Moonshot Goal 6: International Symposium 2023

2023/07/18

Project progress report

"Research and Development of Theory and Software for Fault-tolerant Quantum Computers"

Masato Koashi (Project Manager)

The University of Tokyo

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Projects in Moonshot Goal 6

MOONSHOT
RESEARCH & DEVELOPMENT PROGRAM

- Integration Technologies for Superconducting Quantum Circuits
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- Large-scale quantum hardware based on nanofiber cavity QED
- Large-scale and high-coherence FTQC with dynamical atom arrays
- Large-scale Fault-tolerant Universal Optical Quantum Computers

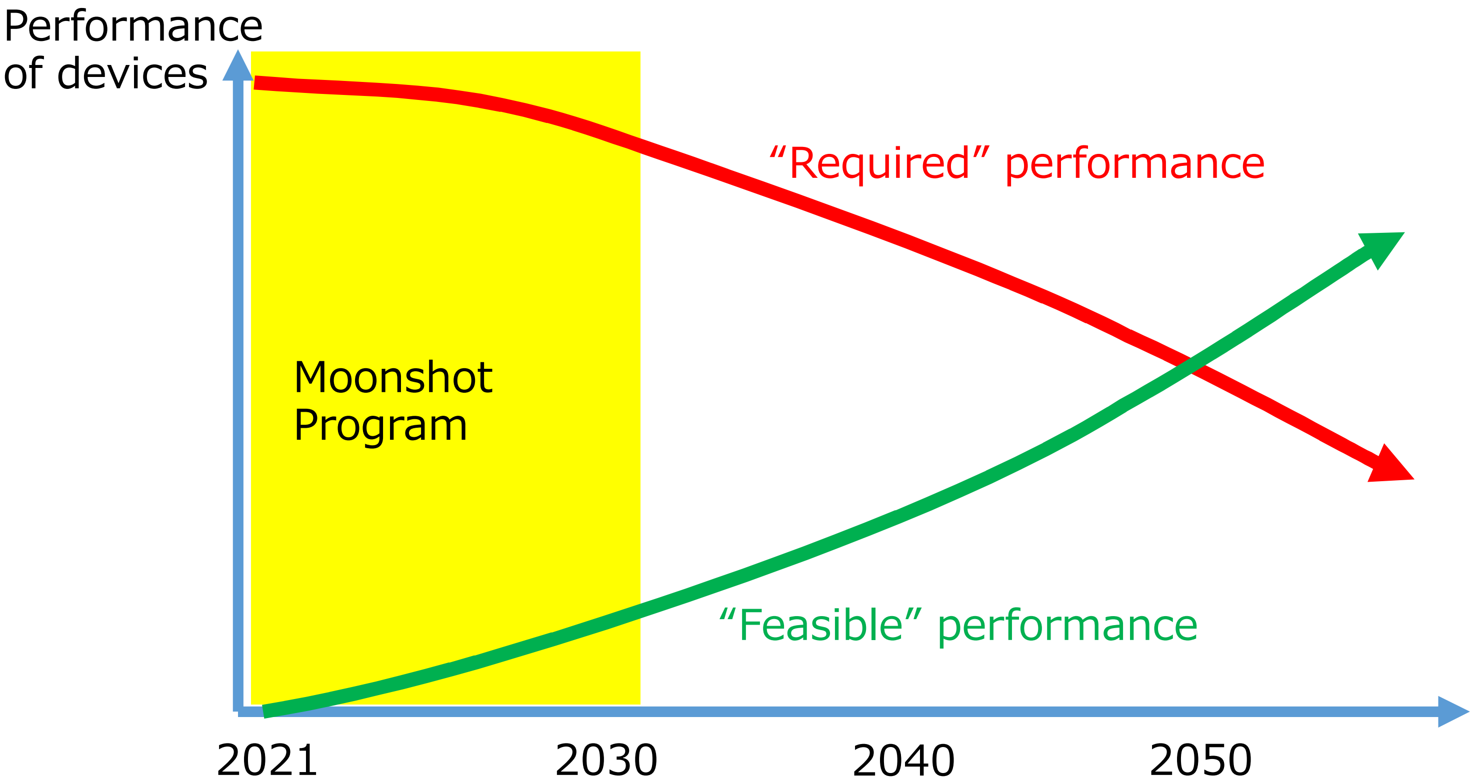
- Quantum Interfaces for Building Quantum Computer Networks
- Quantum Cyberspace with Networked Quantum Computer
- Scalable and Robust Integrated Quantum Communication System

- Scalable, Highly Integrated Quantum Error Correction System

Theory and Software

Mission for Theory/Software PJ

Moonshot Goal 6:
Realization of a fault-tolerant universal quantum computer that will revolutionize economy, industry, and security by 2050.



Mission for Theory/Software PJ

Substantially reducing the device performances required for large-scale fault-tolerant quantum computer.

Project PIs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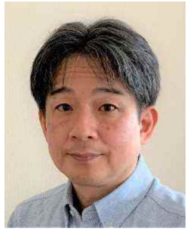
(TMDU)


Masato Koashi
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Kae Nemoto
(OIST)


Koji Azuma
(NTT)

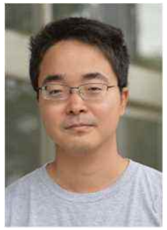

Rodney Van Meter
(Keio U)


Masahiro Takeoka
(Keio U)


Tomoyuki Morimae
(Kyoto U)


Hiroyasu Tajima
(UEC)


Shumpei Masuda
(AIST)


Masahito Yamazaki
(U of Tokyo)

Mission for Theory/Software PJ

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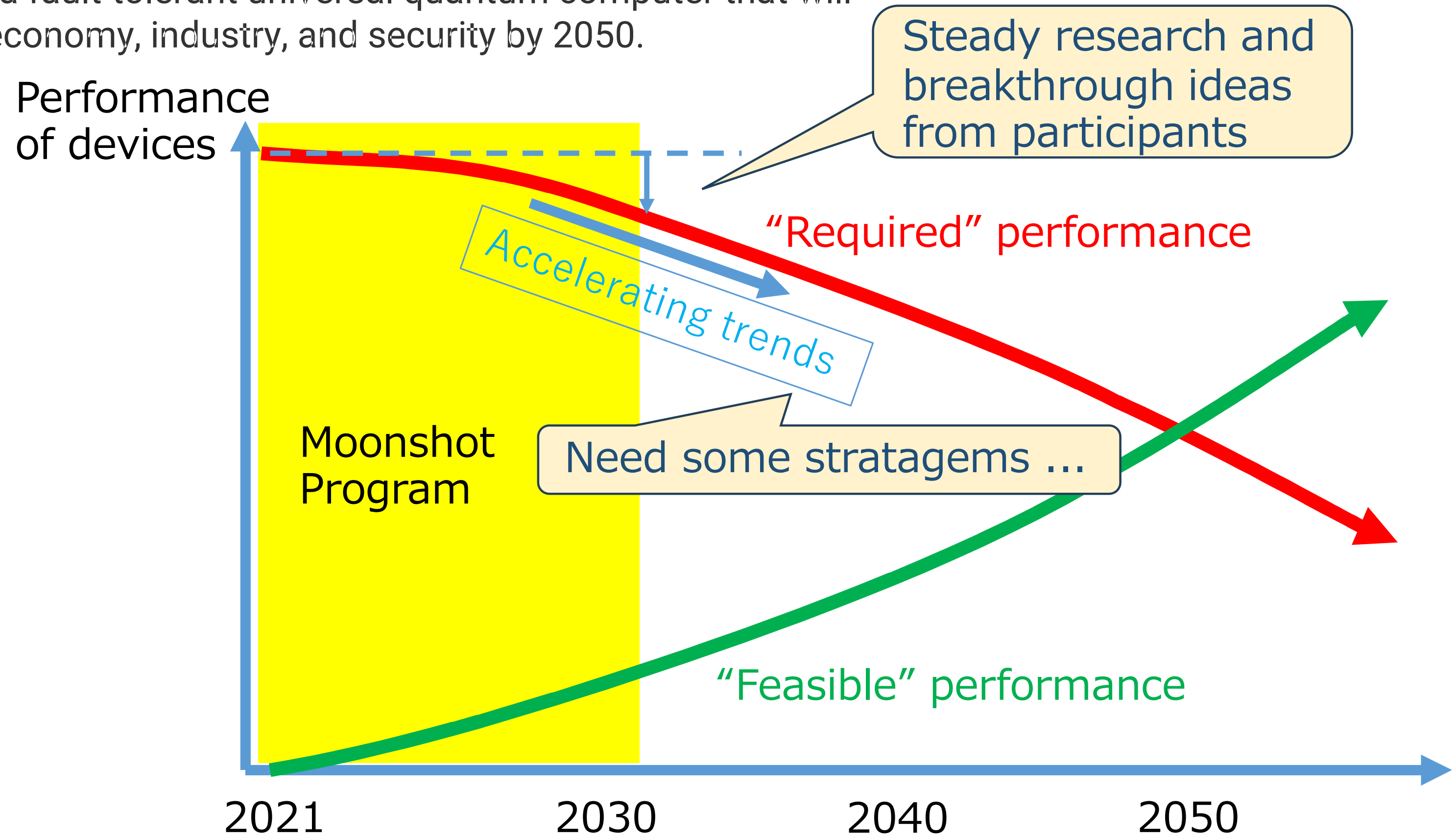
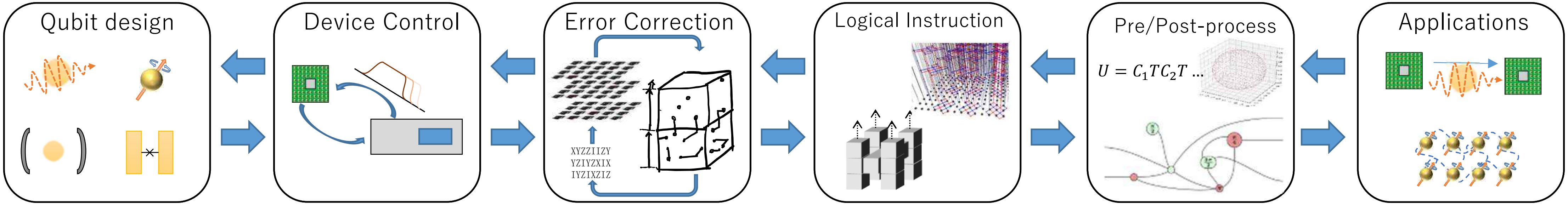


Mission for Theory/Software PJ

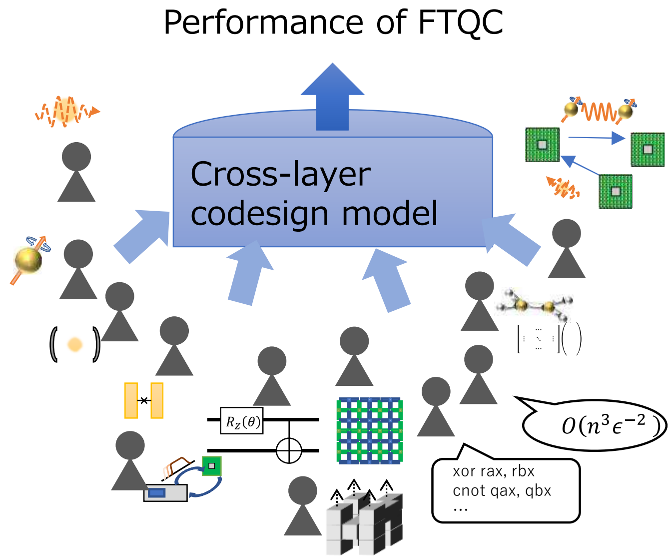
Substantially reducing the device performances required for large-scale fault-tolerant quantum computer.

Development of cross-layer codesign models

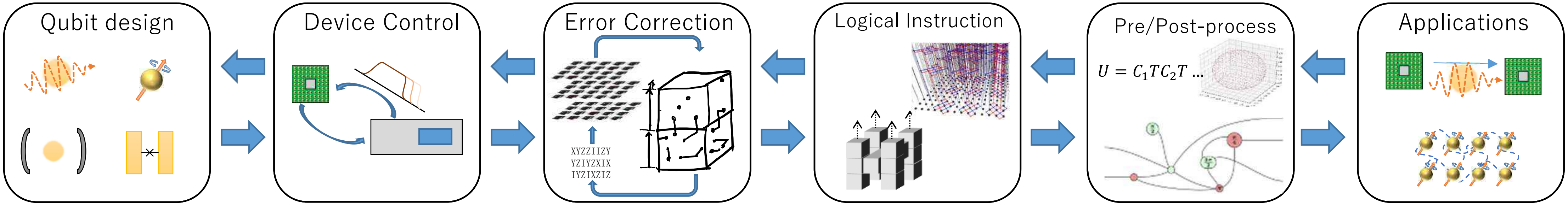


- A fault-tolerant universal quantum computer (FTQC) is a complicated system with many layers, such as designing qubits, controlling qubits, error correction, logical operations, compiling, and applications.

- A cross-layer codesign model is a set of connected software stacks that encompasses metrics and trade-off relations in these layers, and through optimizations and simulations, predicts the performance of the FTQC.



