複数量子回路並列実行のためのクロストークを考慮したNISQコンパイラ

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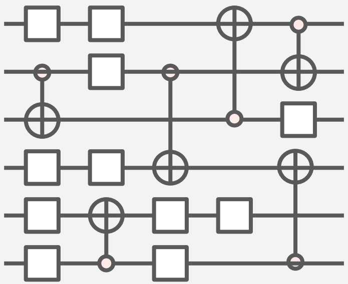
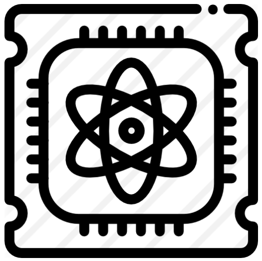
2020 / 10 / 16

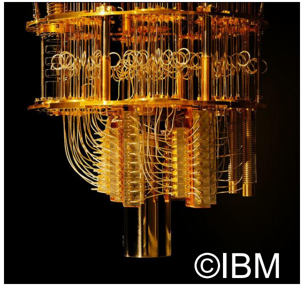
Background: Noisy Intermediate-Scale Quantum(NISQ)



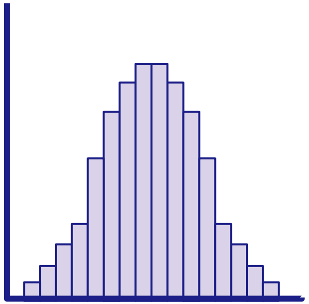
Quantum Circuit

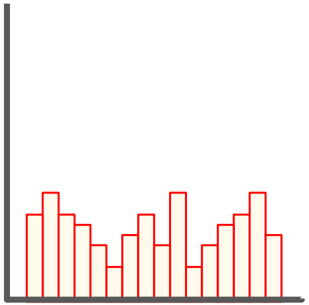


Ideal Quantum device



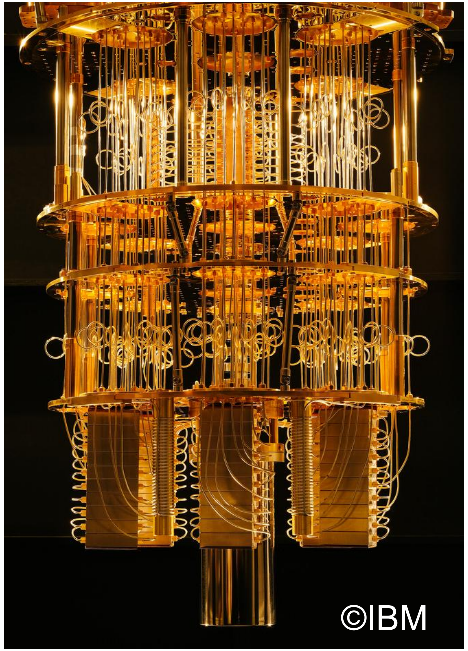
Quantum device with errors

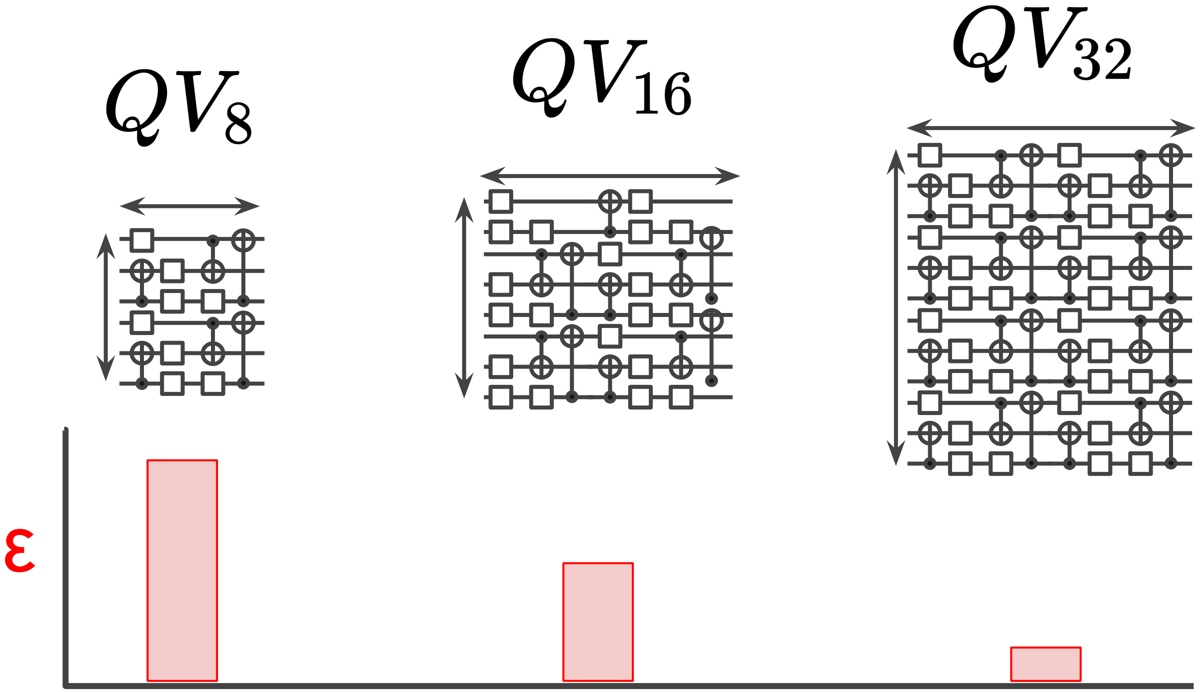




Noisy result

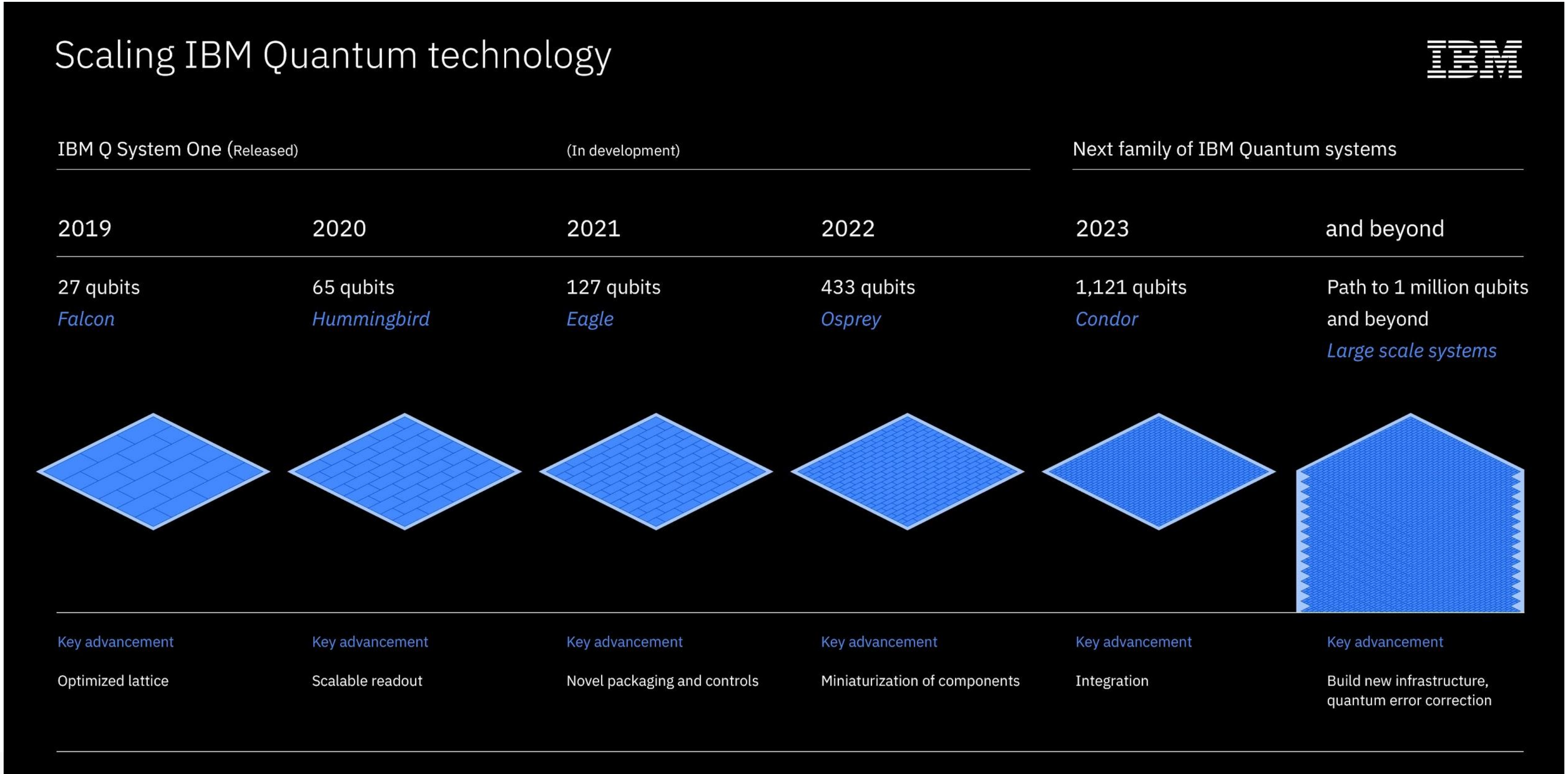
Background: Quantum Volume





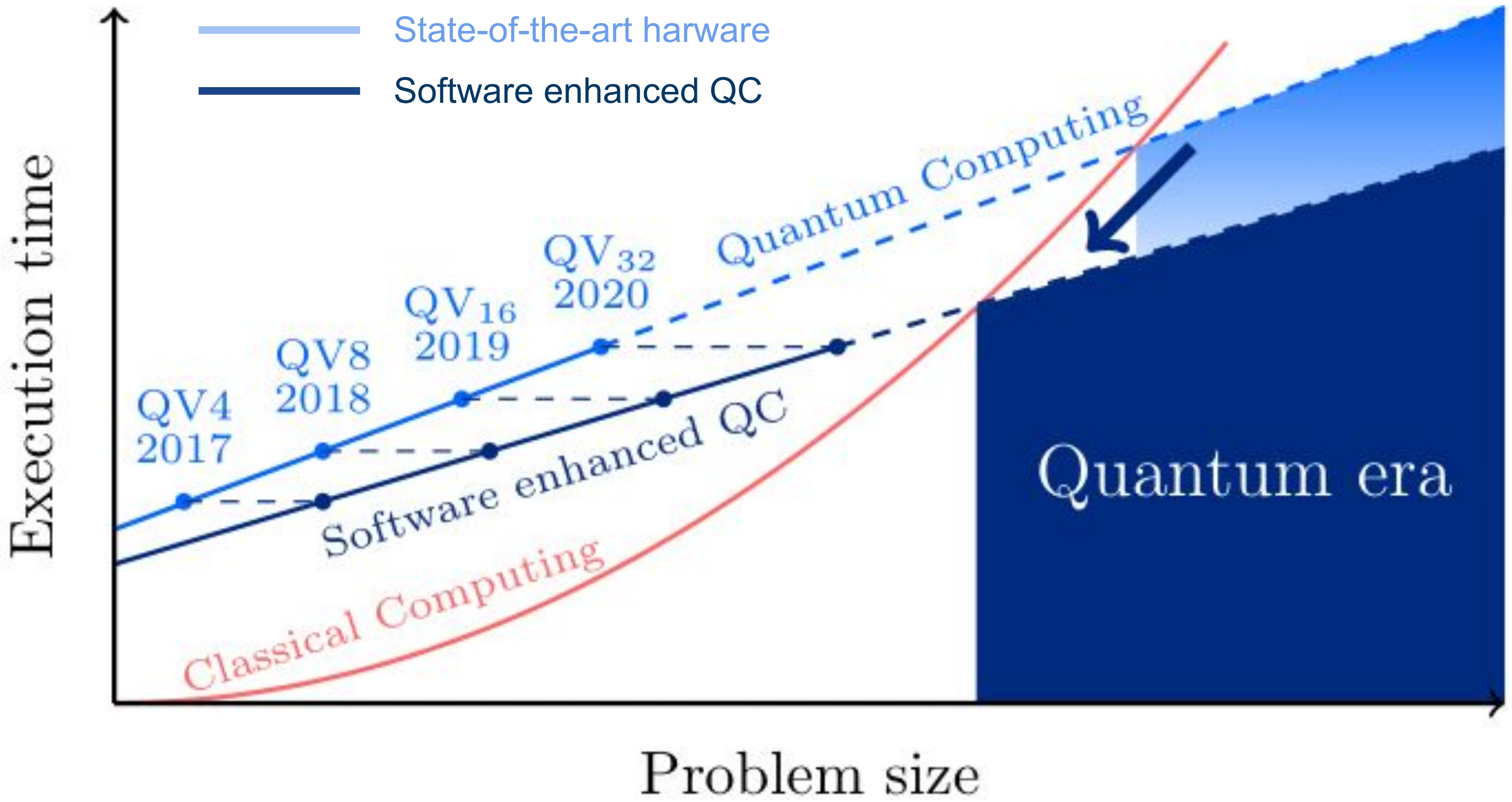
[AND 19] Andrew W. Cross, Lev S. Bishop, Sarah Sheldon, Paul D. Nation, Jay M. Gambetta
Validating quantum computers using randomized model circuits 2019

