SAND2020-5156C

Machine learning of noise-resilient quantum circuits

Lukasz Cincio

together with

K. Rudinger (Sandia), M. Sarovar (Sandia), P. J. Coles (LANL)

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plan

- introduction / motivation

- automating the algorithm discovery
  - general framework
  - methods of evolving quantum algorithms

- examples
  - *general*: state overlap
  - *machine specific*: Quantum Fourier Transform
    - tests on IBM, Rigetti and noisy simulator

- conclusions

why automating?

- algorithms are hard to find

- “programming” is non-intuitive

  “Quantum Algorithm Zoo” website:

  about 70 algorithms, 400 papers on quantum algorithms

- known algorithms may not be the most efficient

  (gate count, number of ancilla qubits)

- known algorithms can’t be directly executed

- quantum hardware is not perfect
  – tailoring algorithms for specific machine counteracting their bias

approach

- task-oriented with minimal input

task
&
resources $\longrightarrow$ algorithm

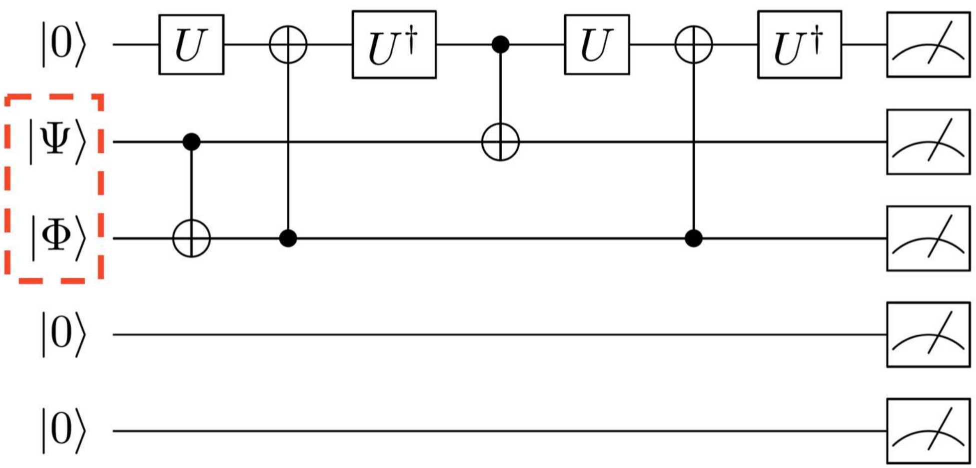
approach

- task-oriented with minimal input

task & resources $\longrightarrow$ algorithm

task: compute

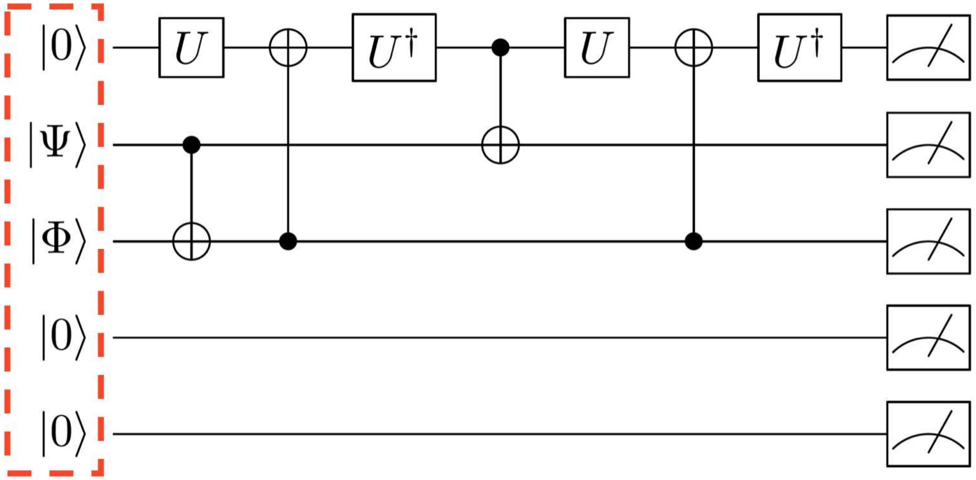
$$|\langle\Phi|\Psi\rangle|^2$$



approach

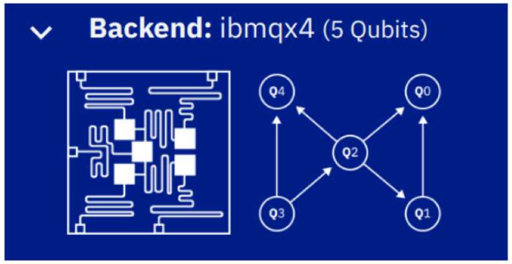
- task-oriented with minimal input

task
&
resources → algorithm



resources: 5 qubits

constrained connectivity, small gate alphabet →



approach

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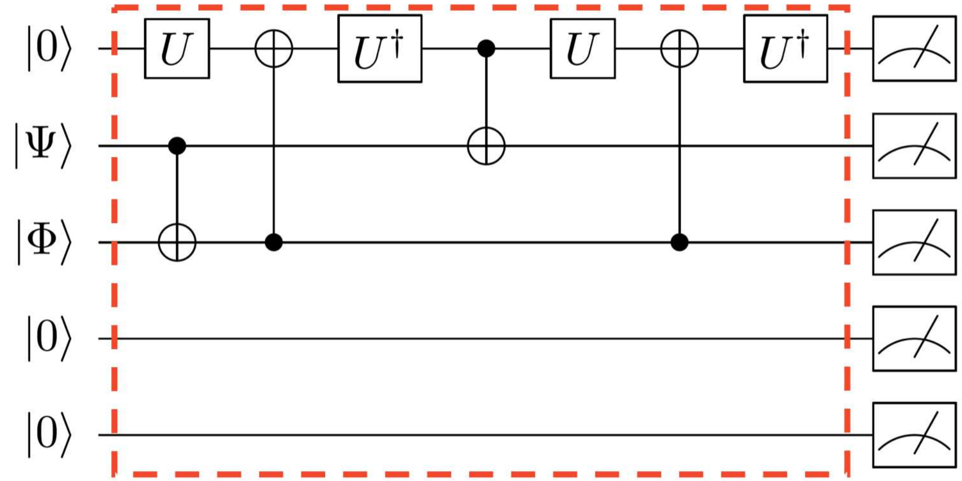
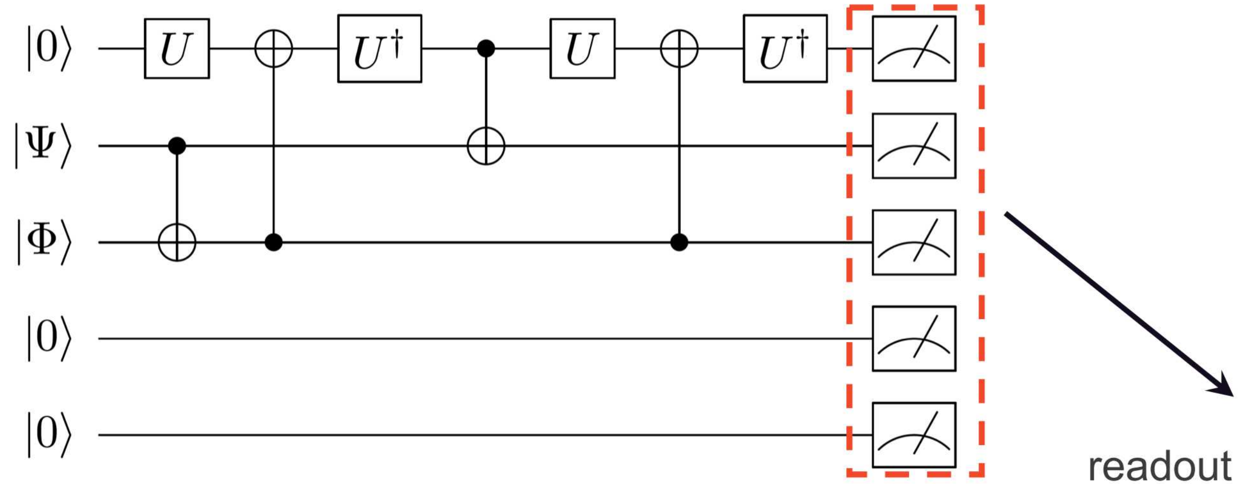