Development of cross-layer codesign models

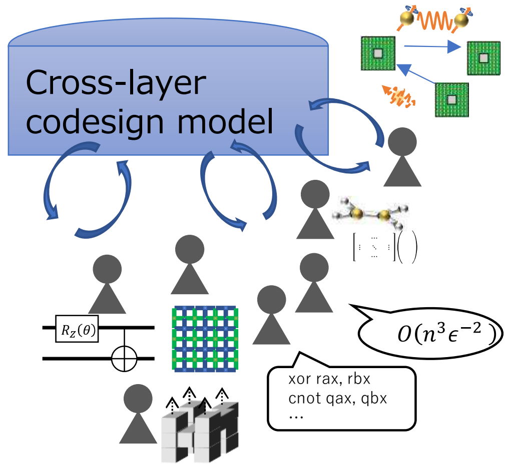


- In the development stage of the cross-layer codesign model, it works as a hub to promote research in the Theory/Software Project.

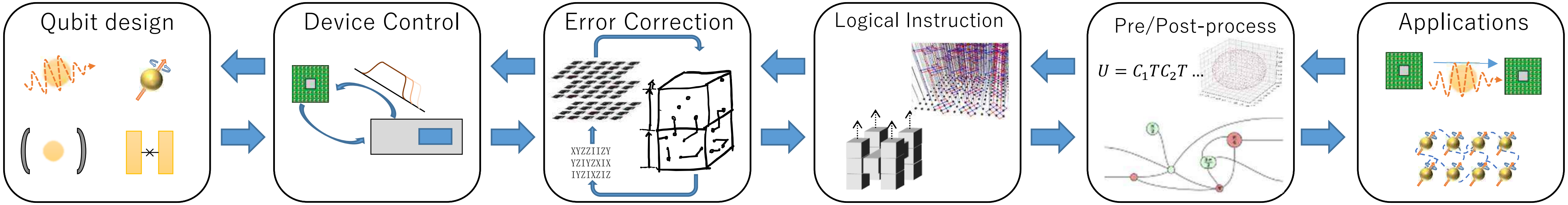
Encouraging interactions among them

Letting them communicate in the same language

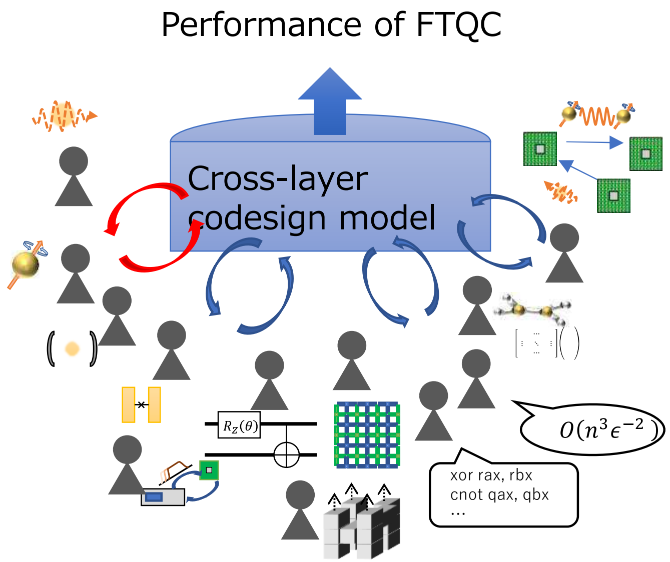
Helping them see the big picture toward the Goal of the Moonshot program.



Development of cross-layer codesign models



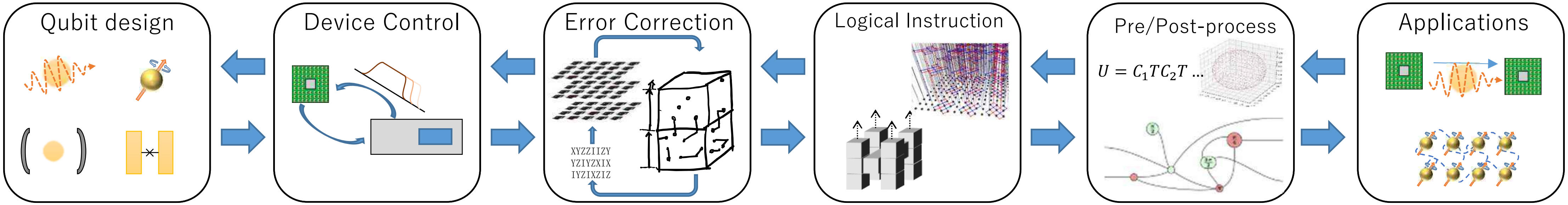
- Once the prototype of the model is constructed, it will work as a pilot to guide the researchers (theoretical/experimental) in the Moonshot Program toward its Goal.



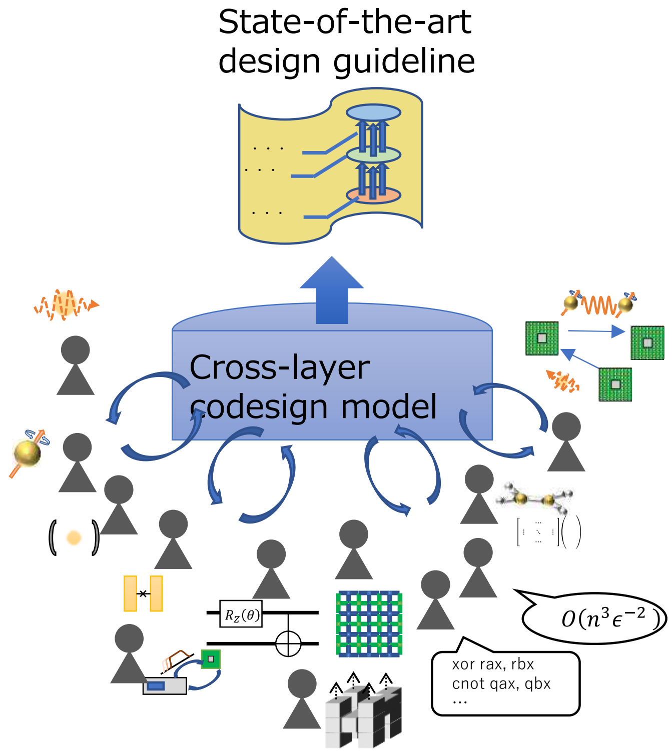
Trade-offs in various levels:
Choice of parameters in hardware design
Allocation of time and money

Hard to know what is the best within a single layer.

Development of cross-layer codesign models

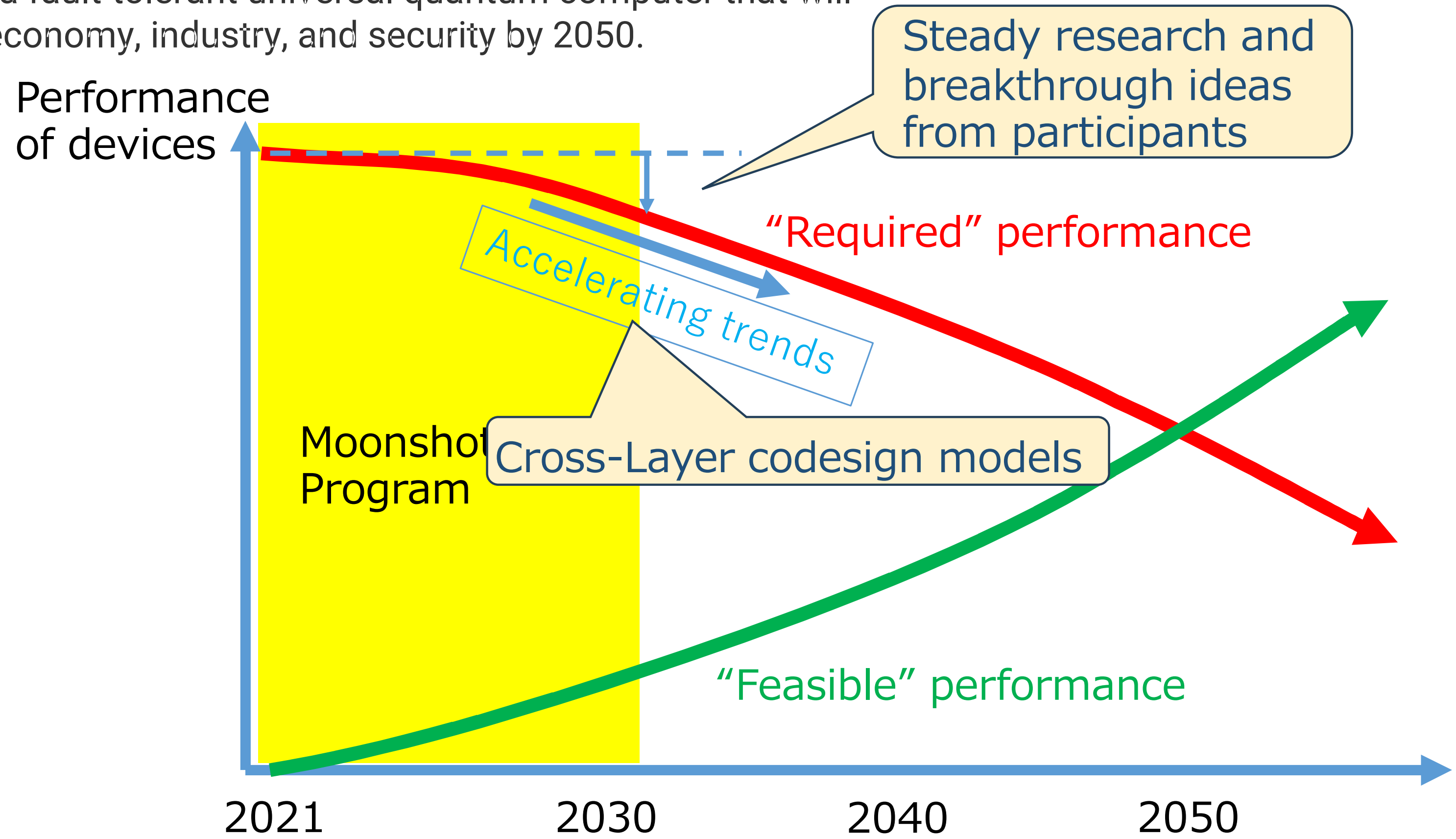


- Eventually, the model can put together the state-of-the-art results in each layer to produce an optimized design of FTQC, serving as a dynamical blueprint.



Mission for Theory/Software PJ

Moonshot Goal 6:
Realization of a fault-tolerant universal quantum computer that will revolutionize economy, industry, and security by 2050.



<u>Mission for Theory/Software PJ</u>

Substantially reducing the device performances required for large-scale fault-tolerant quantum computer.

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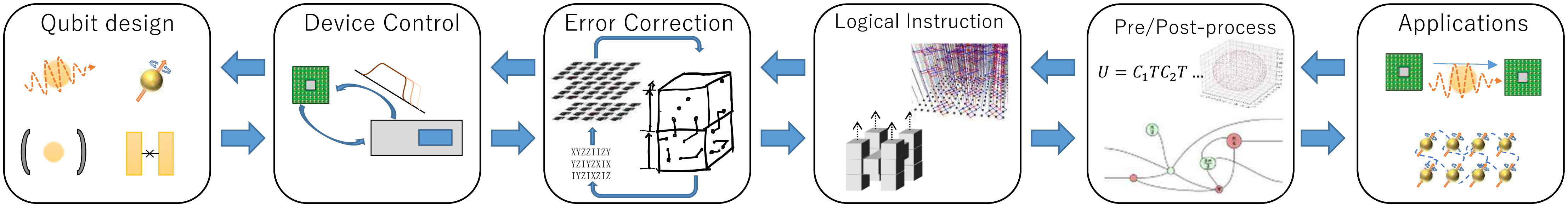
  - Quantum error correcting codes and fault tolerance
  - Hardware-specific results
  - Toward distributed architectures
  - NISQ and FTQC
- Summary and Outlook

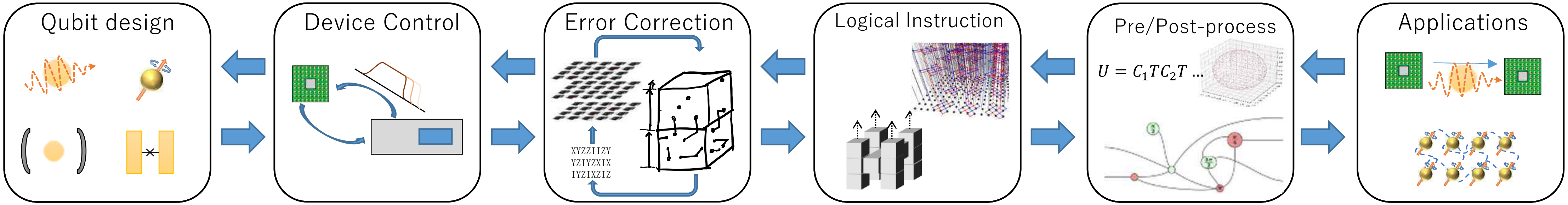
Cross-layer co-design (CLCD) model

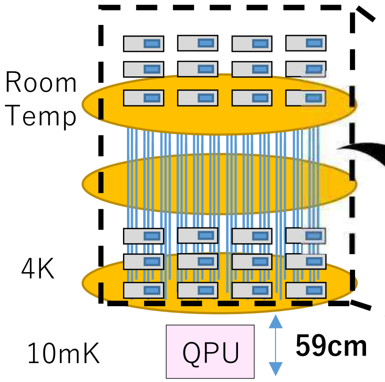
- CLCD models can be used for …
  - Revealing the trade-off relations across multiple layers
  - Evaluating of the true impact of a technological improvement
  - Demonstrating current state-of-the-art design by unifying proposed technologies

- CLCD models should be equipped with functions such as …
  - Evaluating the performance under a provided FTQC configuration
  - Optimizing parameters of FTQC to maximize the performance
  - Substituting mock-up modules depending on available computational resources