Background: IBM ロードマップ

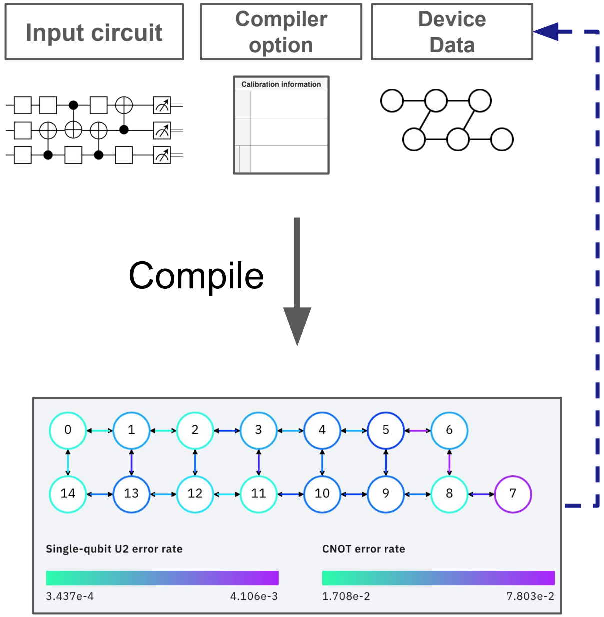


[IBM 20] https://www.ibm.com/blogs/research/2020/09/ibm-quantum-roadmap/

Background: Software enhanced Quantum Computing

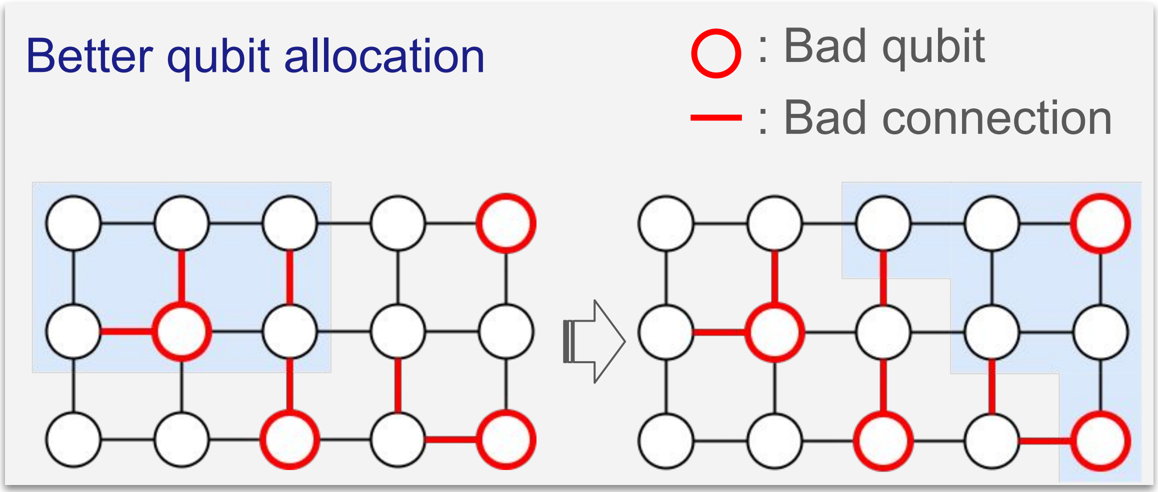


Background: Noise-aware コンパイラ



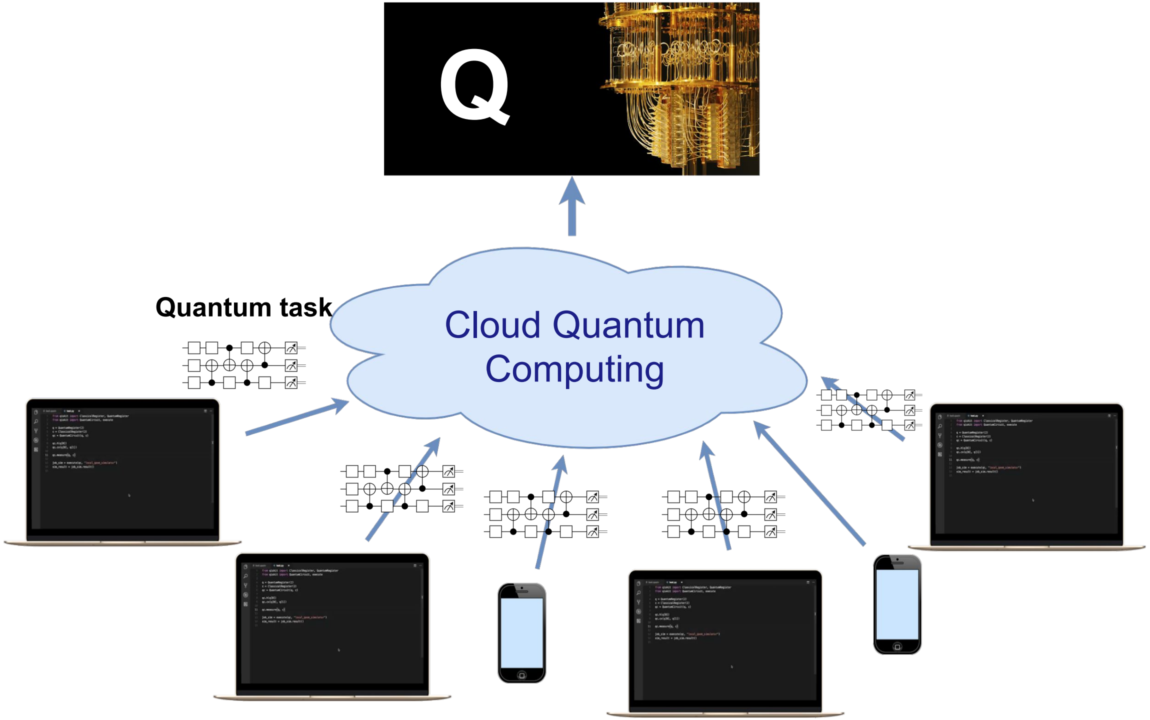
Quantum processor

Find better qubit mapping based on the device error information from calibration [PRA 19].



[PRA 19] Murali, Prakash, et al. "Noise-adaptive compiler mappings for noisy intermediate-scale quantum computers." Proceedings of the Twenty-Fourth International Conference on Architectural Support for Programming Languages and Operating Systems. 2019.

Background: クラウド量子計算



User:
さまざまな背景をもつ研究・開発者

Use as:
Time-Sharing System (TSS)

Target:
NISQ アプリケーション
(VQE, QAOA, etc...)