algorithm $\mathcal{A}$

approach

- task-oriented with minimal input

task
&
resources → algorithm

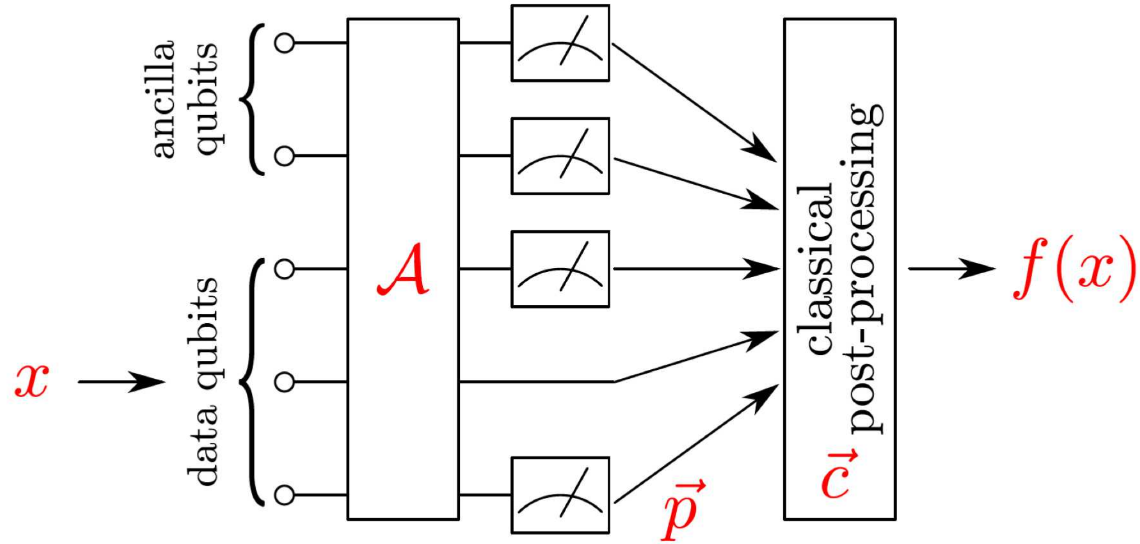


readout and
classical post-processing $\vec{c}$

approach

- task

$$\text{given } x, \text{ compute } f(x)$$



- training set

$$\{x_\alpha, f(x_\alpha)\}$$

- cost function

$$\mathcal{C} = \sum_\alpha |f(x_\alpha) - \mathcal{O}(\mathcal{A}, \vec{c})|^2$$

$$\mathcal{O}(\mathcal{A}, \vec{c}) = \sum_i c_i p_i$$ - measurement and post-processing

$$c_i \in \{-1, 0, 1\}$$

approach

- optimize cost function $\mathcal{C}$
  - algorithm $\mathcal{A}$
    - gate positions
    - gate choice $(\mathrm{CNOT}, H, e^{i\theta X}, \ldots)$
  - measurement
  - classical post-processing $\vec{c}$
  - initialization

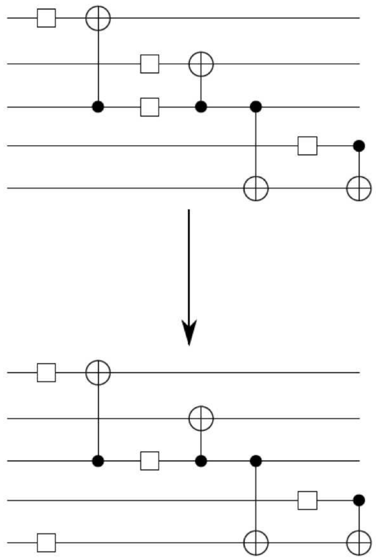
optimization

- universal set of gates: $\{G, \mathrm{CNOT}\}$, where

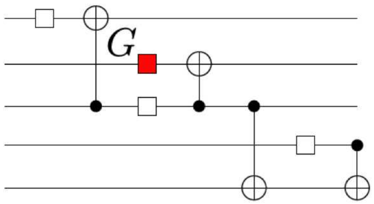
$$G = G(\theta_1, \theta_2, \theta_3), \quad \theta_i \in [0, 2\pi)$$