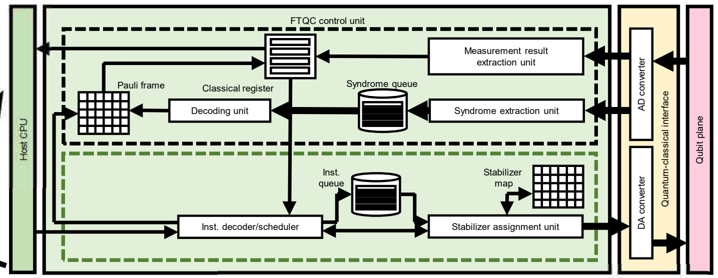
Cross-layer co-design (CLCD) model



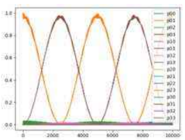


Code cycle: 1us
Bandwidth: 50Mbps per 1 log.q

Digital circuit: 0.41 mW per 1 log.q
Analog circuit: 60W per 1 phys.q

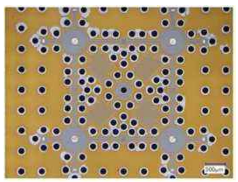


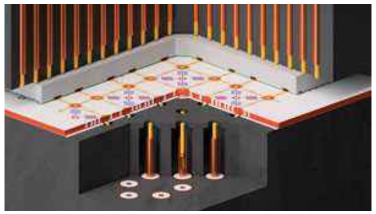
503,608 phys qubits



10^{-3} infidelity

1.2mm

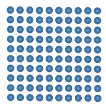




Mnemonic	Operand	Latency	Repr. in physics
INIT_ZERO INIT_PLUS	pos pos	1	$* \mapsto \vert 0\rangle$ $* \mapsto \vert 1\rangle$
INIT_T	pos	random	$* \mapsto \vert A\rangle := (\vert 0\rangle + e^{i\pi/4}\vert 1\rangle)/\sqrt{2}$
OP_H	pos	3d	$\vert\psi\rangle \mapsto H\vert\psi\rangle$
MEAS_X MEAS_Z	pos, addr pos, addr	1	$\vert\psi\rangle \mapsto ((I + (-1)^s X)/2\vert\psi\rangle, s)$ $\vert\psi\rangle \mapsto ((I + (-1)^s Z)/2\vert\psi\rangle, s)$
MEAS_Y	pos, addr	2d	$\vert\psi\rangle \mapsto ((I + (-1)^s Y)/2\vert\psi\rangle, s)$
MEAS_ZZ MEAS_XX	pos1, pos2, addr pos1, pos2, addr	d	$\vert\psi\rangle \mapsto ((I + (-1)^s XX)/2\vert\psi\rangle, s)$ $\vert\psi\rangle \mapsto ((I + (-1)^s ZZ)/2\vert\psi\rangle, s)$
READ	addr	random	$s \mapsto s_{\mathrm{corrected}} := s \oplus e$

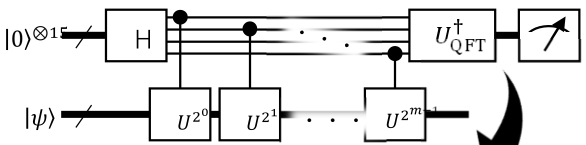
842,694,656 instructions
120 logical qubits
(456 logical qubits with ancillary space)

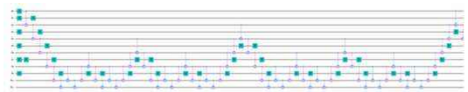
Ground energy estimation of 10x10 Heisenberg model with accuracy 10^{-2}

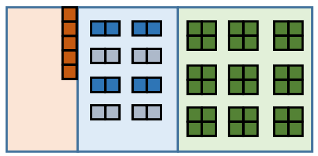


$$H = \sum_i \alpha_i P_i$$

Qubitization-based phase estimation







Compiler optimization and logical qubit layout

Example system design
that outperforms classical computing

Runtime

14 hours

(22 hours with a CPU)

Power consumption

About 22MW

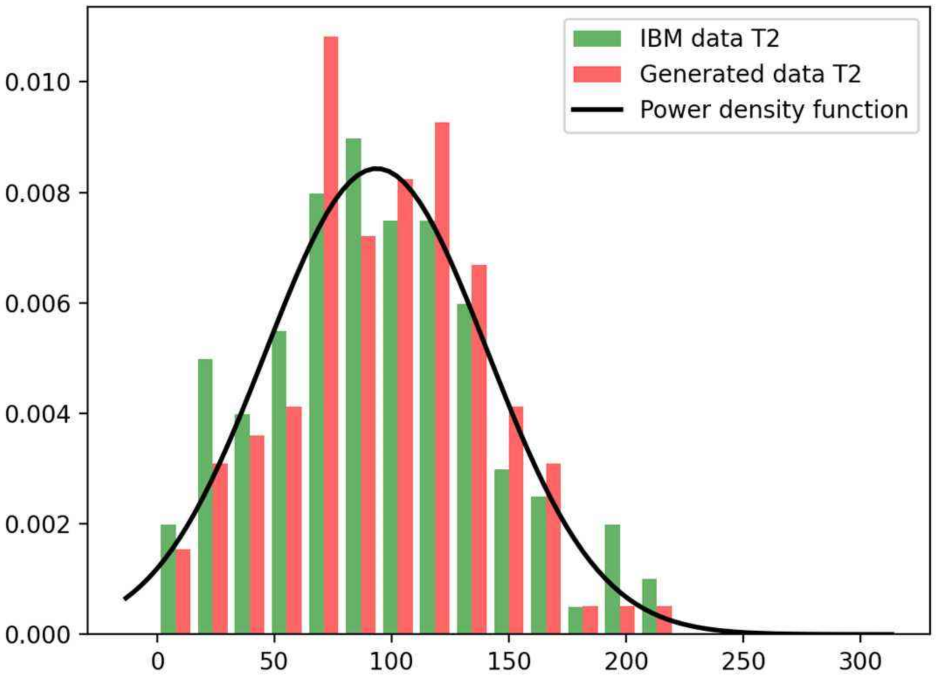
(13MW in K-computer)

Managing inhomogeneous qubit qualities

(NTT, U of Tokyo)

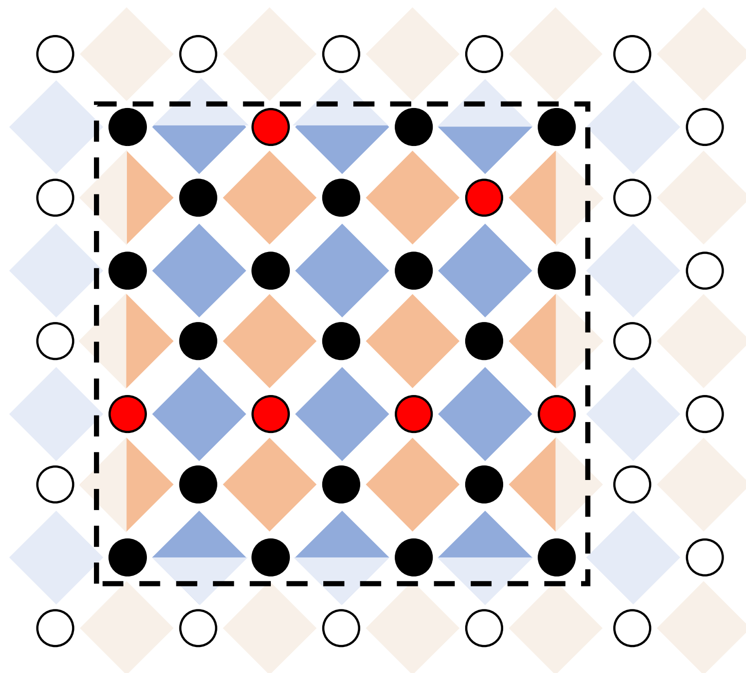
Background

Low-quality qubits are unavoidable in large-scale integration



Lifetime from IBMQ chip

Unfavorable bad-qubit allocation results in bad logical qubit.



Low-quality physical qubit

Managing inhomogeneous qubit qualities

(NTT, U of Tokyo)

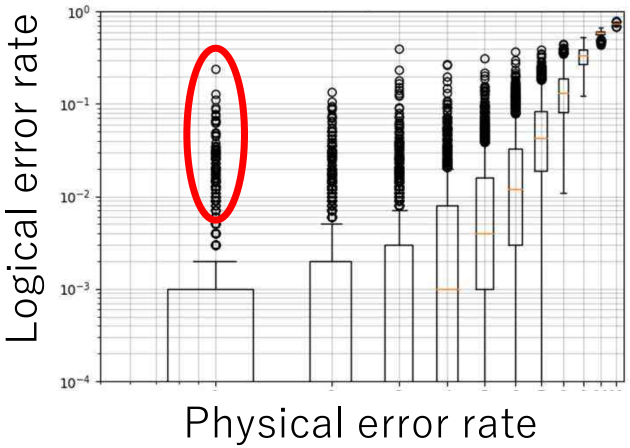
Our contribution

We developed fast error-estimation circuits on FPGAs considering error-rate variations.

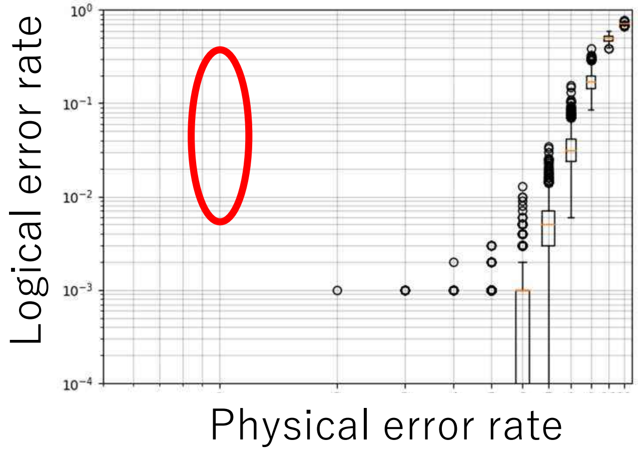
Performance evaluation

Liao, Suzuki, Tanimoto, Ueno, Tokunaga, the 28th Asia and South Pacific Design Automation Conference (ASP-DAC), Online (2023).

Baseline

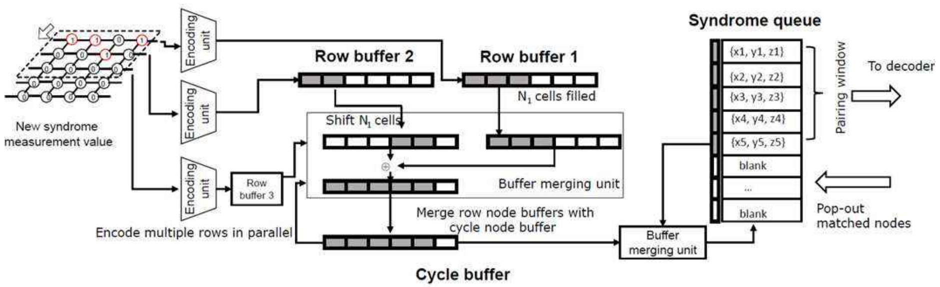


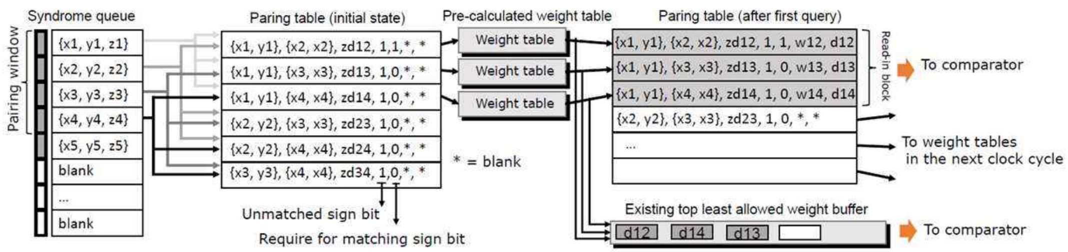
WIT-Greedy (our proposal)



High-logical-error logical qubits appear with the existing error-estimation methods. Our proposal successfully reduce them.

Key technology For fast error-estimation, we partially utilize pre-calculated look-up tables in a scalable way.



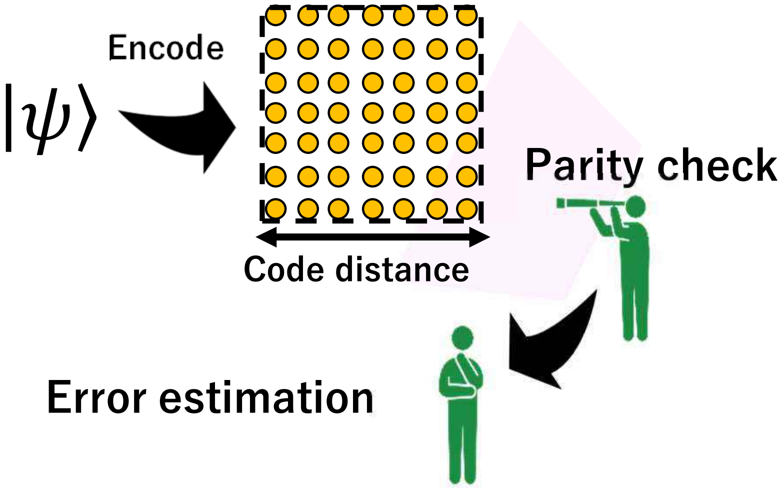


Burst-error tolerant FTQC

(NTT, U of Tokyo)

Background

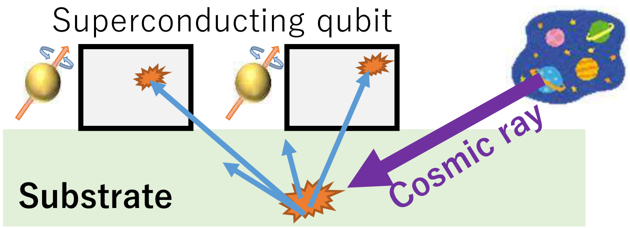
Typical QEC schemes assume uniform error rates in error estimation



Current QEC scheme assumes error properties are static. However, they can vary during long-term computation.