[IBM 19] IBM Q - Quantum Computing at IBM https://www.ibm.com/quantum-computing/learn/what-is-ibm-q/
[RIG 20] Rigetti. Rigetti Quantum Cloud Services.https://qcs.rigetti.com/.

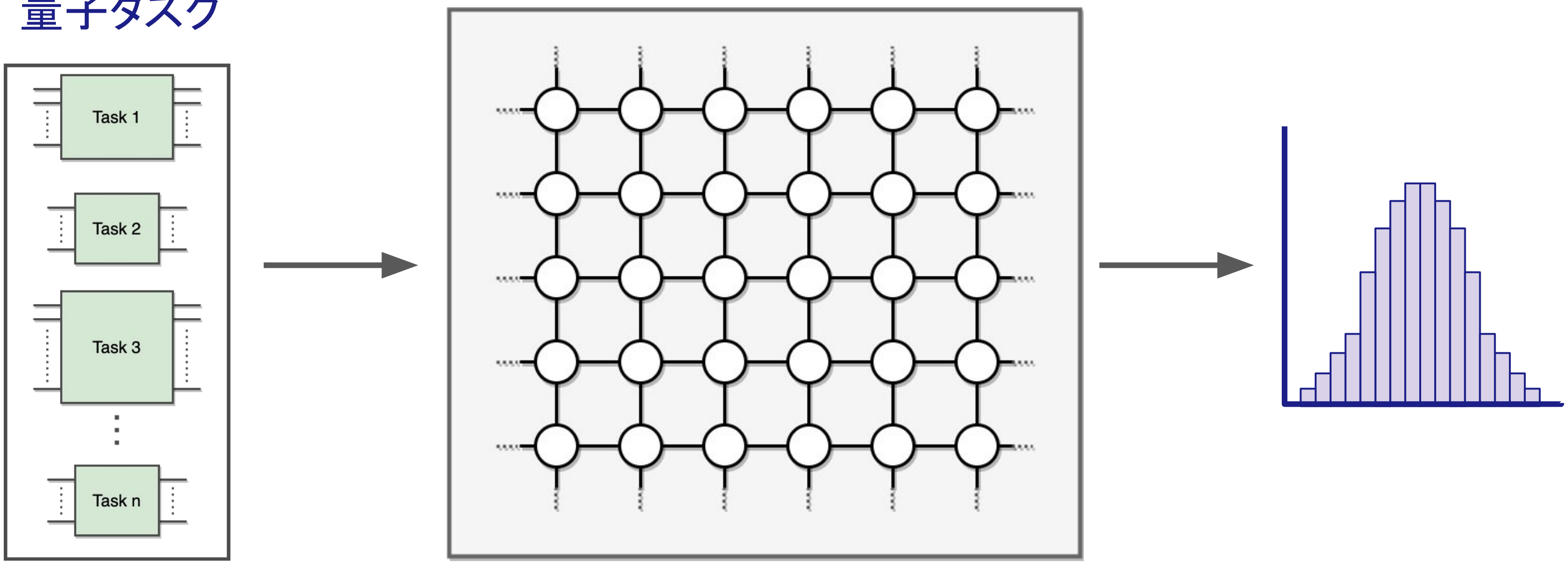
Background: NISQプロセッサのスループット

効率的なQPU運用か？ (より信頼性の高い結果、より高速なタスク実行、最大性能を引き出す)

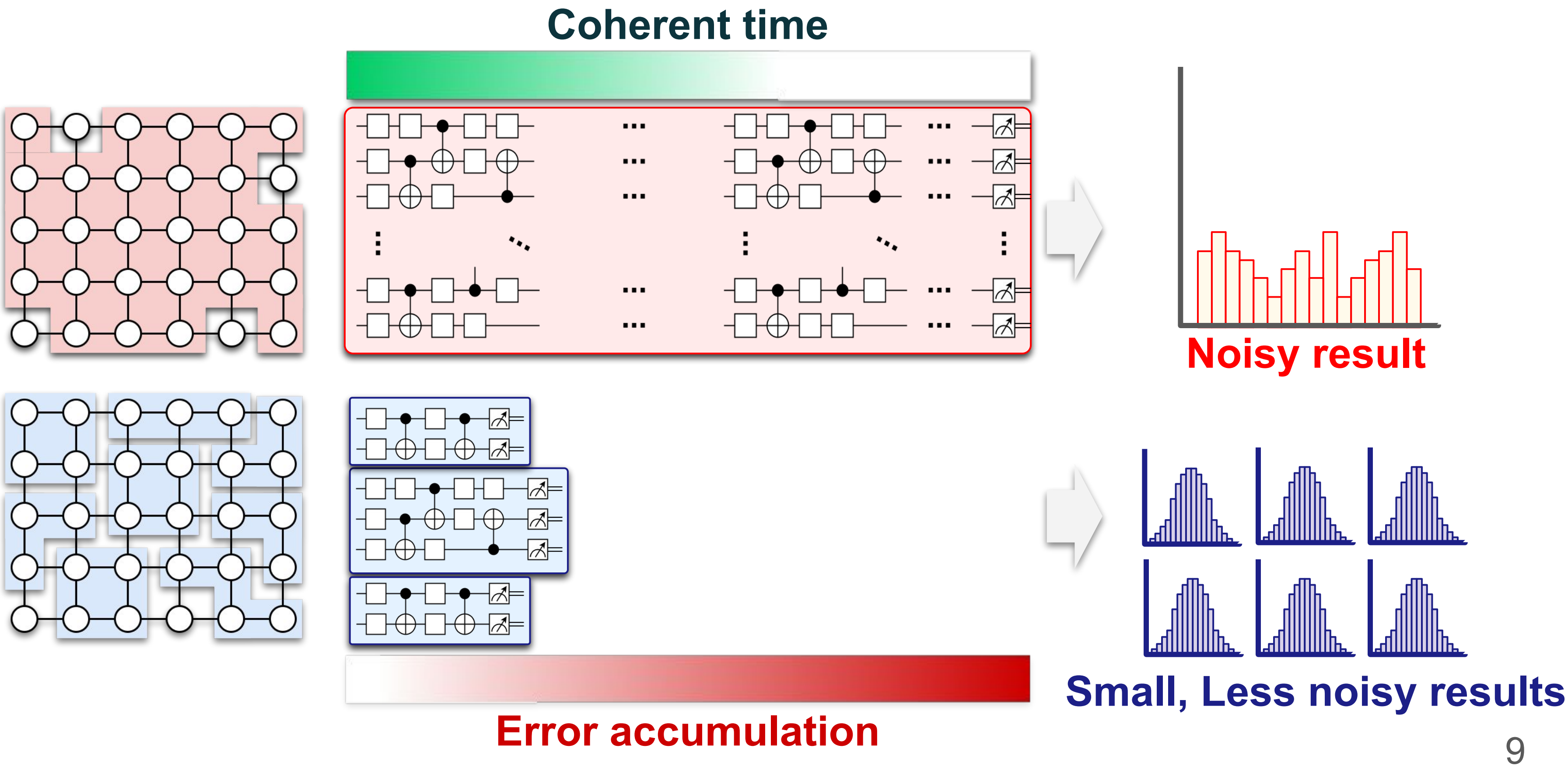
キューされた
量子タスク

QPU

結果



Background: 単一実行 / 並列実行

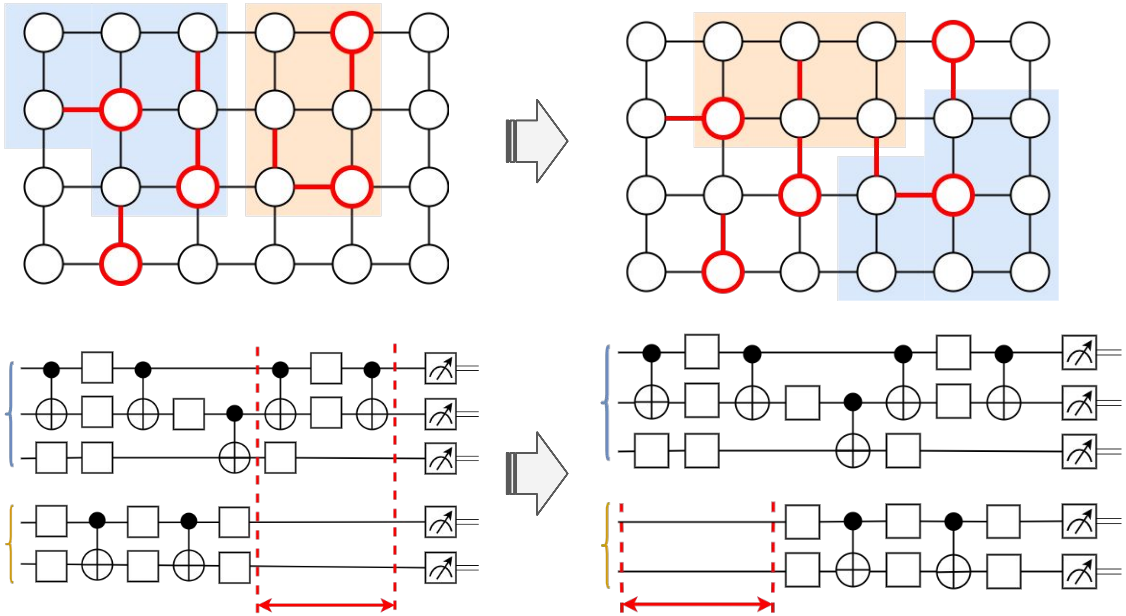


Background: 量子回路並列実行

Execute more than one circuits simultaneously. [POU 19]

Related work:

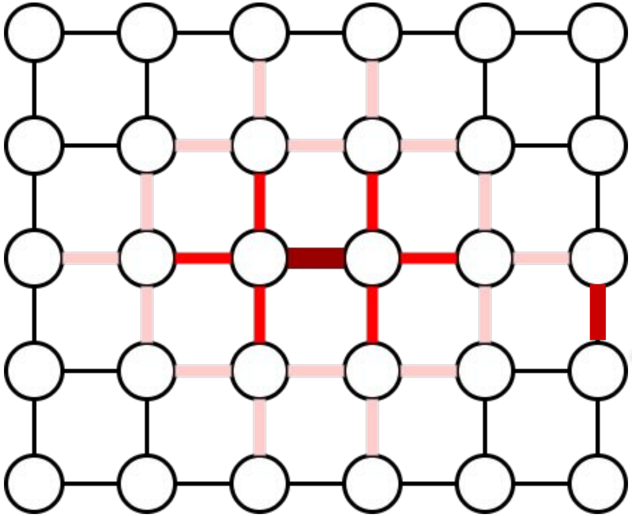
- Fair qubit allocation
- Better Operation timing
- Single or multi?