optimize structure

optimize continuous variables



- gate position
- gate removal
- compress
- rewrite
- …



minimize the cost function over $G = G(\theta_1, \theta_2, \theta_3)$

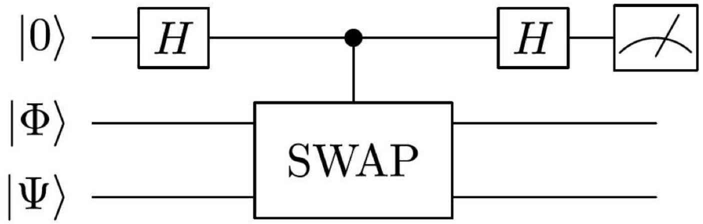
discrete

continuous

example: state overlap (*general*)

- given states $|\Psi\rangle$ and $|\Phi\rangle$, compute $|\langle\Phi|\Psi\rangle|^2$

- textbook version



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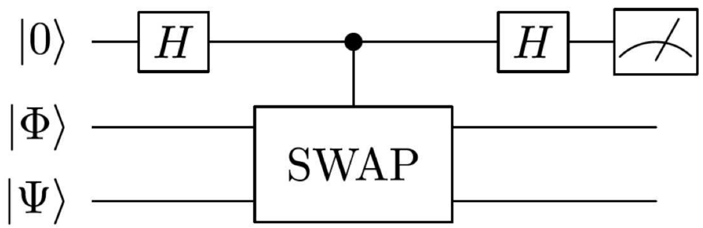
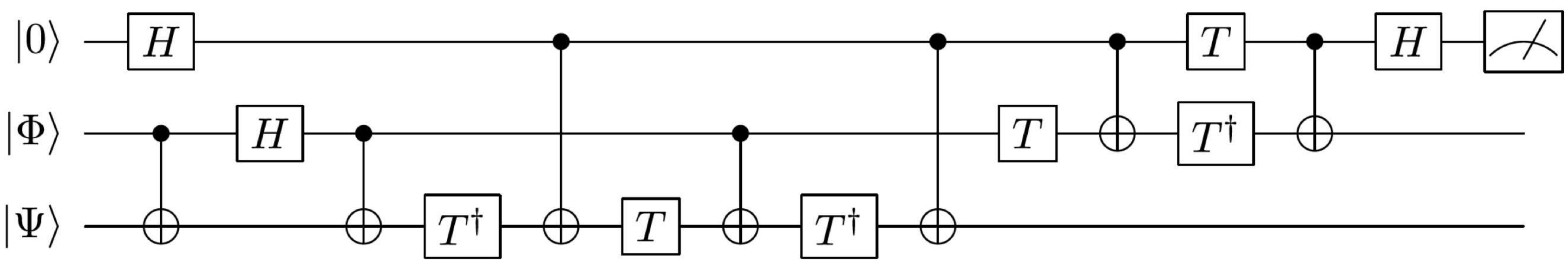


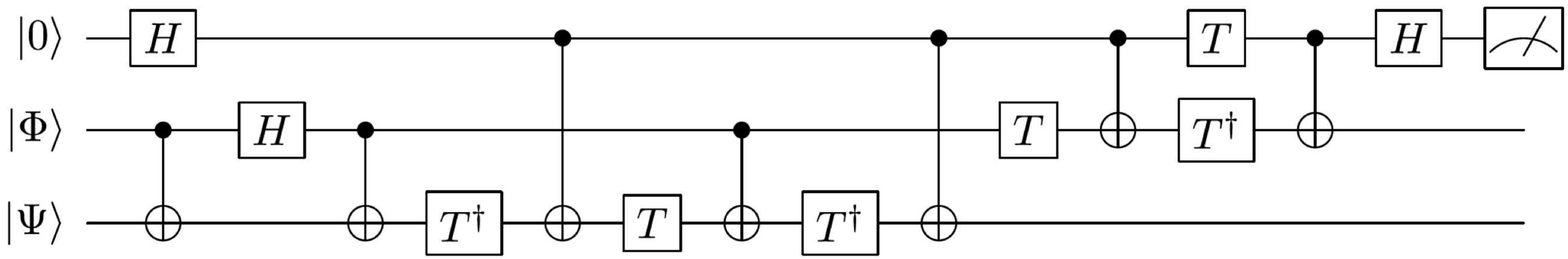
- textbook version using available gates