Phenomena resulting in time-varying error properties

Cosmic-ray bust errors



Property of cosmic-ray strike

Duration： 26ms
Area： 4x4 qubit area
Error rate：x30
Frequency：0.1Hz in 26-qubit chip area

M.McEwen *et al.*, NatPhys **18**, 107-111 (2022)

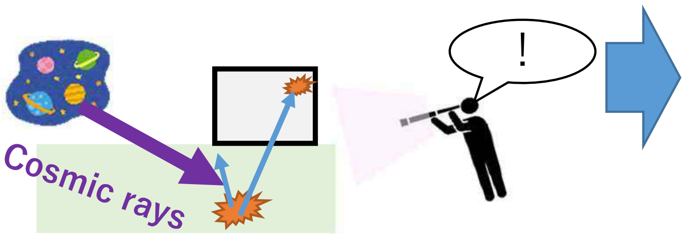
FTQC is expected to run for several hours to show asymptotic speed-up. Thus, time-varying properties can spoil the scalability of FTQC architecture.

Burst-error tolerant FTQC

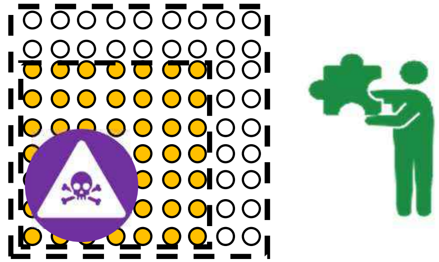
(NTT, U of Tokyo)

Key idea: Quickly detect time-varying errors and mitigate them with two strategies

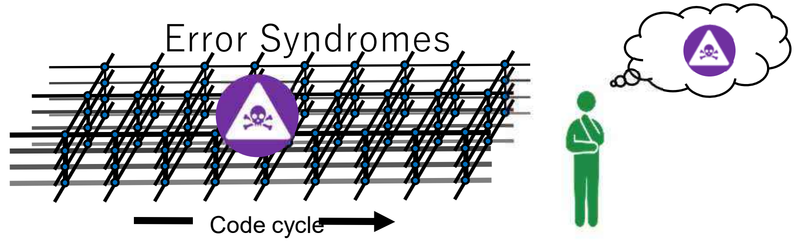
Detect time variation with anomaly detection



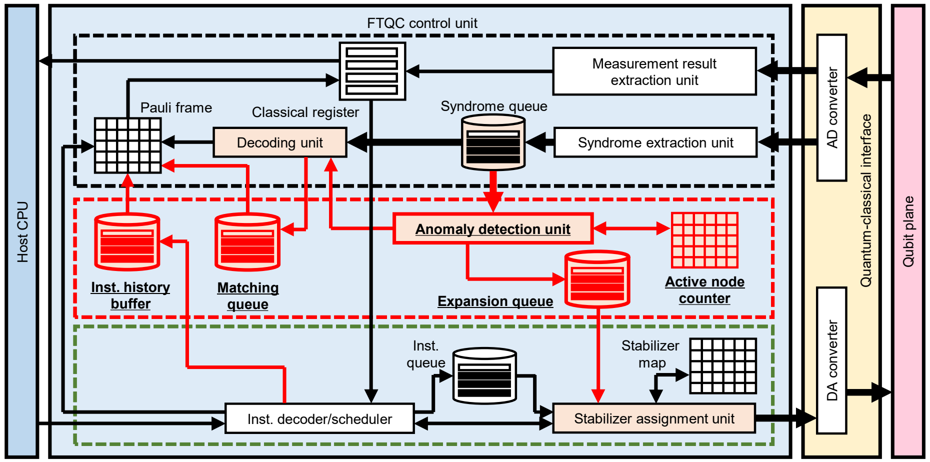
Expand code distances of affected regions



Re-estimate errors with considering detection



We designed FTQC control units and show its feasibility with FPGAs



Resource usage

Configuration	FF (%)	LUT (%)	throughput
40 – BASE	8,991 (4)	14,679 (6)	4.66
40 – Q3DE	13,855 (6)	20,279 (9)	4.25
80 – BASE	13,211 (6)	36,668 (16)	1.81
80 – Q3DE	22,751 (10)	54,638 (24)	1.79

Memory and latency overhead.

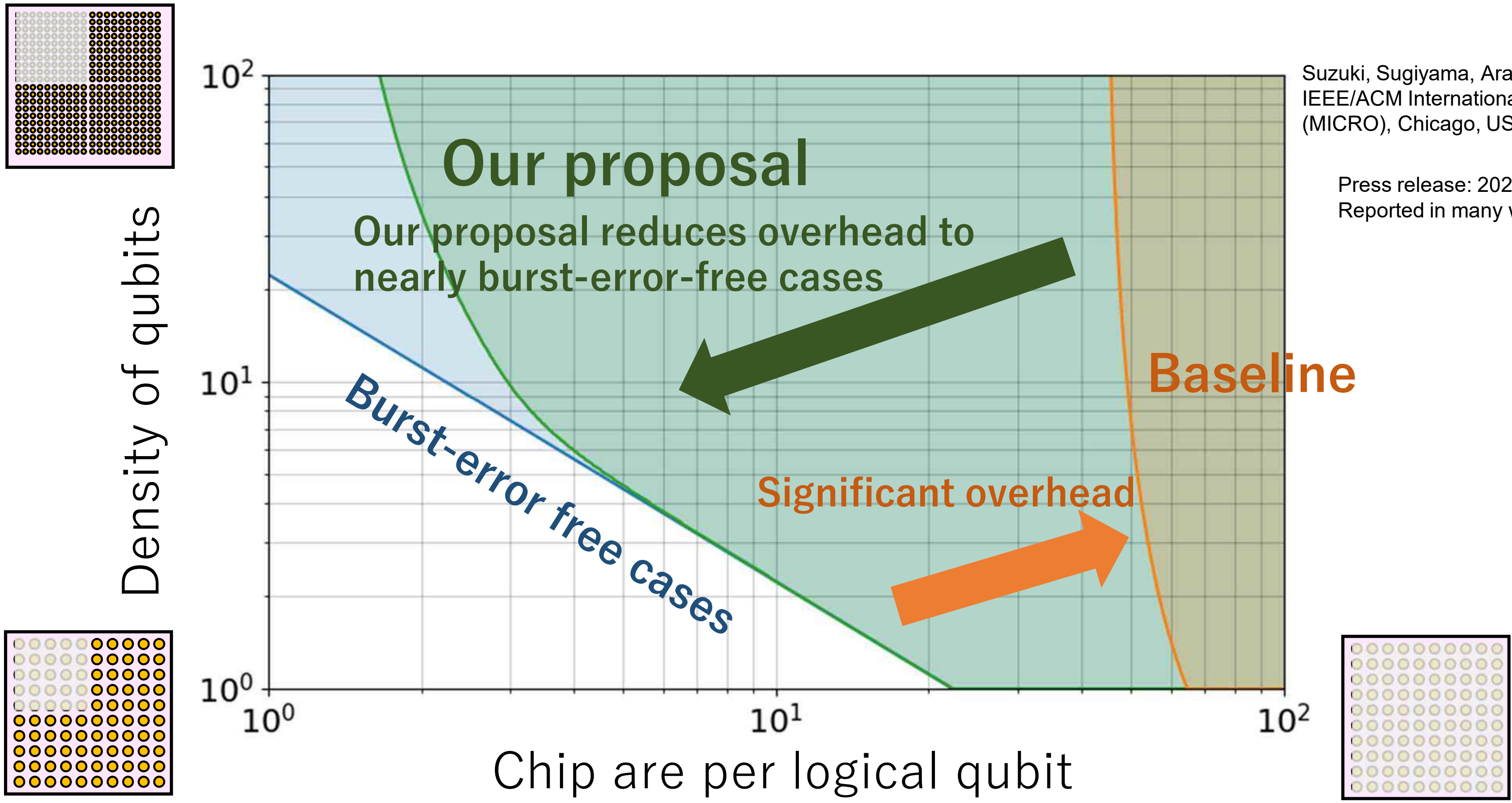
Unit	Order	Size
syndrome queue	$2d^2(c_{\mathrm{win}} + \sqrt{2c_{\mathrm{win}}})$	623 kbit
active node counter	$2d^2 \log_2 c_{\mathrm{win}}$	16 kbit
matching queue	$2d^2 \sqrt{c_{\mathrm{win}}/2}$	24 kbit
inst. hist. buffer	negligible	–
expansion queue	negligible	–

Burst-error tolerant FTQC

(NTT, U of Tokyo)

Baseline evaluation and our contribution

Hardware requirement to achieve 10^{-10} logical error rates under cosmic-ray burst errors.
(Achievable hardware configurations are shaded)



Suzuki, Sugiyama, Arai, Liao, Inoue, Tanimoto, the 55th IEEE/ACM International Symposium on Microarchitecture (MICRO), Chicago, USA(2022).

Press release: 2022/9/30
Reported in many web and news media

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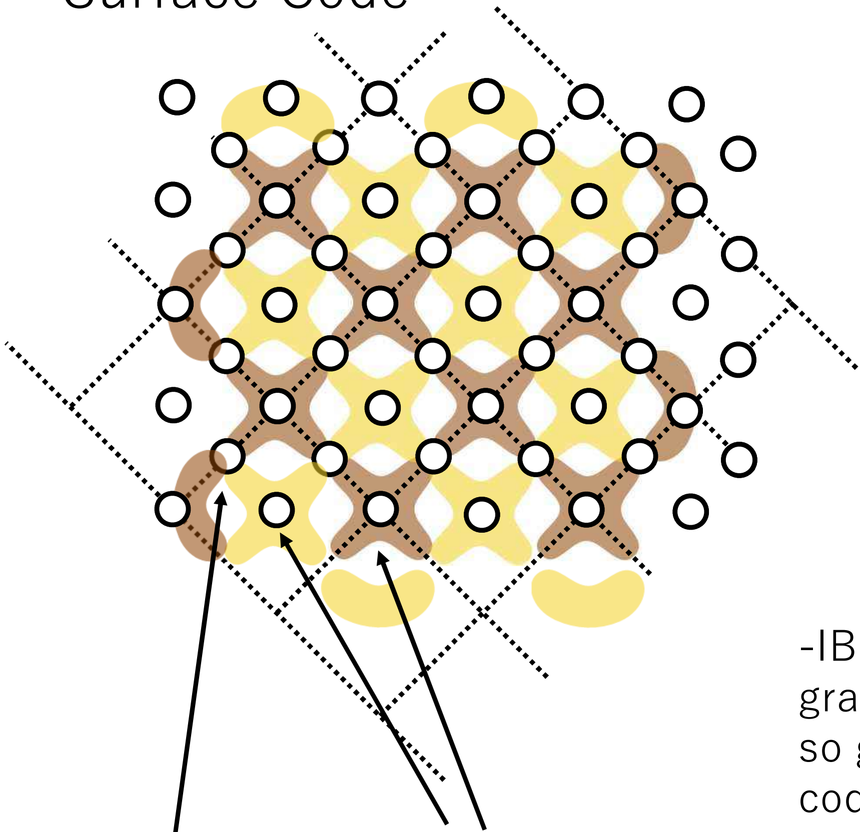
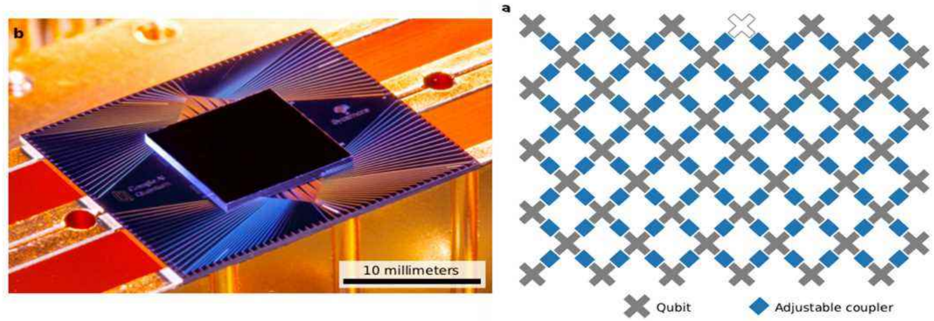
Improving connectivity of surface code via dynamic code concatenation

(Osaka U)

Surface Code



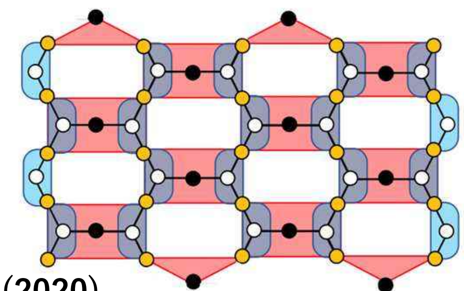
- Can be implemented with qubits aligned on a two-dimensional plane or square lattice.
- Error tolerance is high, up to about 1%.



Google team, Nature **574** 510 (2019)

- Coupling with adjacent 4 qubits makes frequency collision issue and causes error via crosstalk.