[POU 19] Das, Poulami, et al. "A case for multi-programming quantum computers." Proceedings of the 52nd Annual IEEE/ACM International Symposium on Microarchitecture. 2019.

Background: クロストーク

There are unwanted correlation in quantum device due to the processor design or some reason.



It is called crosstalk, a major source of noise in NISQ system [PRA 20]

In general, the weight of correlation effect is loosed **spatially**.
But in some cases, there are relatively big correlation even in **remote locations**.

[HAR 19] Harper, R., Flammia, S. T., & Wallman, J. J. (2019). Efficient learning of quantum noise. arXiv preprint arXiv:1907.13022
[PRA 20] Murali, Prakash, et al. "Software Mitigation of Crosstalk on Noisy Intermediate-Scale Quantum Computers." arXiv preprint arXiv:2001.02826 (2020).

Related work

Name	Error type	Single-programming	Multi-programming
Gate error	It occurs each gate operation	Optimizing qubit allocation [PRA 19] ↑ **qiskit**	Optimizing qubit allocation [POU 19] [LIU 20]
Measurement error	It occurs when qubit is measured	Measurement error mitigation [IBM M19] ↑ **qiskit**	
T1, T2	The loss of quantum coherence in time	Optimize operation schedule ← **qiskit**	Delay schedule of shorter circuit [POU 19]
Crosstalk	Unwanted correlation between physical qubits	Mitigating by echo pulse [DAV 20] Optimize operation schedule [PRA 20]	

Related work

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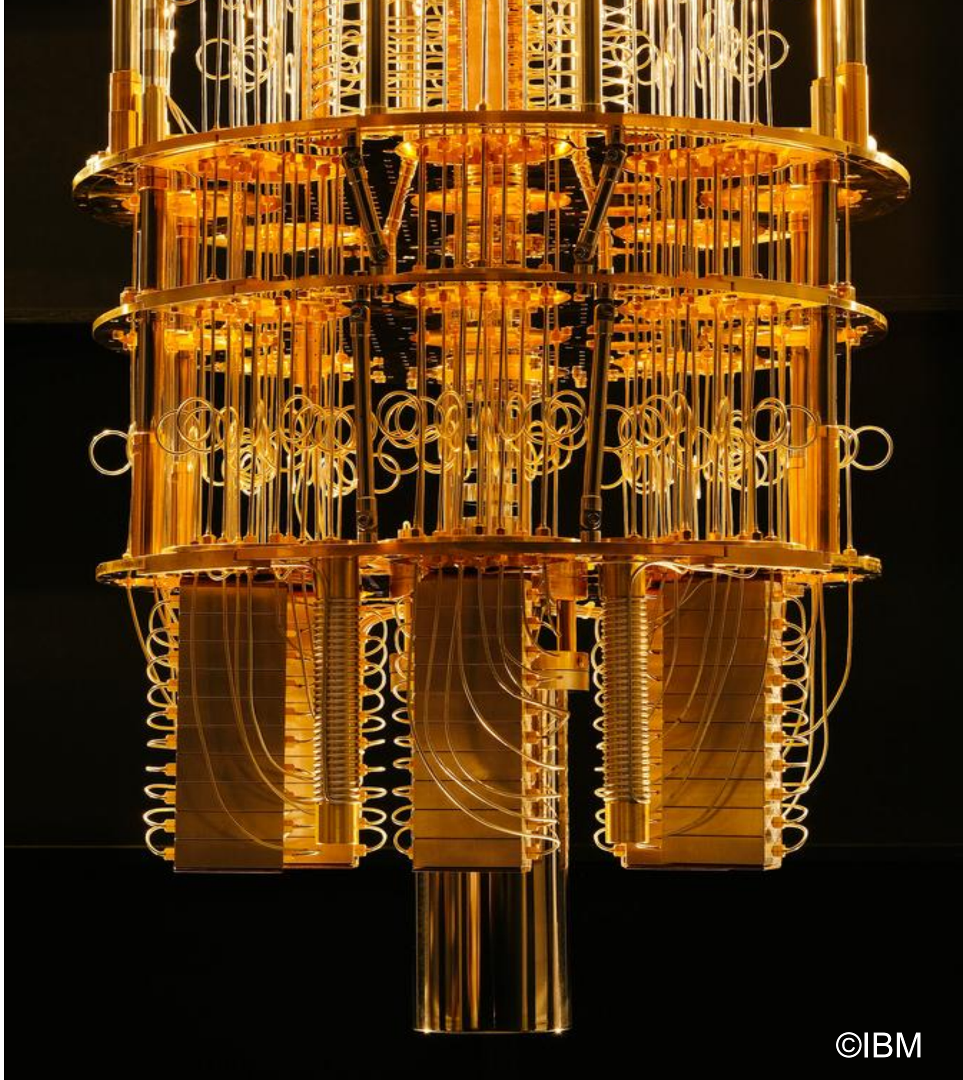
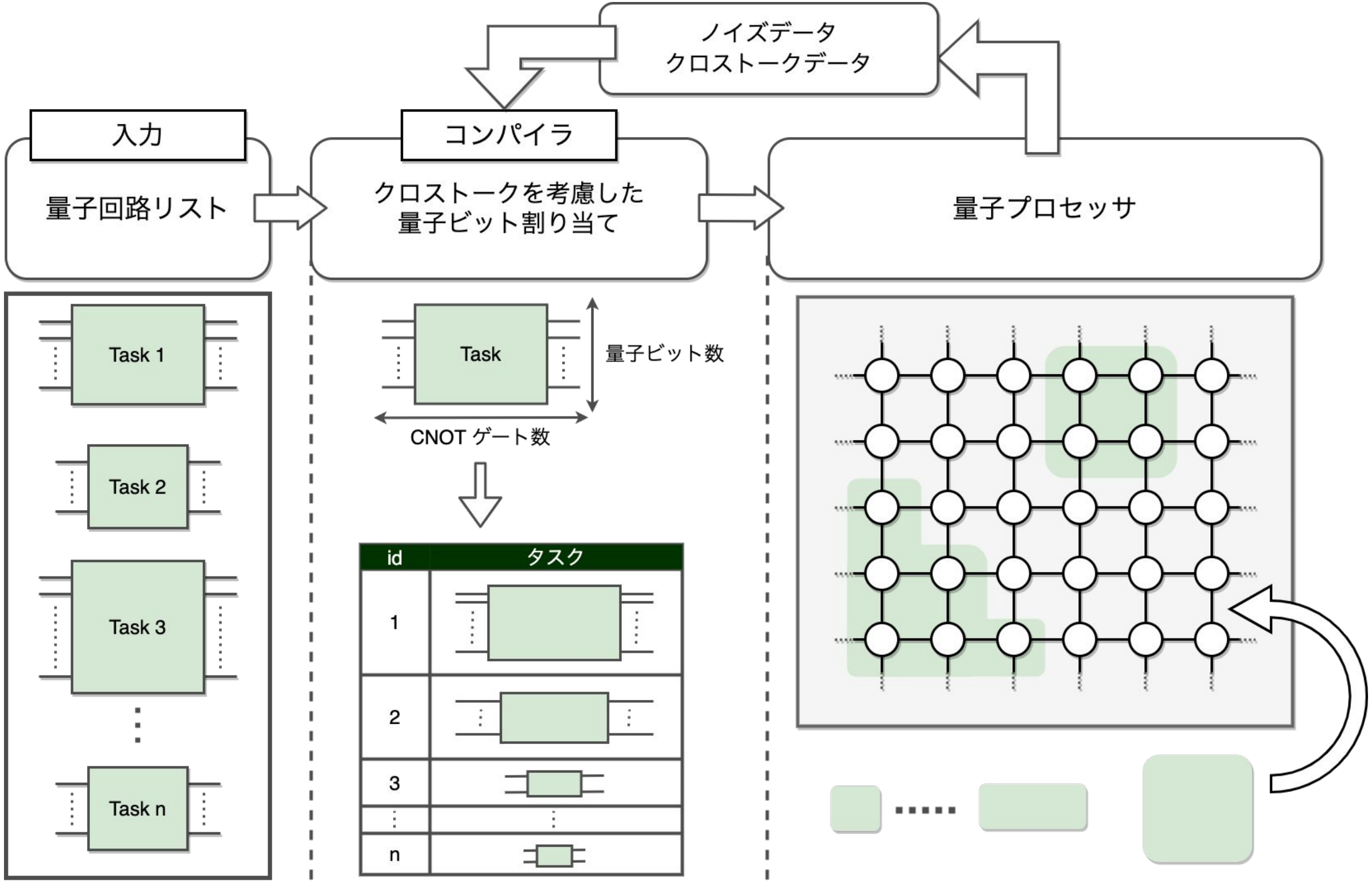
Crosstalk	Unwanted correlation between physical qubits	Mitigating by echo pulse [DAV 20] Optimize operation schedule [PRA 20]	**This proposal !**