(16 gates)

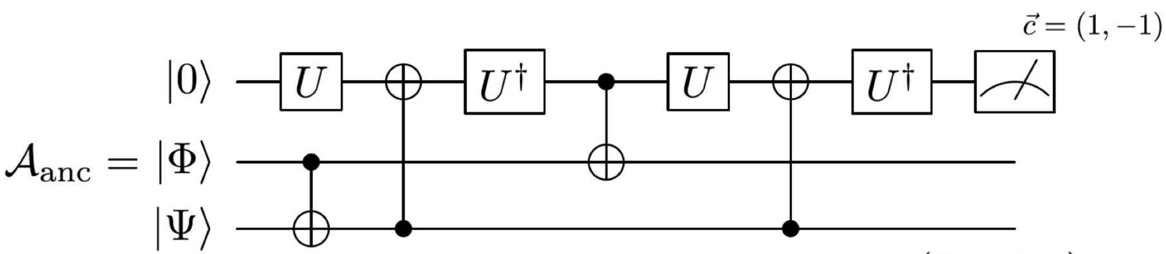
example: state overlap (*general*)

- textbook (human generated)



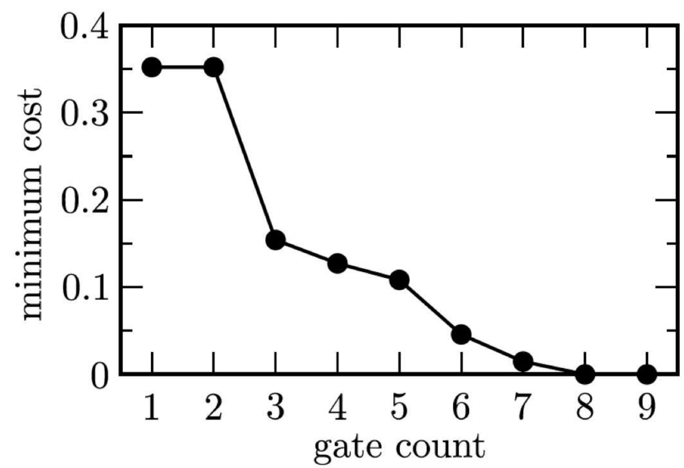
(16 gates)

- computer generated (Ancilla-Based)
  - assumptions: 1 ancilla, measure 1 qubit



(8 gates)

$(U = HT^\dagger)$



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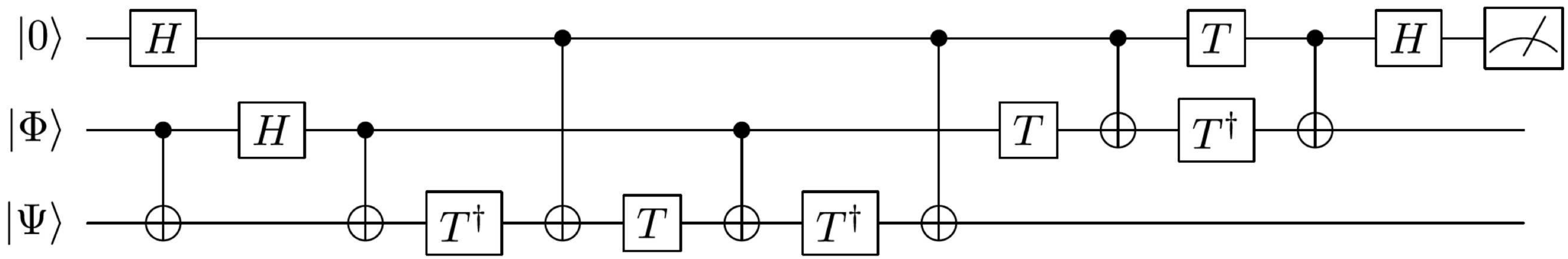
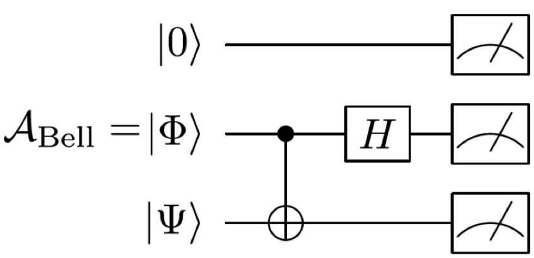