-IBM proposed a method using a graph of order 3 (performance is not so good because it uses subsystem code)

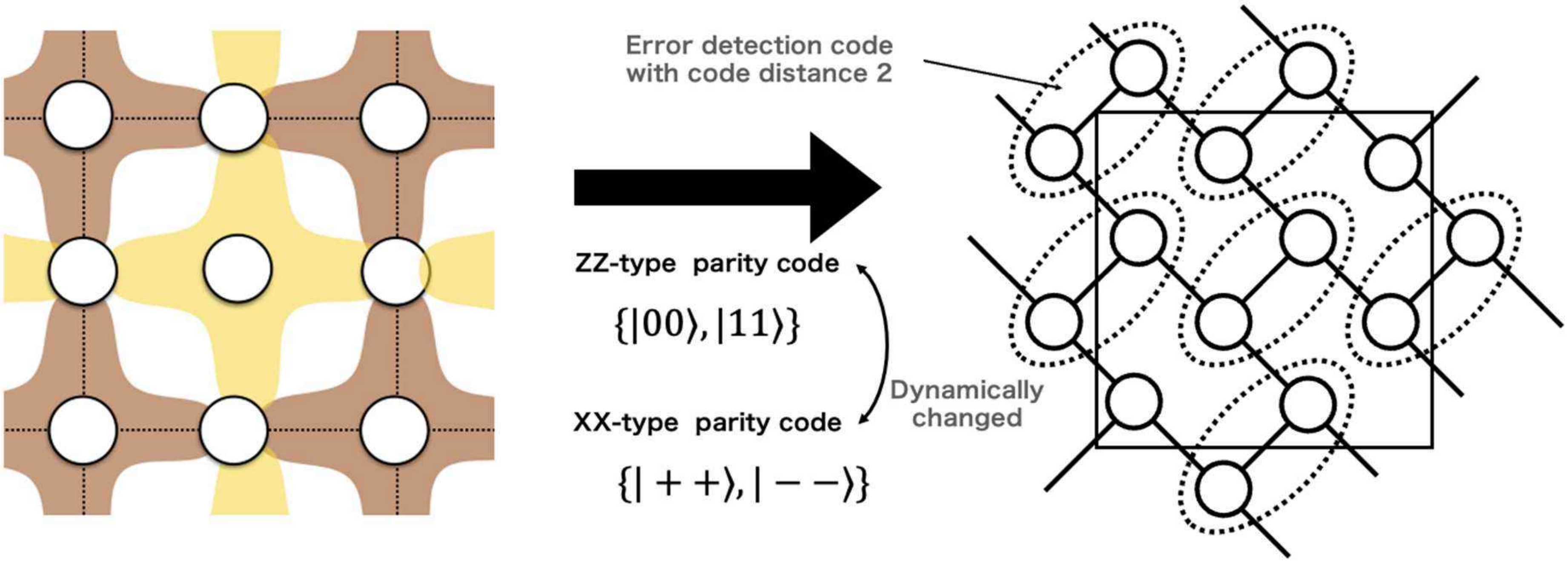


C. Chamberland et al, Phys. Rev. X 10, 011022 (2020)

Improving connectivity of surface code via dynamic code concatenation

(Osaka U)

- The proposed method is based on **dynamic concatenation** of small distance codes and surface codes.
- Surface codes can be constructed on a graph of **degree 3**.
- The small distance code can **detect errors and raise a flag**.
- Constructed an **accurate decoder using the flag information**.

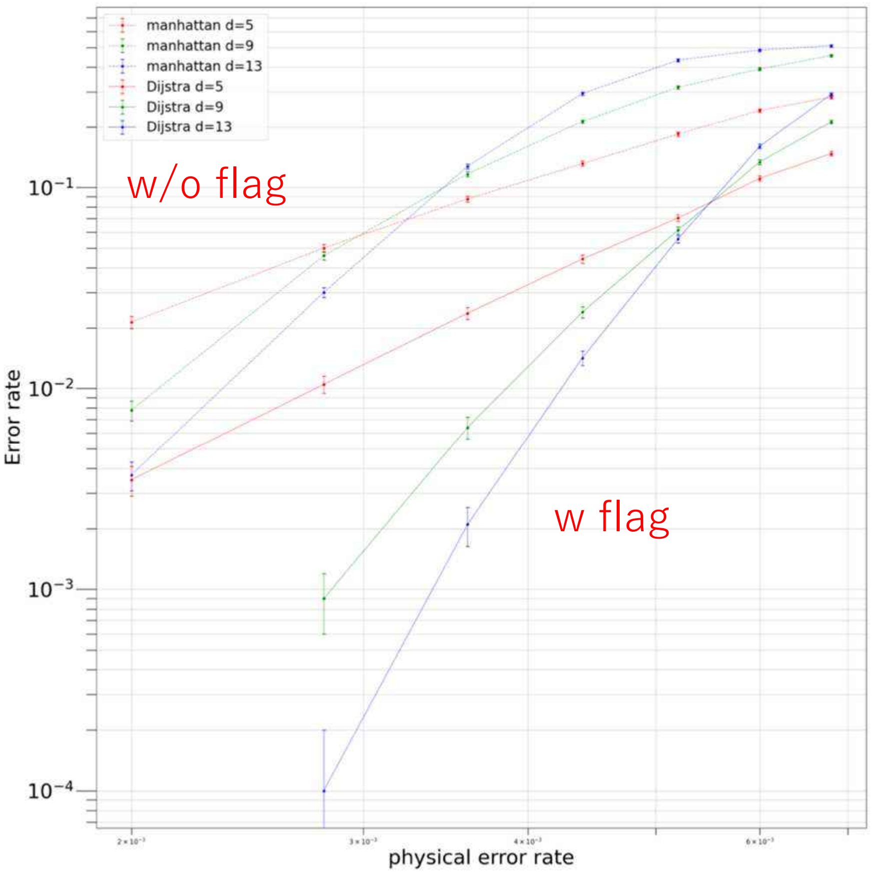


Improving connectivity of surface code via dynamic code concatenation

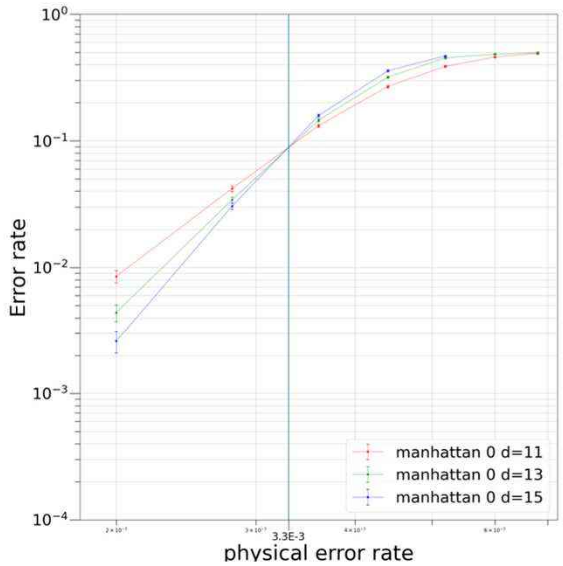
MOONSHOT RESEARCH & DEVELOPMENT PROGRAM

(Osaka U)

Logical error probability

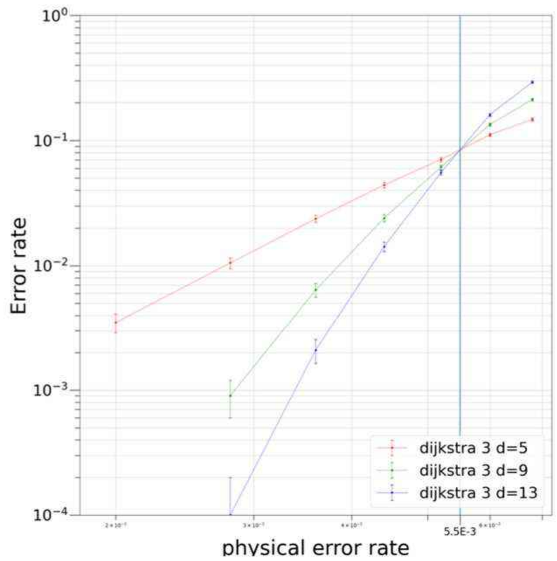


Physical error probability



約3.3×10^{-3}

w/o flag information



約5.5×10^{-3}

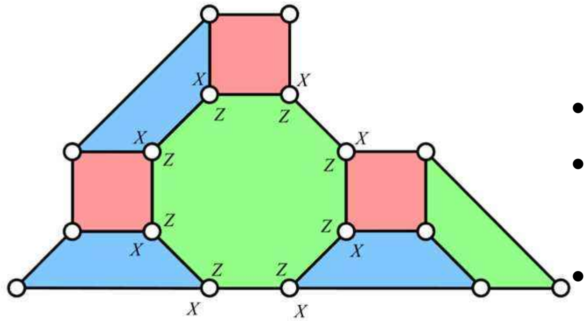
W flag information

- The validity of decoding with flag is confirmed.
- The threshold values are almost the same as that for the conventional method with degree 4 graph.
- Higher threshold and lower logical error rate compared to previous studies with other codes.

Decoding color code by simulated annealing

MOONSHOT RESEARCH & DEVELOPMENT PROGRAM
(Osaka U)

Y. Takada et al., arXiv:2303.01348.

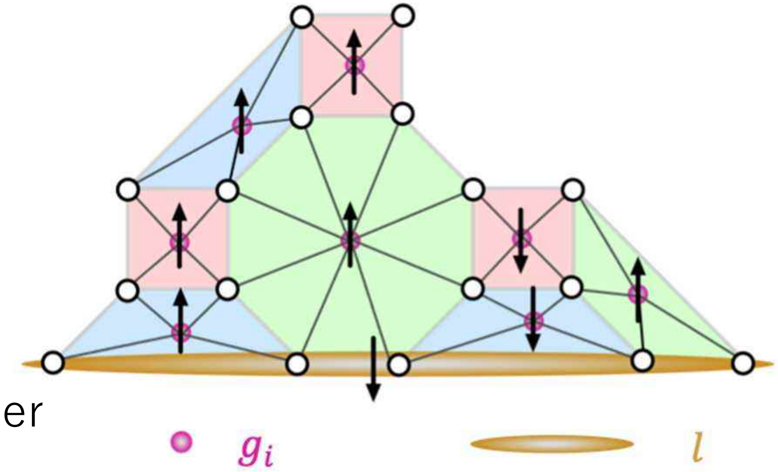


- Transversal gates are supported for all Clifford gates.
- The threshold is one order of magnitude smaller when circuit-level noise is considered.
- Decoding is difficult, and even performance evaluation is not so easy.

Proposed method: Assign a classical spin variables to each stabilizer, and find the error location with the lowest weight by minimizing cost functions.

Error decomposition：$\boldsymbol{E = T(S)GL}$

$T(S)$: A fixed error (pure error) defined by S.
$G = \prod_i G_i^{g_i}$: Stabilizer operator G_i and corresponding binary valuable g_i.
$L = L_X^{l_x} L_Z^{l_z}$: Logical operator L_x, L_z and corresponding binary valuables.
→Find $\{g_i\}, l_x, l_z$ that minimize the weight $\mathrm{wt}(E)$ by higher order Ising optimization problem.



Decoding color code by simulated annealing

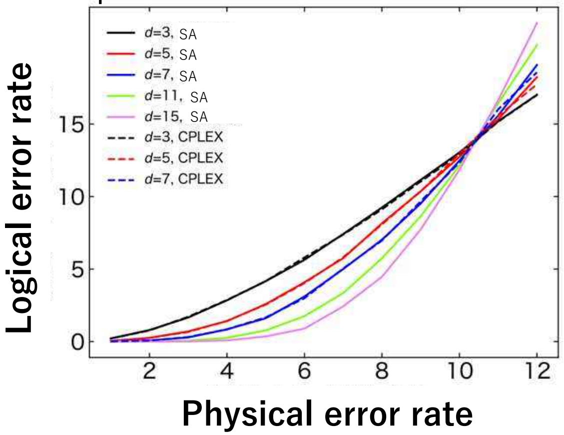
MOONSHOT RESEARCH & DEVELOPMENT PROGRAM

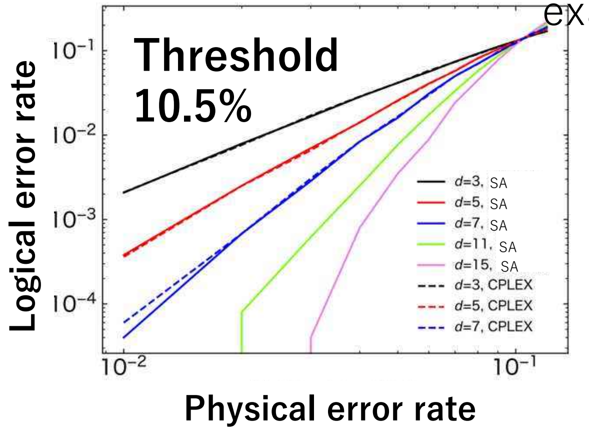
(Osaka U)

Comparison of CPLEX and SA for exact optimal solution

Y. Takada et al., arXiv:2303.01348.

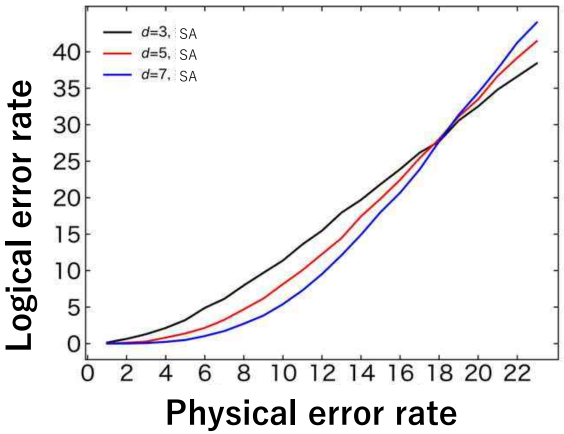
Bit flip error

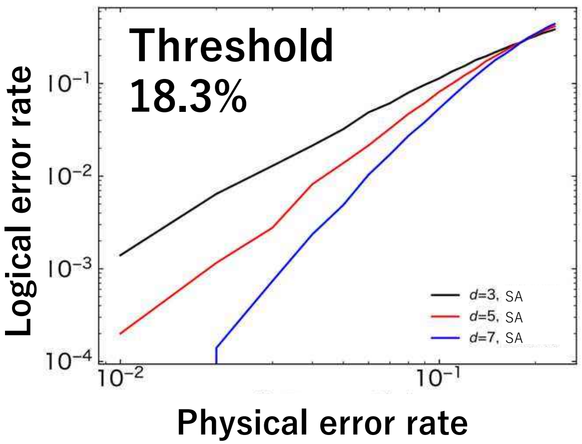




→Comparable to exact solver, CPLEX.