Proposal

クロストークを考慮した
並列実行コンパイラ

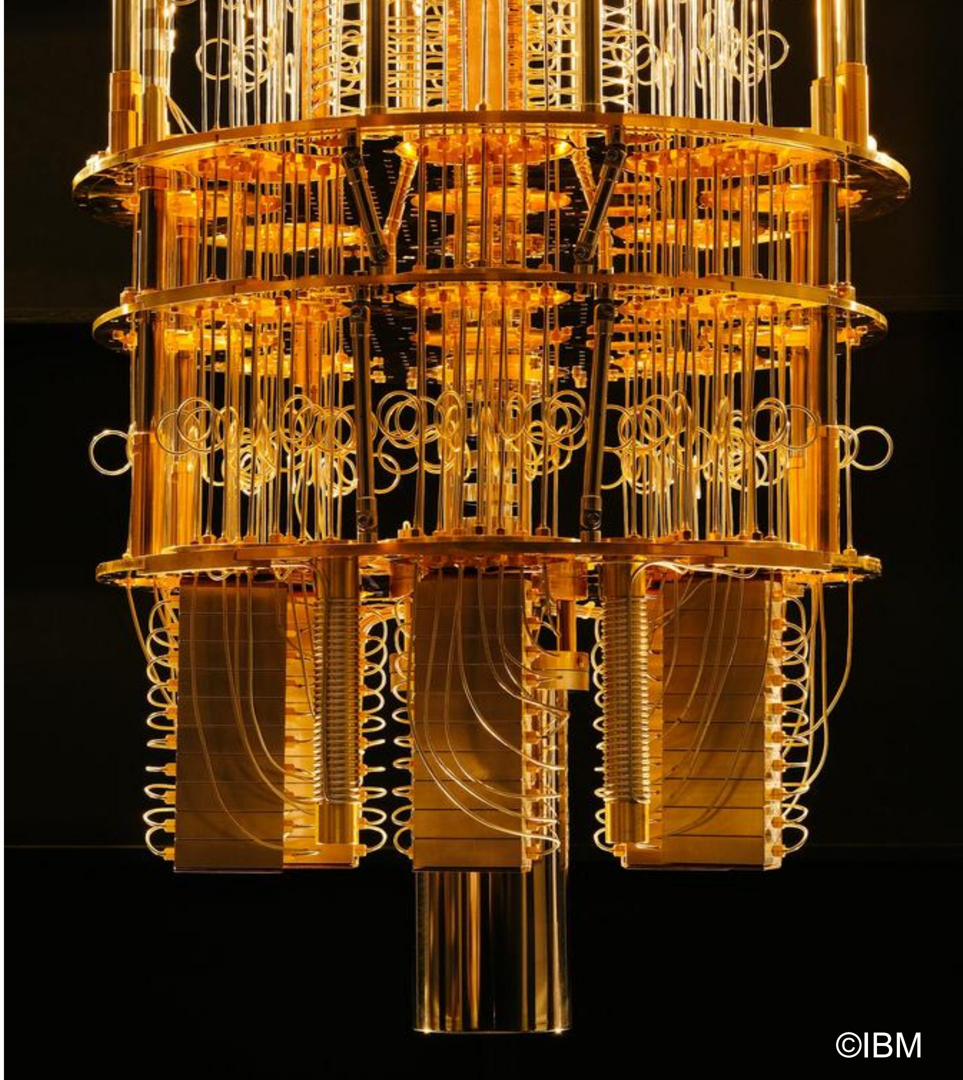


Proposal: Noise-aware multi-task compiler



Experiments

IBMQのクロストーク検知



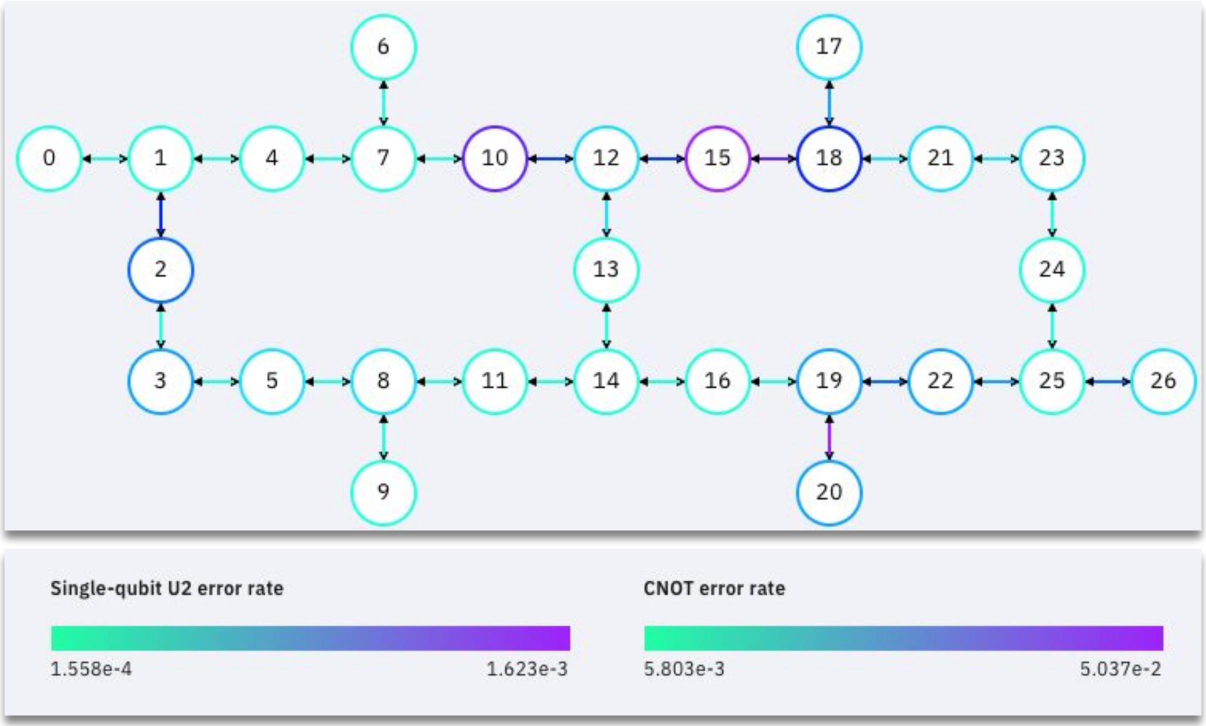
System: IBMQ プロセッサのエラー情報

IBMQ Toronto (27 qubits)

提供されている情報

- １量子ゲートエラー
- ２量子ゲートエラー
- 測定エラー
- T1, T2時間

クロストークノイズ情報は
提供されていない



[IBMQ] IBM Quantum Device https://quantum-computing.ibm.com/

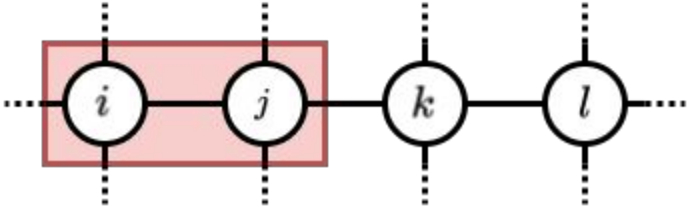
Background: 量子操作エラー

量子操作	最大値	最小値	平均値	回路図
U2ゲート	2.01E-03	1.87E-04	5.16E-04	U2
CNOTゲート	2.73E-02	5.73E-03	1.17E-02	
測定	1.98E-01	1.17E-02	4.61E-02	

[PHI 19] Krantz, Philip, et al. "A quantum engineer's guide to superconducting qubits." Applied Physics Reviews 6.2 (2019): 021318.

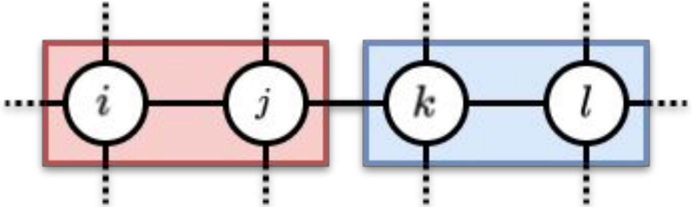
Method: クロストーク検知

Randomized Benchmarking (RB)



$$\epsilon_{(i,j)}$$

Simultaneous Randomized Benchmarking (SimRB)

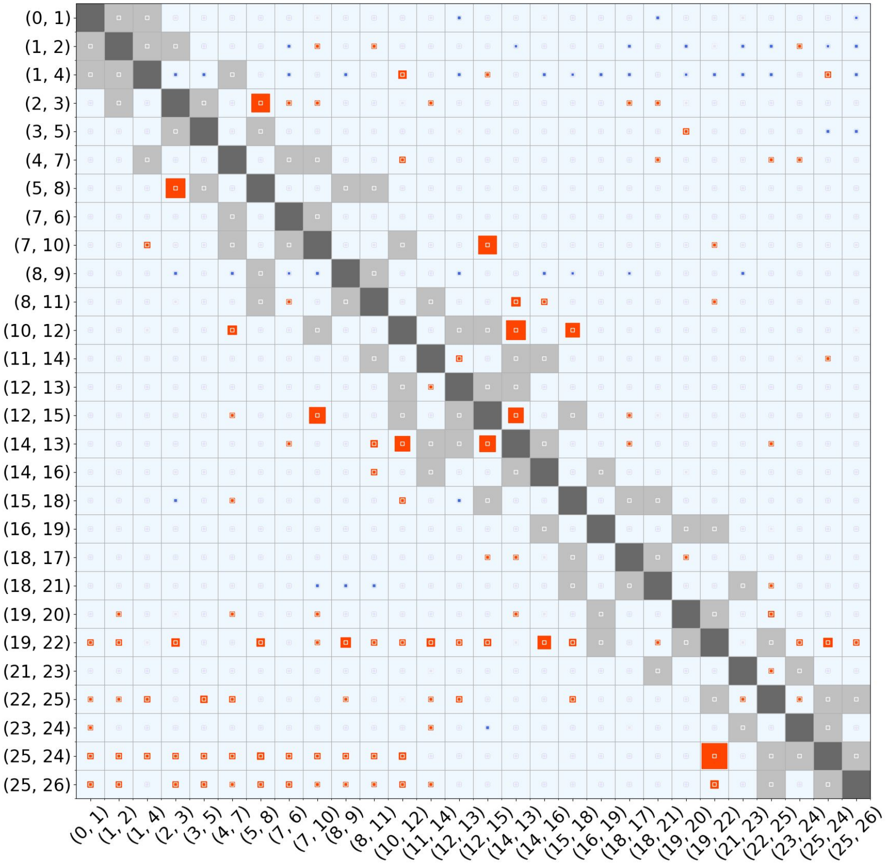


$$\epsilon_{(i,j)|(k,l)}$$

単体実行時のエラー率と
同時実行時のエラー率の
比率をクロストークの影響とする

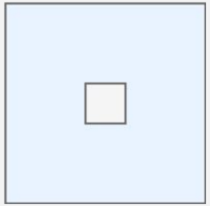
$$\text{Xtalk ratio} = \frac{\epsilon_{(i,j)|(k,l)}}{\epsilon_{(i,j)}}$$

