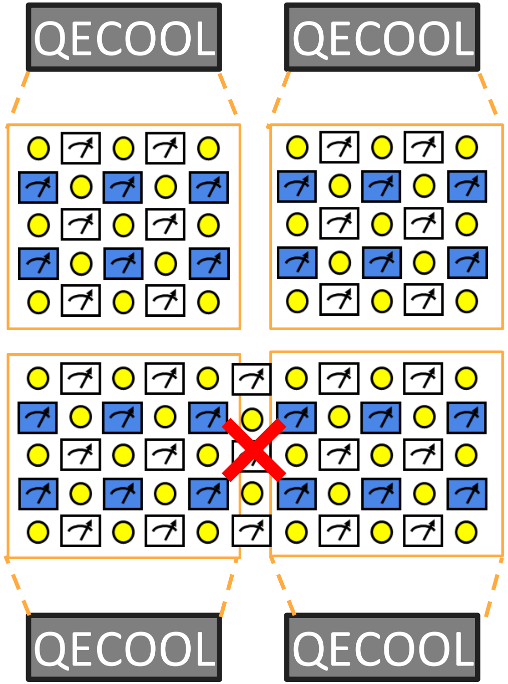
QULATIS decoders



Decode lattice surgery by orchestrating multiple QULATIS decoders

Brief summary of QECOOL and QULATIS decoders

QECOOL decoders



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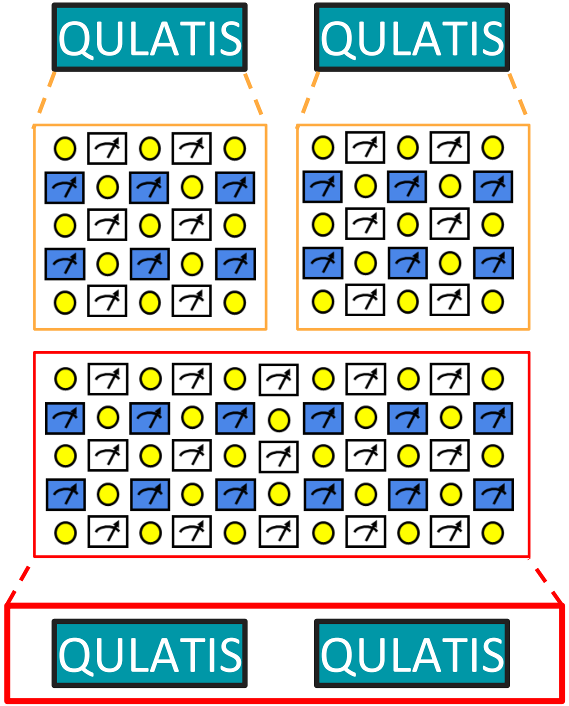
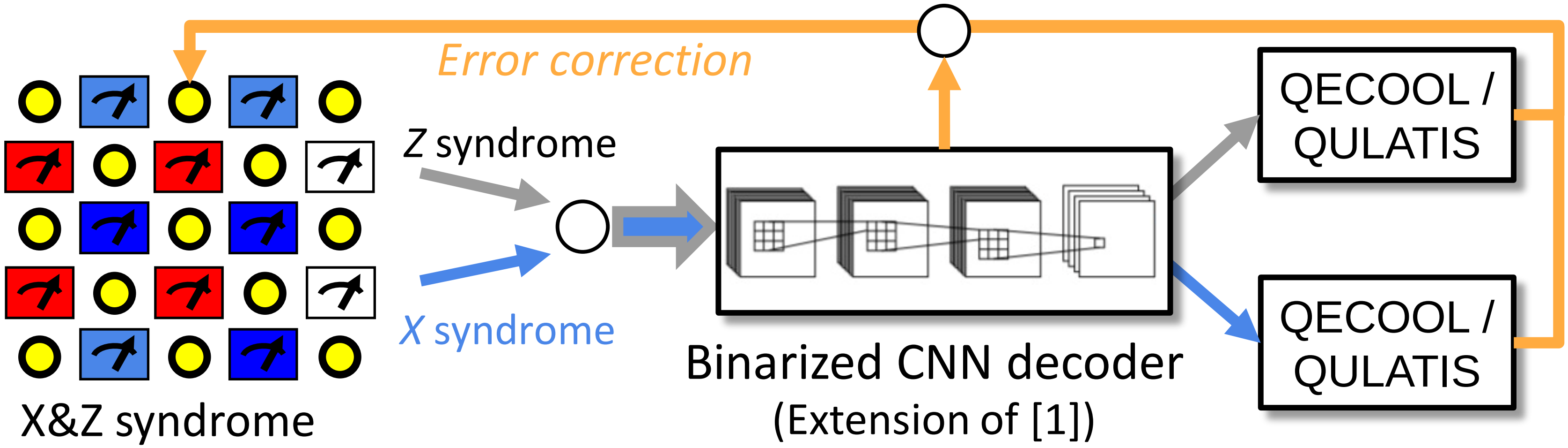


Decode lattice surgery by orchestrating multiple QULATIS decoders

NEO-QEC: NN enhanced online QEC



- A two-stage decoder with binarized CNN and QECOOL/QULATIS
  - Improve threshold values of QECOOL/QULATIS
- SFQ design of **Neural Processing Unit** for binarized CNN
  - Suitable for **online decoding in a cryogenic environment**

[1] S. Gicev, L. C. Hollenberg, and M. Usman, A scalable and fast articial neural network syndrome decoder for surface codes, arXiv preprint arXiv:2110.05854 (2021).