Depolarizing error





Decoding time

	$d = 3$	$d = 5$	$d = 7$
SA	0.027 sec	0.027 sec	0.065 sec
CPLEX	0.059 sec	0.289 sec	0.453 sec

Thresholds by existing decoders

Renormalization group decoder [3]	8.7%
Union find decoder [4]	9.8%
Restriction decoder [4]	10.2%
Least-weight correction [5]	10.6%

Future direction:

- Extend the system to handle more realistic noise.
- Investigate a method to measure the syndrome of color codes without degrading the threshold.

Local probabilistic decoding

MOONSHOT RESEARCH & DEVELOPMENT PROGRAM

(OIST)

T. R. Scruby and K. Nemoto, arXiv:2212.06985.

- Commonly assumed in the literature:

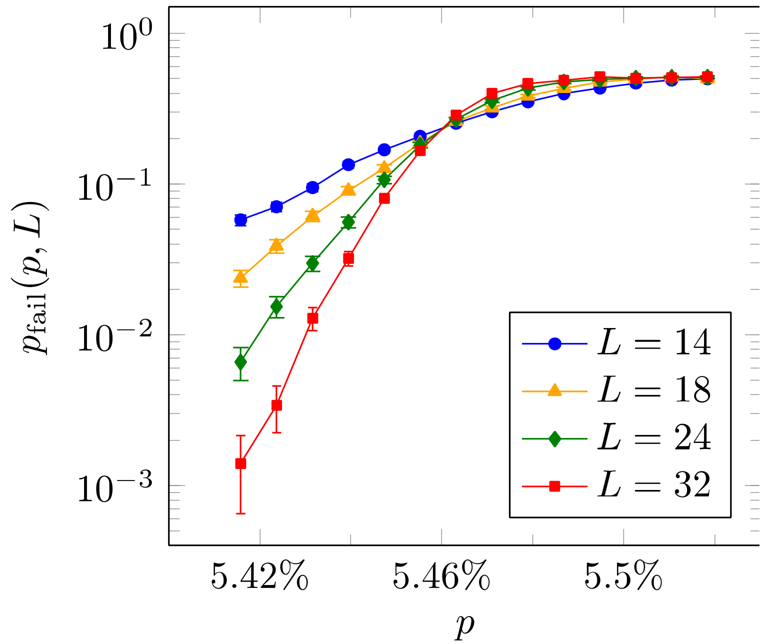
  A useful quantum decoder should be able to correct all "constant weight" errors

  The simple <u>"flip" decoder</u> wouldn't work

  Very fast.
  The error pattern search is locally done by flipping only one bit at a time.

- But.. that's not the case!!

  A novel decoder for the 3D Toric code:



A novel decoder for the 3D Toric code:

	Runtime	Threshold
Proposed	$O(n)$	5.5%
Best Known*	$O(n^3)$	7.1%

(*) Higgott and Breuckmann, arXiv.2206.03122.

Efficiency of FTQC in the large-scale limit

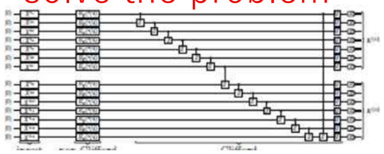
(U of Tokyo)

- Overheads for fault-tolerant quantum computing

M: size of the problem

The circuit to solve the problem

\# of logical qubits
$W(M) = O(\mathrm{poly}(M))$



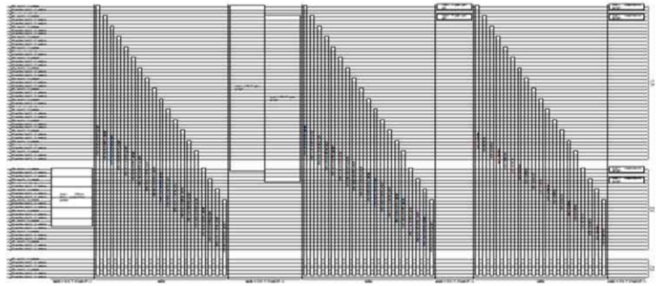
$D(M) = O(\mathrm{poly}(M))$
\# of logical steps

Compiling

\# of physical qubits
$W(M) \times \boxed{???}$

Space overhead

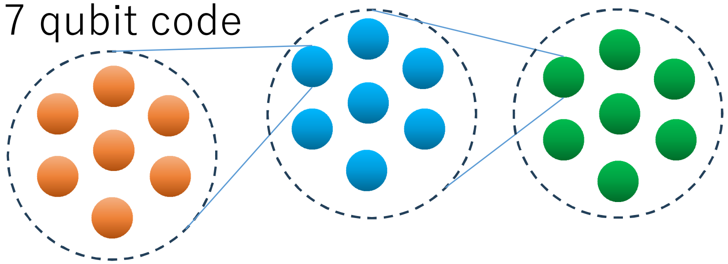
The actual FTQC circuit



$D(M) \times \boxed{???}$ ← Time overhead
\# of actual steps

Concatenated codes

Nesting the same small code repeatedly.

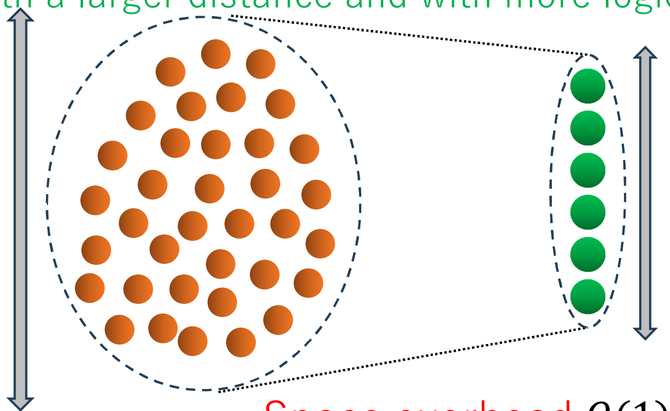


A bigger problem ⇨ More nesting levels

Space overhead $O(\mathrm{polylog}(M))$

Quantum LDPC codes (with a nonzero rate)

A bigger code with a larger distance and with more logical qubits



Space overhead $O(1)$

Needs concatenated codes to assist a gate operation.
Gates cannot be operated cannot be in parallel if one wants to save the space overhead.

Time overhead
$\mathrm{poly}(M)$

Efficiency of FTQC in the large-scale limit

(U of Tokyo)

Yamasaki and Koashi, arXiv:2207.08826.

・A novel architecture of concatenated codes:

Space overhead $O(1)$

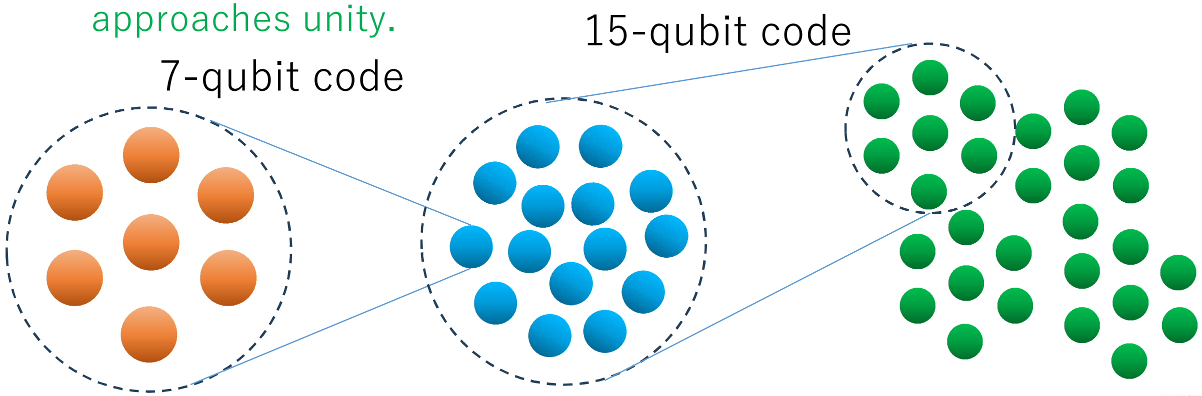
Time overhead $\exp\left(O(\mathrm{polylog}(\log M))\right) \ll \exp(O(\log M)) = \mathrm{poly}(M)$

・Instead of repeating the same code in the conventional concatenation,

we use a series of gradually growing sizes of codes (Quantum Hamming codes)

The code distance is always 3

The number of logical qubits increases and the rate approaches unity.

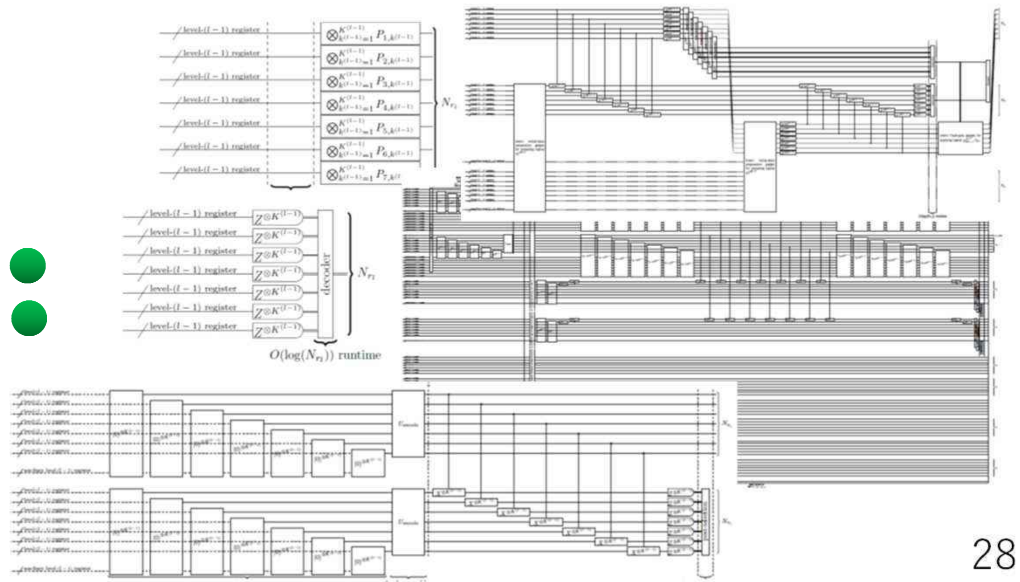


Concatenation of these codes forms a big code with a non-zero rate.

・Decoding is done in each level and is very simple.

(The threshold and the overhead scaling were analytically proved even with the runtime of classical computation is taken into account.)