Data: デバイスのクロストークノイズ



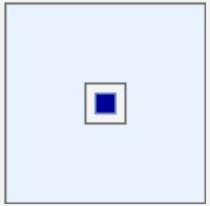
IBMQ Toronto (27 qubits)

表記抜粋: ボックスのサイズが
クロストークの強さを表す



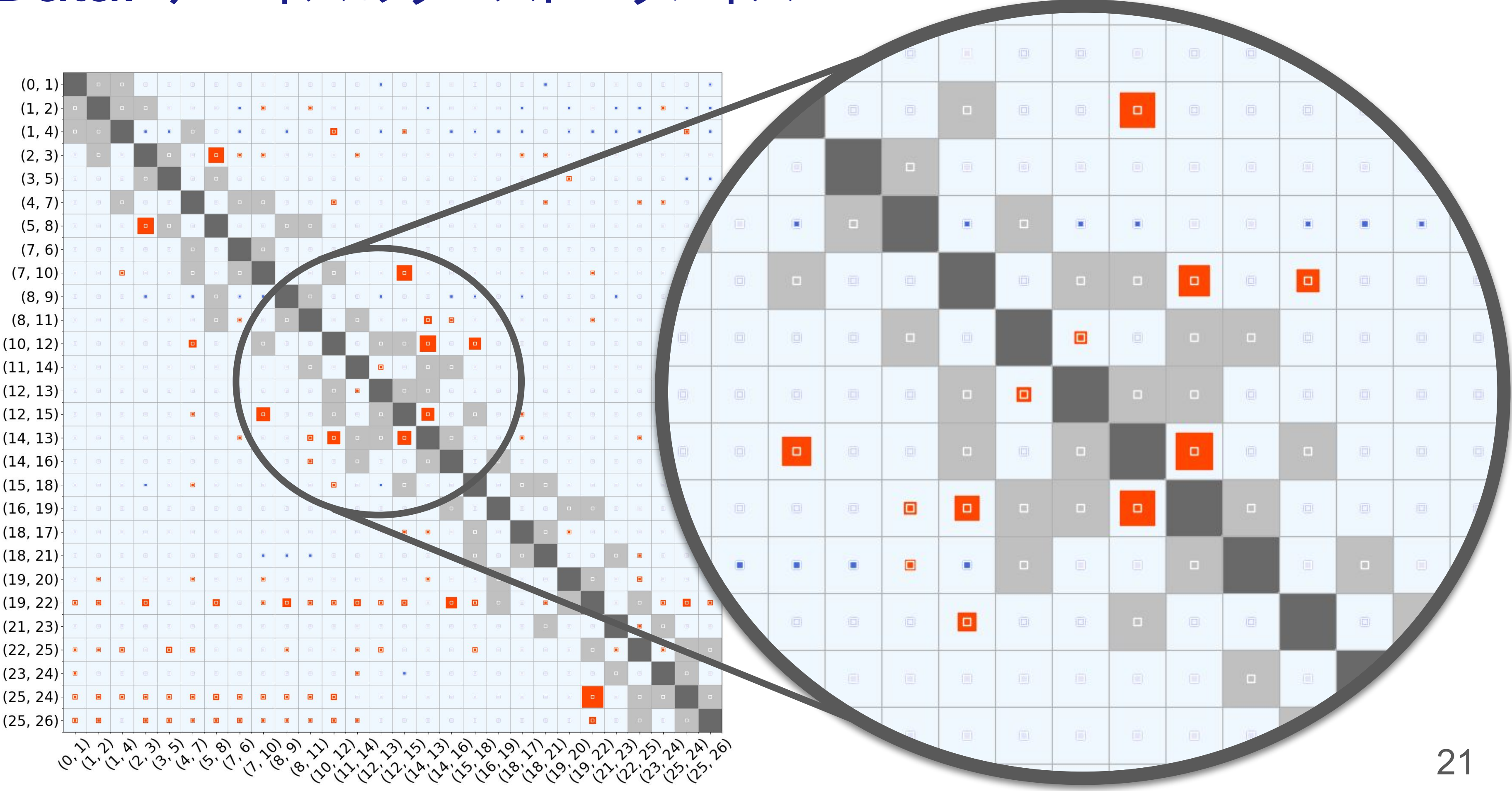
サイズ固定の中央のボックスは
単体実行時のエラー率
(基準値)を示す

単体実行時よりもエラー率が
高くなる場合
e.g. (5, 8)|(2, 3)

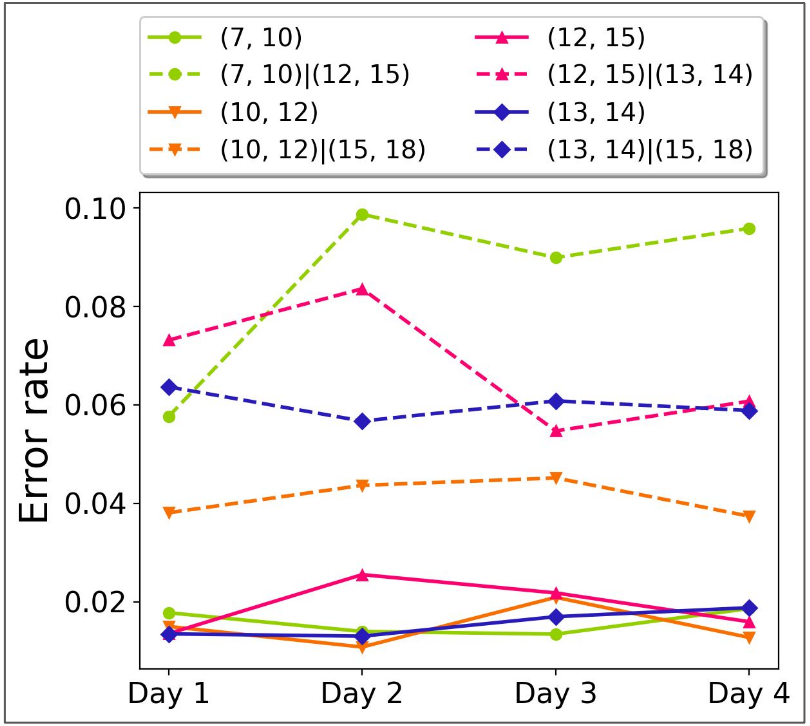


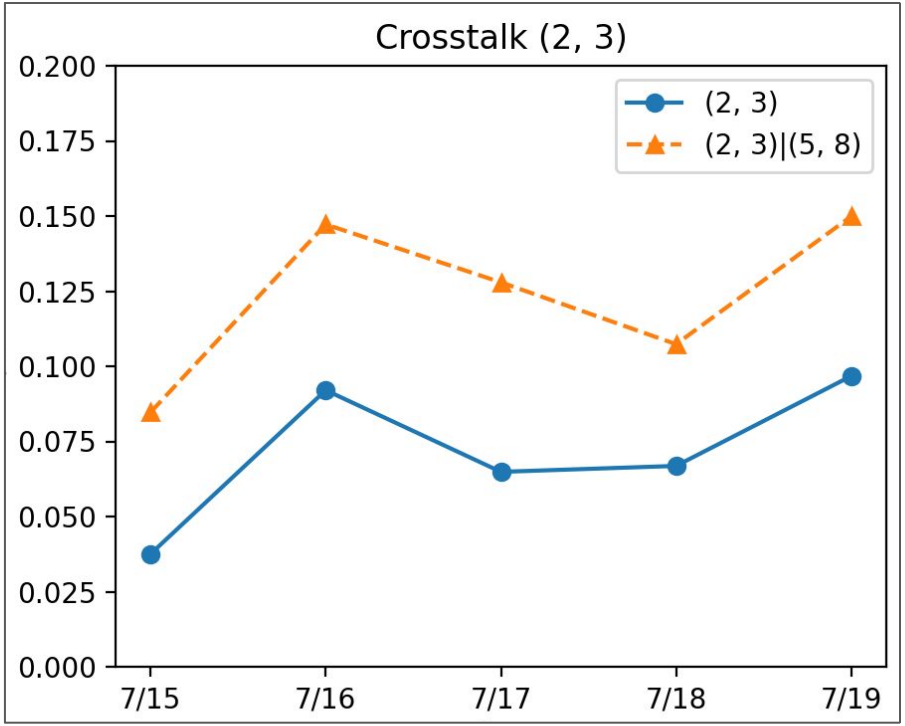
単体実行時よりもエラー率が
低くなる場合
e.g. (14, 16)|(0, 1)

Data: デバイスのクロストークノイズ



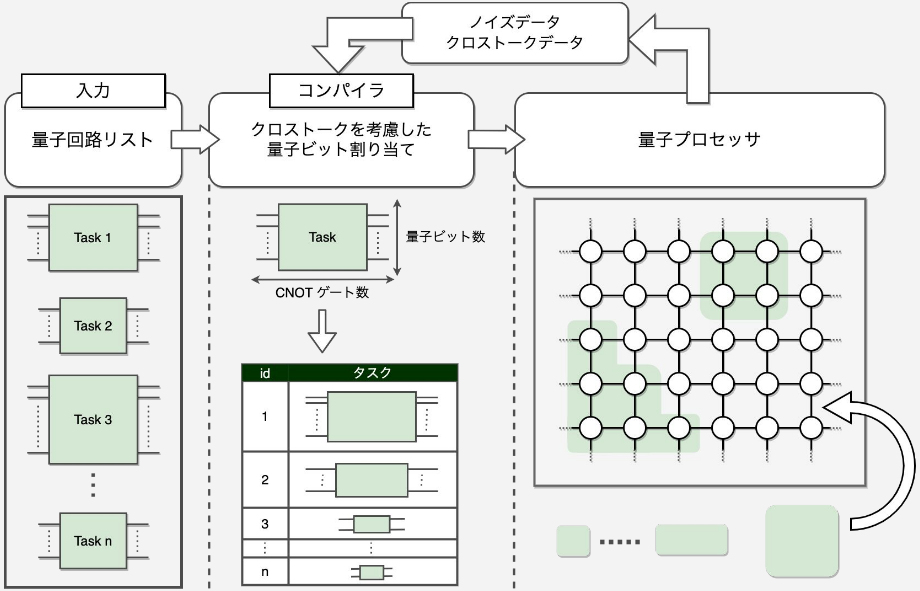
Data: 日毎のクロストークの影響





Experiments

IBMQを用いた提案手法の評価



Metric: Jensen-Shannon Divergence

二つの確率分布の差異を計る尺度

Kullback–Leibler divergence: $D(p||q) = \sum_i p(i) \ln \frac{p(i)}{q(i)}$

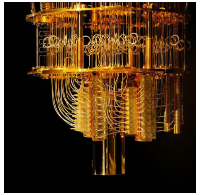
$$\mathrm{JSD} = \left[\frac{1}{2}D(p||(\frac{p+q}{2})) + \frac{1}{2}D(q||(\frac{p+q}{2}))\right]^{\frac{1}{2}}$$

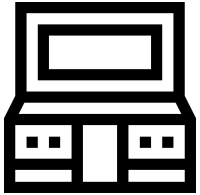
e.g.

同じ確率分布同士: JSD = 0

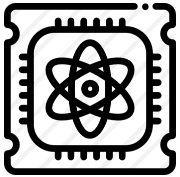
Metric: Jensen-Shannon Divergence

一様分布

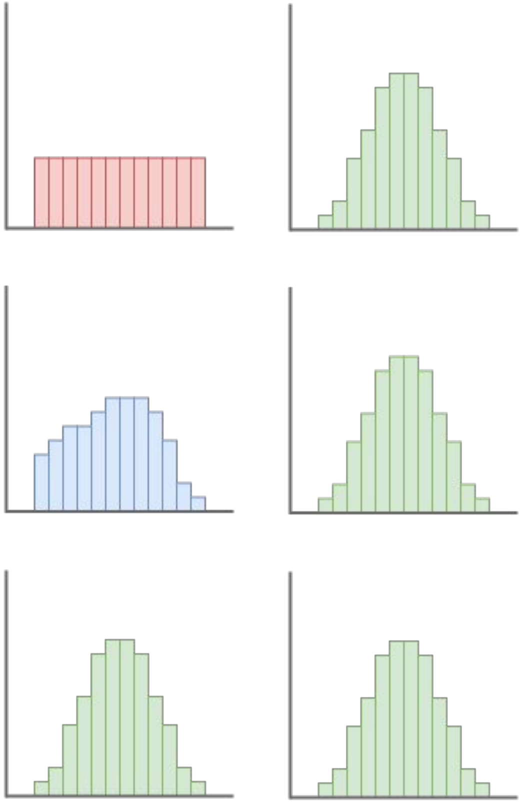


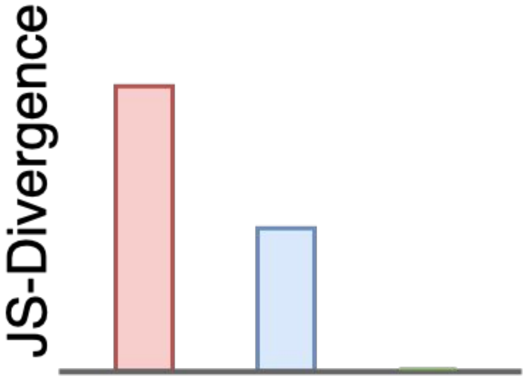


NISQ + **Compiler**

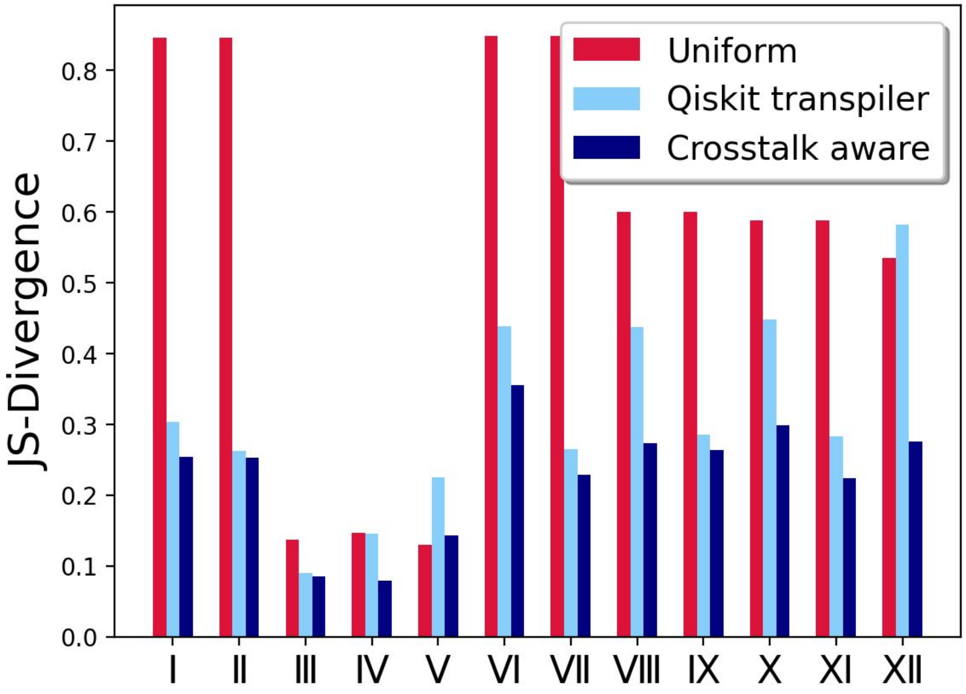


Ideal Quantum device





Results: IBMQ systemを用いたベンチマーク



ラベル	並列量子回路	量子ビット数	CNOT 数
I	QFT_2, Toffoli	2 + 3	5 + 6
II	QFT_2, Toffoli_SWAP	2 + 3	5 + 7
III	QFT_2, QAOA3	2 + 3	5 + 2
IV	QFT_3, QAOA_3	3 + 3	5 + 2
V	QFT_3, QAOA_4	3 + 4	5 + 3
VI	Toffoli, QAOA_3	3 + 3	6 + 2
VII	Toffoli_SWAP, QAOA_3	3 + 3	7 + 3
VIII	Toffoli, QAOA_4	3 + 4	6 + 3
IX	Toffoli_SWAP, QAOA_4	3 + 4	7 + 3
X	QFT_2, QAOA3, Toffoli	2 + 3 + 3	5 + 2 + 6
XI	QFT_2, QAOA3, Toffoli_SWAP	2 + 3 + 3	5 + 2 + 7
XII	QFT_2, QAOA_4, Toffoli	2 + 4 + 3	5 + 3 + 6

Conclusion

量子回路並列実行のためのコンパイラを提案

IBMQ torontoのクロストークノイズを検知

Qiskit 標準コンパイラと比較、提案手法優位

Future work

包括的なコンパイルシステム

- 並列実行タスクの組み合わせ最適化
- クロストークを考慮した量子操作スケジューリング最適

Reference

[PRA 19] Murali, Prakash, et al. "Noise-adaptive compiler mappings for noisy intermediate-scale quantum computers." Proceedings of the Twenty-Fourth International Conference on Architectural Support for Programming Languages and Operating Systems. 2019.

[PHI 19] Krantz, Philip, et al. "A quantum engineer's guide to superconducting qubits." Applied Physics Reviews 6.2 (2019): 021318.

[IBM M19] https://qiskit.org/textbook/ch-quantum-hardware/measurement-error-mitigation.html

[POU] Das, Poulami, et al. "A case for multi-programming quantum computers." Proceedings of the 52nd Annual IEEE/ACM International Symposium on Microarchitecture. 2019.

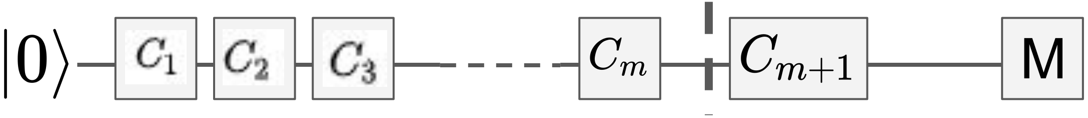
[LIU 20] Liu, Lei, and Xinglei Dou. "A New Qubits Mapping Mechanism for Multi-programming Quantum Computing." arXiv preprint arXiv:2004.12854 (2020).

[DAV 20] McKay, David C., et al. "Correlated randomized benchmarking." arXiv preprint arXiv:2003.02354 (2020).

[PRA 20] Murali, Prakash, et al. "Software mitigation of crosstalk on noisy intermediate-scale quantum computers." Proceedings of the Twenty-Fifth International Conference on Architectural Support for Programming Languages and Operating Systems. 2020.