Fault-tolerant gadgets for multiple logical qubits (registers)



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- Overview of the Theory/Software Project
- Progress report
  - A prototype of cross-layer codesign model and related results
  - Quantum error correcting codes and fault tolerance
  - Hardware-specific results
  - Toward distributed architectures
  - NISQ and FTQC
- Summary and Outlook

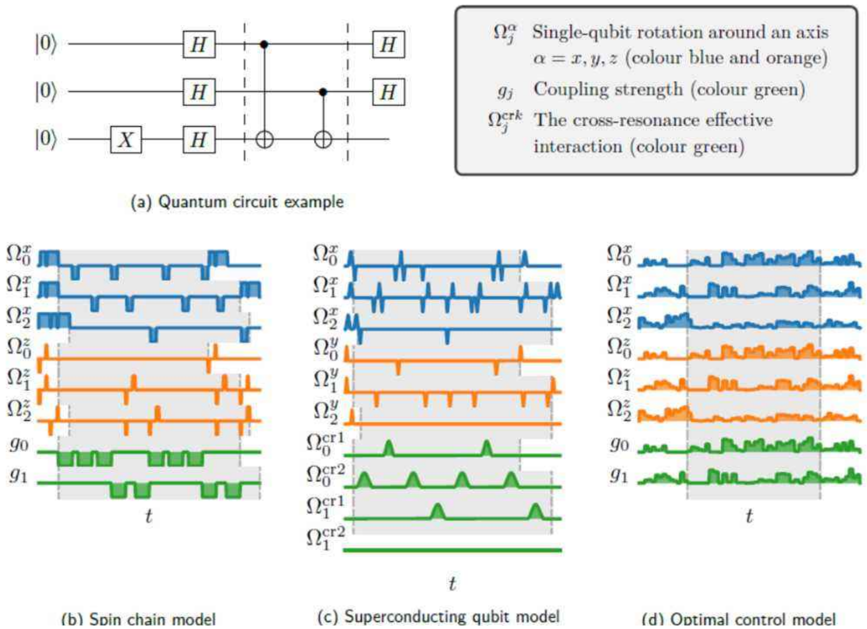
QuTiP (the Quantum Toolbox in Python) (RIKEN)

Open-source numerical package for the general simulation of open quantum systems

More than 1 million downloads

A new package (qutip-qip), which addresses pulse-level simulation of noisy quantum circuits

B. Li *et al.*, Quantum **6**, 630 (2022).

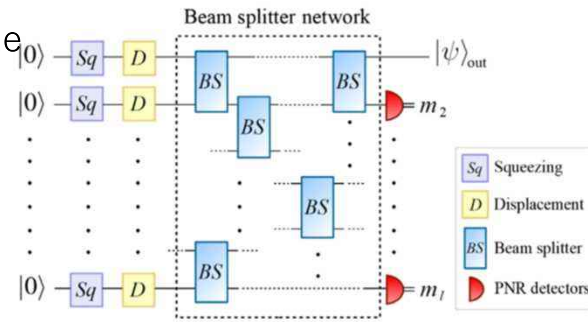


Efficient backcasting search for optical quantum state synthesis (U of Tokyo)

K. Fukui *et al.*, Phys. Rev. Lett. **128**, 240503 (2022).

Designing a way to synthesize non-Gaussian states

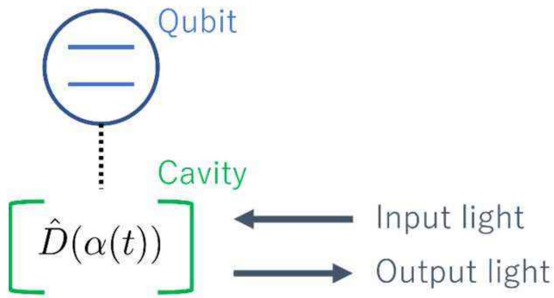
Reducing the computational cost to polynomial instead of exponential.



Simulation method for dynamics of superconducting qubits interacting with optical modes with large amplitudes. (TMDU)

Perturbation is not allowed.

A novel method using displacement operators to reduce the computational costs.

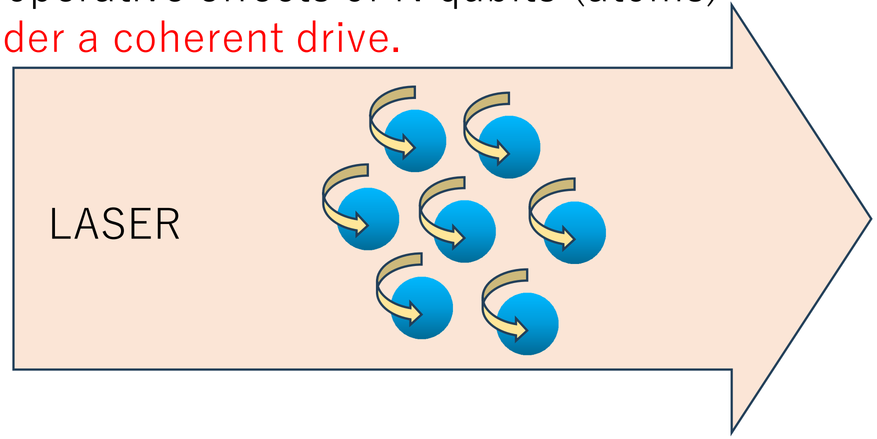


Super absorption by multiple qubits

(Tsukuba U)

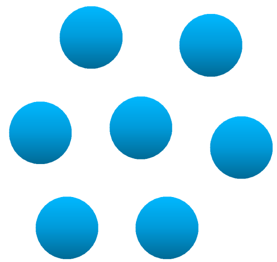
S. Kamimura *et al.*, Phys. Rev. Lett. **128**, 180602 (2022).
S. Kamimura *et al.*, to appear in Phys. Rev. Lett (2023).

Cooperative effects of N qubits (atoms)
under a coherent drive.

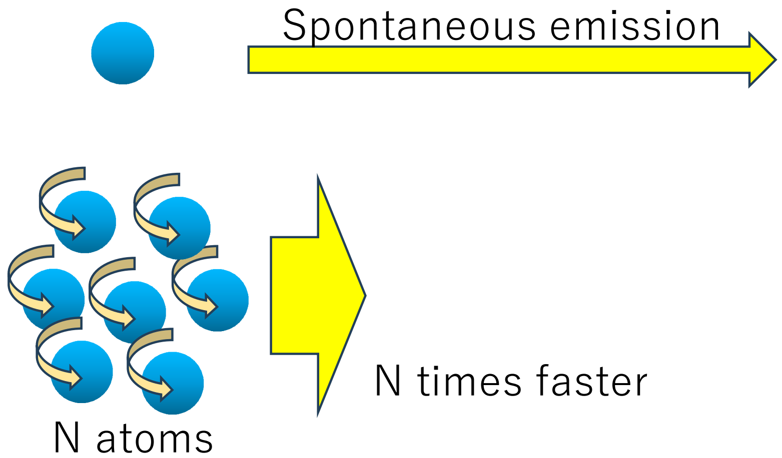


The N atoms oscillate in sync with the drive, leading to enhanced effects.

Cooperative effects of N qubits (atoms)
without a coherent drive?



Dicke superradiance

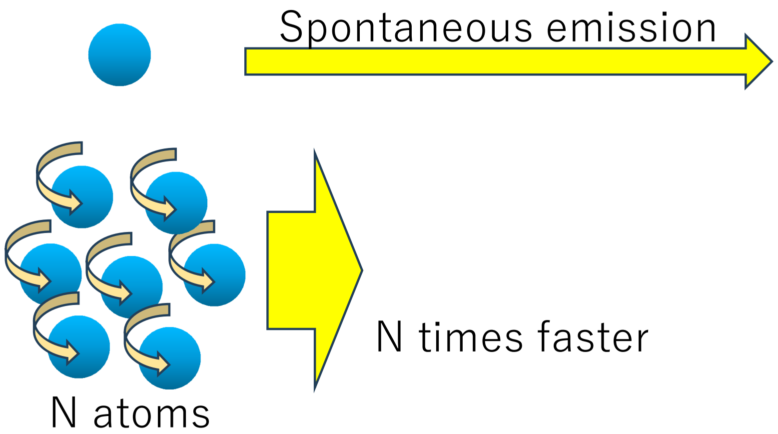


Super-absorption by multiple qubits

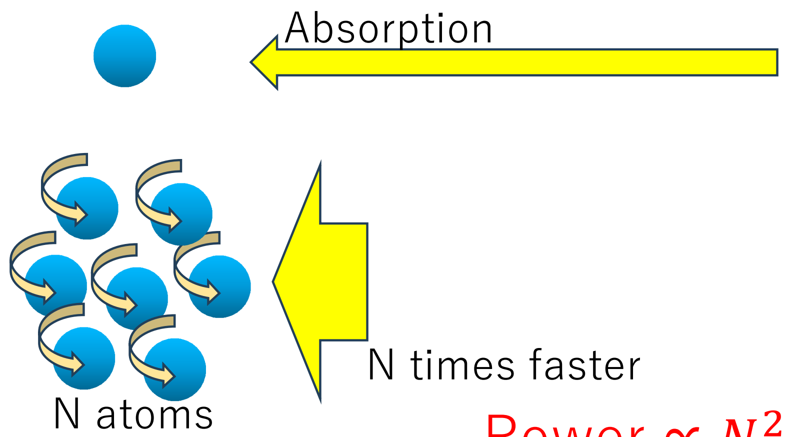
(Tsukuba U) S. Kamimura *et al.*, Phys. Rev. Lett. **128**, 180602 (2022).
S. Kamimura *et al.*, to appear in Phys. Rev. Lett (2023).

Discovery that the opposite phenomenon is feasible.

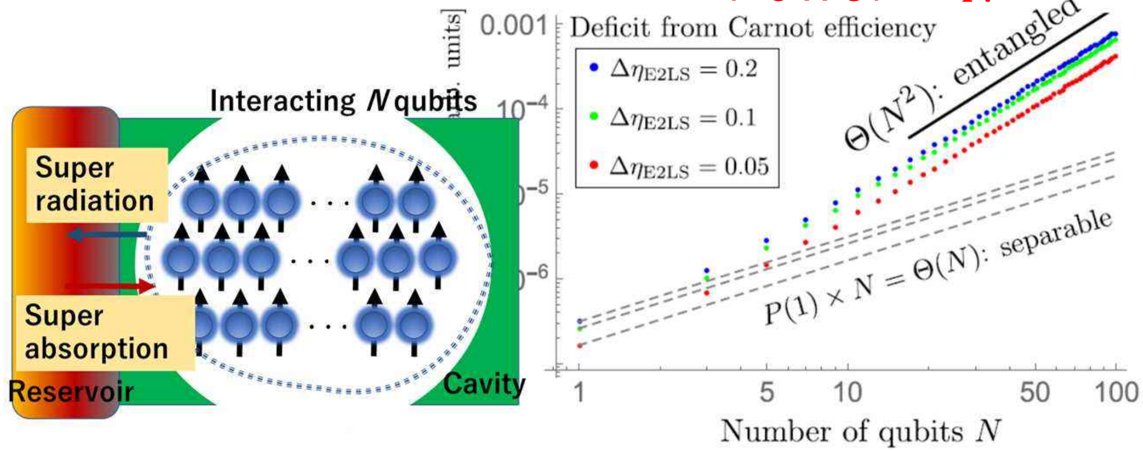
Dicke superradiance



“Super-absorption”



Power $\propto N^2$



Combining the two phenomena forms a heat engine with a quantum acceleration.

New possibility for fast control of qubits such as initialization and preparation.

Toward distributed architectures

Optimal entangle distribution via dispersive matter-light interaction

(NTT、U of Tokyo)

Azuma, Koashi, and Imoto, Phys. Rev. A **105**, 062432 (2022).

・Entangling remote qubits via light:

Dispersive interaction between a qubit and a "classical" light pulse (coherent state).

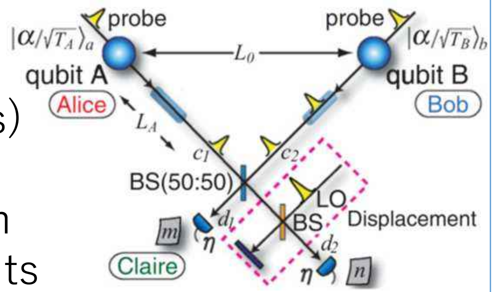
$$\hat{V}|0\rangle_A|\alpha\rangle_a = |0\rangle_A|\alpha_0\rangle_a$$

Lossy optical channel.

$$\hat{V}|1\rangle_A|\alpha\rangle_a = |1\rangle_A|\alpha_1\rangle_a$$

・ Found the optimal yield of entanglement (largely independent of applications)

・ The optimality is achievable with photon number parity measurements

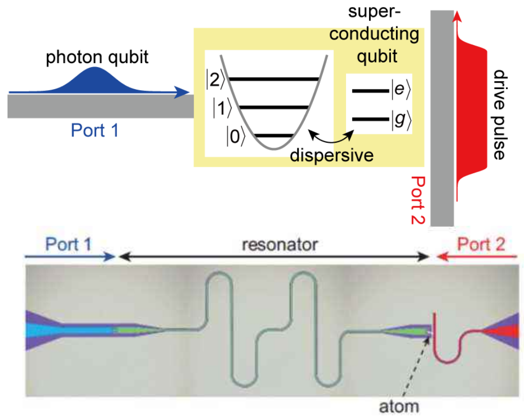


Demonstration of SWAP gate between a photon qubit and a superconducting qubit

(TMDU with AIST in Yamamoto superconducting PJ)

・Very simple method: Reflecting a microwave photon qubit on a superconducting qubits.

・A fidelity of ~0.8 was demonstrated.



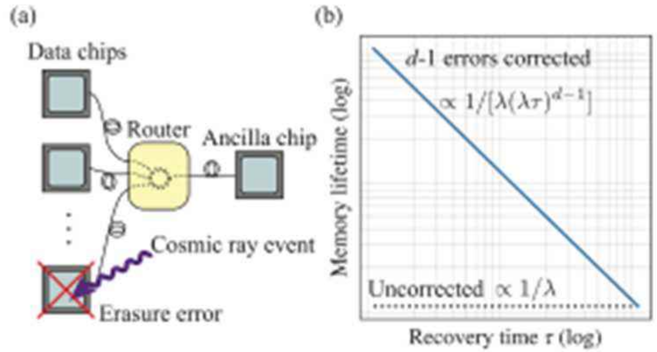
Koshino and Inomata, arXiv:2302.04548.

Distributed quantum error correction for chip-level catastrophic errors

(Keio U)

・Quantum error correction across separate chips in a distributed quantum-computing setup.

・Even if arbitrary data in a chip is destroyed, by connecting data chips and an ancilla chip, the data can be retrieved.

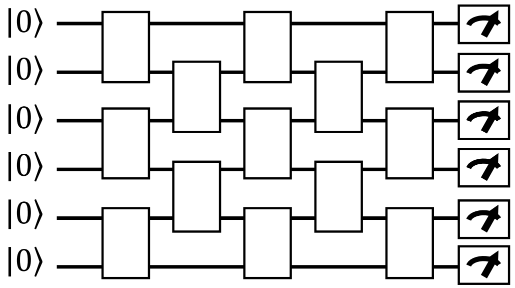


Xu, Seif, Yan, Mannucci, Ousmane Sane, Van Meter, Cleland, Jiang, Phys. Rev. Lett. **129**, 240502 (2023).

Bridging the gap between NISQ and FTQC

MOONSHOT RESEARCH & DEVELOPMENT PROGRAM

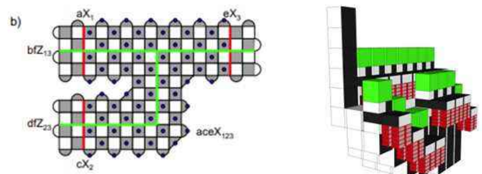
Current regime: NISQ



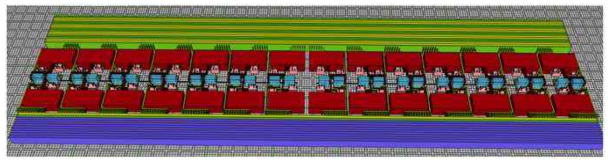
- Qubit: Physical
- Noise: Not negligible
- #qubit: $10^0 \sim 10^2$

A discontinuous gap

Future: Long-term FTQC



Picture from A. G. Fowler and C. Gidney., arXiv:1808.06709 (2018).



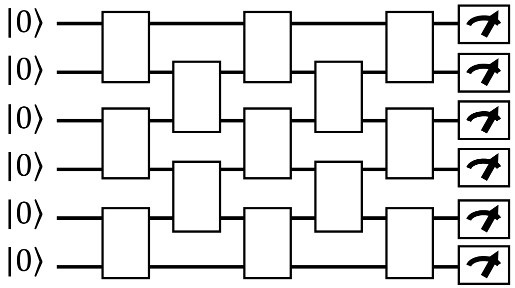
Picture from C. Gidney and M. Ekerå., arXiv:1905.09749 (2019).

- Qubit: Logical
- Noise: Negligible
- #qubit: $10^6 \sim 10^8$

Bridging the gap between NISQ and FTQC

MOONSHOT RESEARCH & DEVELOPMENT PROGRAM

Current regime: NISQ



- Qubit: Physical
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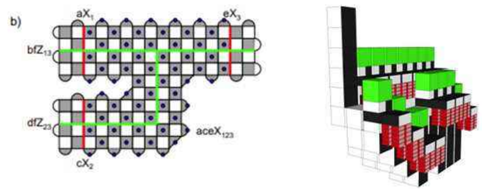
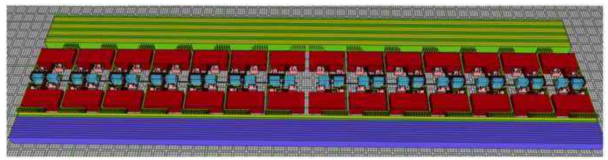
A discontinuous gap

Future: Long-term FTQC



Picture from A. G. Fowler and C. Gidney., arXiv:1808.06709 (2018).



Picture from C. Gidney and M. Ekerå., arXiv:1905.09749 (2019).

- Qubit: Logical
- Noise: Negligible
- #qubit: $10^6 \sim 10^8$

Surpassing the bound on NISQ computing by using FTQC technique

Reducing overheads in FTQC by using NISQ technique

A new "early-FTQC" architecture
(in the previous tutorial talk)

Akahoshi, Maruyama, Oshima, Sato, Fujii, arXiv:2303.13181

Error mitigation meets the error correction

Error mitigation meets the error correction

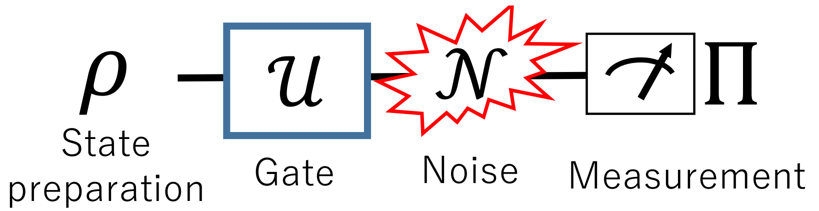
MOONSHOT RESEARCH & DEVELOPMENT PROGRAM

Probabilistic error cancellation (PEC)

Temme, Bravyi, Gambetta, Phys. Rev. Lett. **119**, 180509 (2017). (NTT, Osaka U)

PEC is a method of quantum error mitigation to reduce the effect of noise in computation

Without probabilistic error cancellation



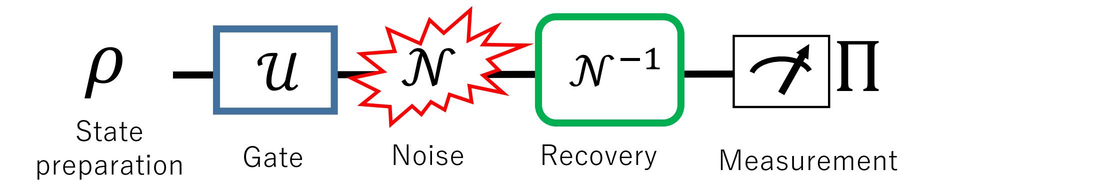
What we want to know:

$$\langle \Pi \rangle_{\text{ideal}} = \langle\langle \Pi | \mathcal{U} | \rho_0 \rangle\rangle$$

What is actually obtained:

$$\langle \Pi \rangle_{\text{noisy}} = \langle\langle \Pi | \mathcal{N} \mathcal{U} | \rho_0 \rangle\rangle$$

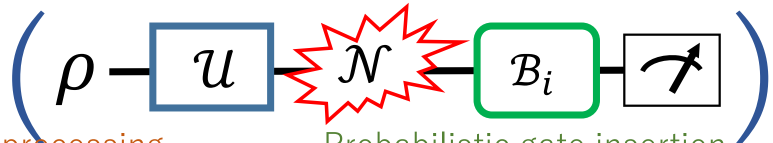
With probabilistic error cancellation



$$\langle \Pi \rangle_{\text{qem}} = \langle\langle \Pi | \mathcal{N}^{-1} \mathcal{N} \mathcal{U} | \rho_0 \rangle\rangle = \langle\langle \Pi | \mathcal{U} | \rho_0 \rangle\rangle$$

$\mathcal{N}^{-1}$ is not physical, but a linear combination of physical processes.

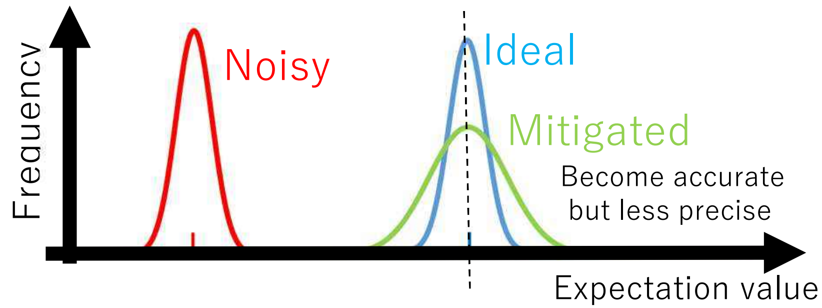
$\mathcal{N}^{-1} = \sum_i \eta_i \mathcal{B}_i$ for $\eta_i \in \mathbb{R}$ and $\mathcal{B}_i$ is physical

$\langle \Pi \rangle_{\text{qem}} = \sum_i \eta_i$ 

Attach coef. in post-processing

Probabilistic gate insertion

We can trade "bias" and "variance" with PEC.
Errors by variance can be reduced with more sampling.



Error mitigation meets the error correction

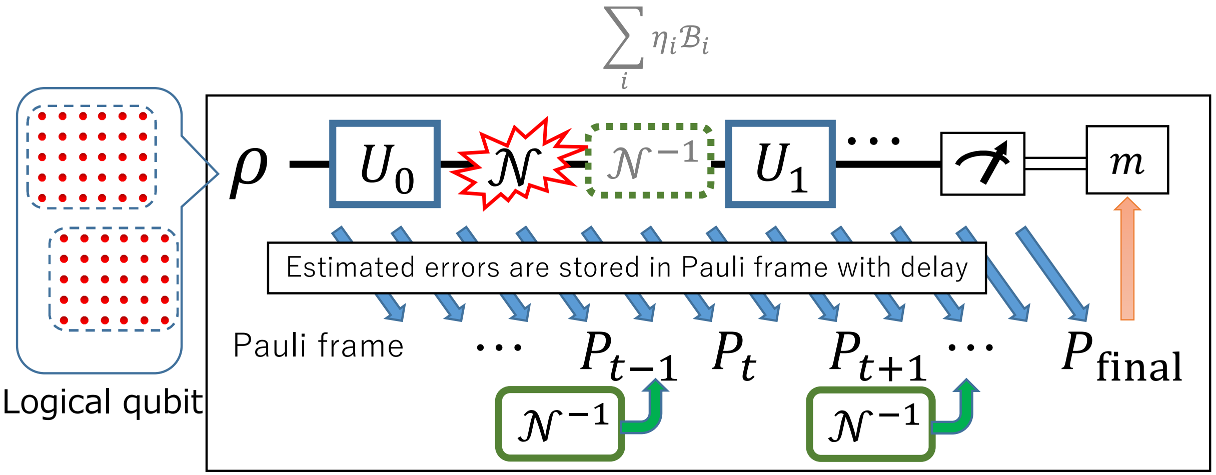
Our contribution We unified QEM and QEC on the equal footing. (NTT, Osaka U)

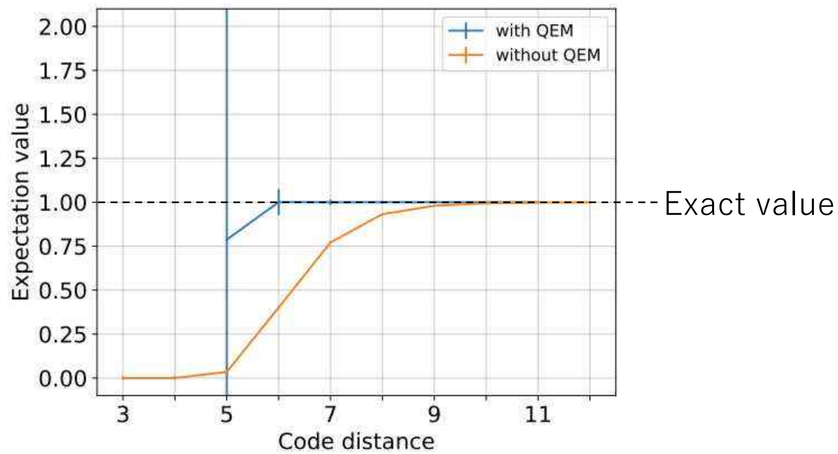
Suzuki, Endo, Fujii, Tokunaga, PRX Quantum **3**, 010345 (2022).

Reduce required code distances by applying QEM to error-estimation errors in QEC.

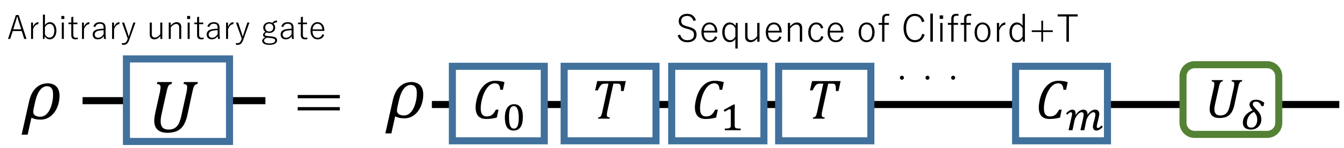
- Errors on the logical qubits tend to be approximated by Pauli errors.
  S. Bravyi, et al., *npj Quant. Inf.* 4.1 (2018).
- Why not making full use of the Pauli frame.

No change in quantum gates.
Error cancellation is done by classical processing only.





Reduce # of T-gates by applying QEM to approximation errors in Solovay-Kitaev decompositions.



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Summary and outlook of the project

Summary of the current progress

・We have constructed connected software stacks including all the layers of FTQC from hardware to software, which is a prototype of the cross-layer co-design model.

  ・The model has already contributed to several research outcomes that are impossible without the model, such as a proposal of a solution across multiple layers.

・The participants of the Project in each layer are also steadily developing various approaches toward reduction in hardware requirements for realizing a fault-tolerant quantum computer.

  ・They cover many grounds, such as improving the mainstream methods, pioneering new possibilities, and deepening the fundamental understandings.

Outlook

・We plan to improve the software stacks such that they enable co-designing and make them a really useful tool. At the same time, we will continue various attempts in each technology layer for reducing hardware requirements.

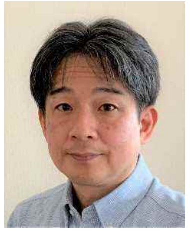
・ Eventually, we expect cycles of harvesting and cultivating of the co-design model, in which researchers exploit the model to accelerate their research and feed back the outcomes to help the evolution of the model itself.

Project PIs


Yuuki Tokunaga
(NTT)


Yasuhiro Tokura
(U of Tsukuba)


Kazuki Koshino
(TMDU)


Masato Koashi
(U of Tokyo)


Franco Nori
(RIKEN)


Keisuke Fujii
(Osaka U)


Kae Nemoto
(OIST)


Koji Azuma
(NTT)

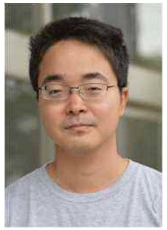

Rodney Van Meter
(Keio U)


Masahiro Takeoka
(Keio U)


Tomoyuki Morimae
(Kyoto U)


Hiroyasu Tajima
(UEC)


Shumpei Masuda
(AIST)


Masahito Yamazaki
(U of Tokyo)

Thank you.