Appendix: Randomized Benchmarking (RB)

Procedure



$$C_{m+1} = \left(\prod_{i=1}^{m} C_i\right)^\dagger$$

1. Determine gate length m
2. Choose gates $(C_1, \ldots, C_m)$ from Clifford group and arrange those in the quantum register
3. Put $C_{m+1} = \left(\prod_{i=1}^{m} C_i\right)^\dagger$ as an uncomputation
4. Measure the quantum register
5. Repeat 1~4, and fit fidelity f to the function of circuit length m

https://qiskit.org/textbook/ch-quantum-hardware/randomized-benchmarking.html

良い点

Scalability:

量子ビット数に対し効率的に
実行可能

悪い点

Imperfect noise detection:

It estimate decay rate of qubits, but the result contains State preparation and Measurement (SPAM) error

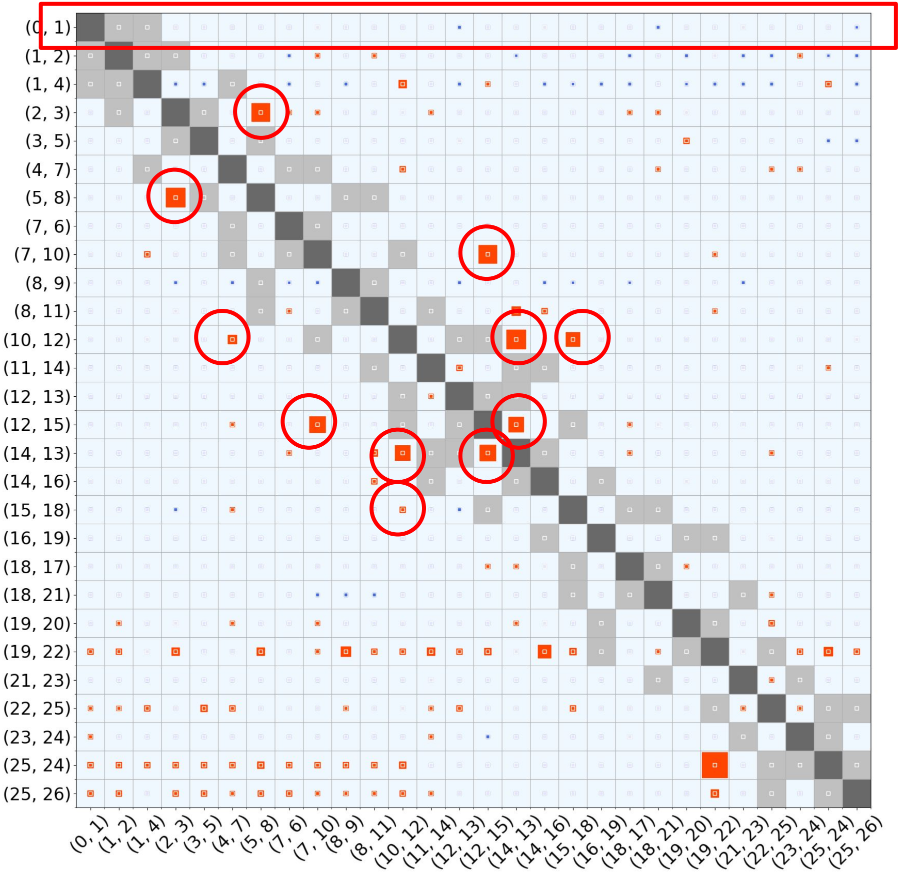
Appendix: Crosstalk detection / クロストーク検知

But it is very costly that detecting whole characterization of crosstalk because the error characteristics increase exponentially.

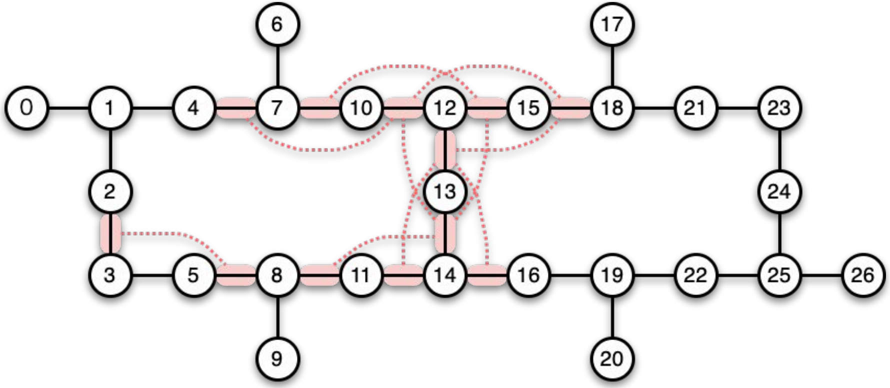
e.g.
In practice, it is known that to detect the whole crosstalk of 20-qubits IBMQ device, it takes 8 hours [PRA 20]

[HAR 19] Harper, R., Flammia, S. T., & Wallman, J. J. (2019). Efficient learning of quantum noise. arXiv preprint arXiv:1907.13022
[PRA 20] Murali, Prakash, et al. "Software Mitigation of Crosstalk on Noisy Intermediate-Scale Quantum Computers." arXiv preprint arXiv:2001.02826 (2020).

Appendix: 実機上でのノイズ検知コストについて



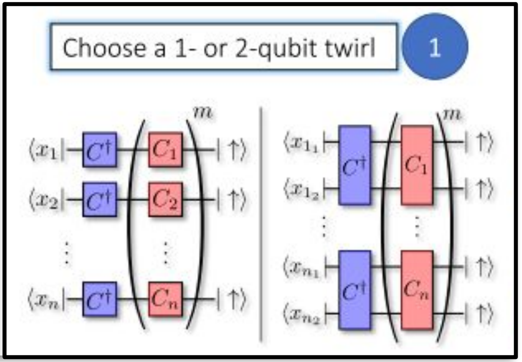
実機を用いたの調査では、
一つの2量子ゲートにつき数時間要する

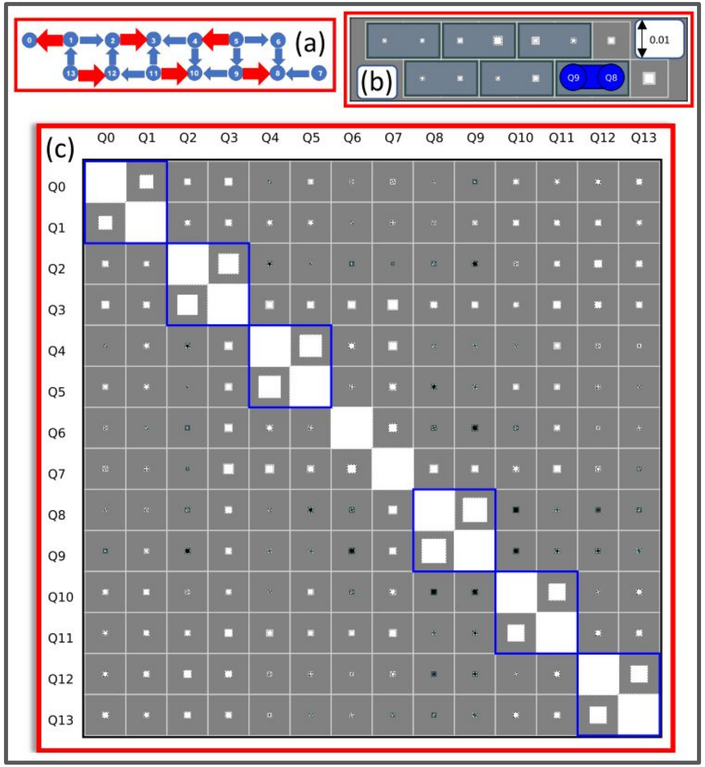


Appendix: Crosstalk detection / クロストーク検知

The correlation matrix corresponding to the distinct qubit-pair groupings [HAR 19]

Two-qubits protocol:

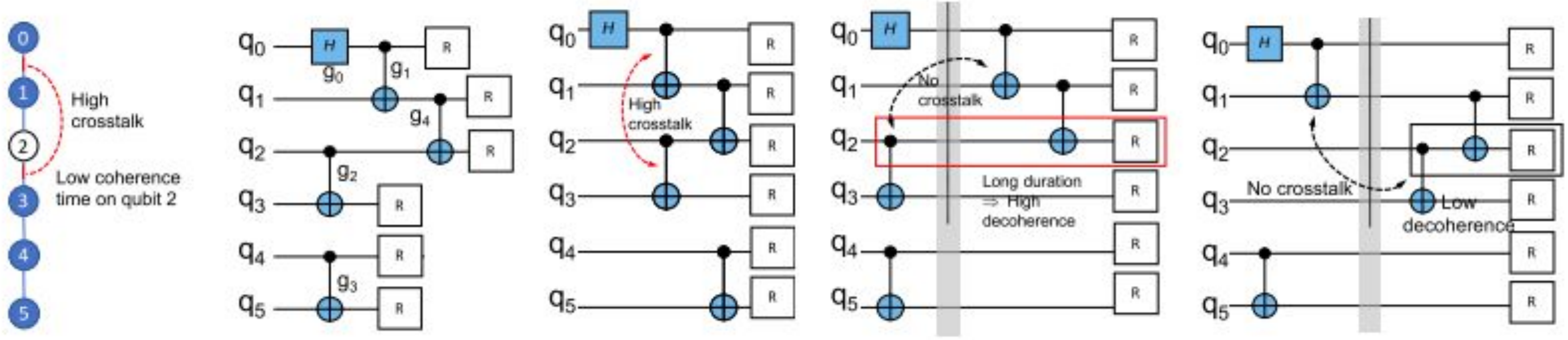




[HAR 19] Harper, R., Flammia, S. T., & Wallman, J. J. (2019). Efficient learning of quantum noise. arXiv preprint arXiv:1907.13022

Appendix: Avoidance of Crosstalk error / 相関エラー回避手法

Previous work showed it is important that **balance** between shorter operation and crosstalk separation by optimizing schedule. [PRA 20]



In this work, we call it **Local task optimization**

[PRA 20] Murali, Prakash, et al. "Software Mitigation of Crosstalk on Noisy Intermediate-Scale Quantum Computers." arXiv preprint arXiv:2001.02826 (2020).