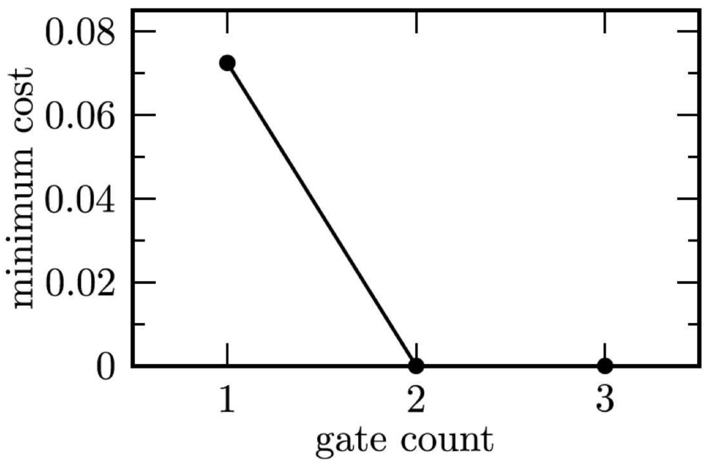
(16 gates)

- computer generated (Bell-Based)
  - assumptions: 1 ancilla, measure everything



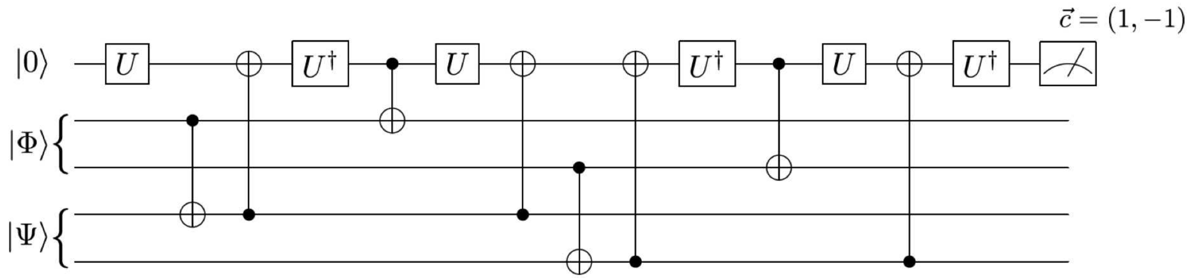
$\vec{c} = (1, 1, 1, -1)$

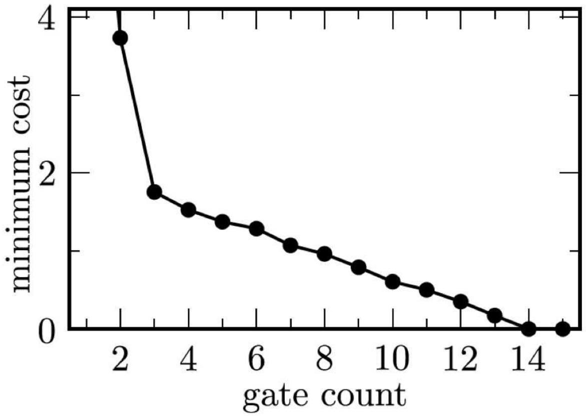
$\mathcal{O} = p_{00} + p_{01} + p_{10} - p_{11}$



discover the scaling: Ancilla-Based algorithm

- solve larger problem





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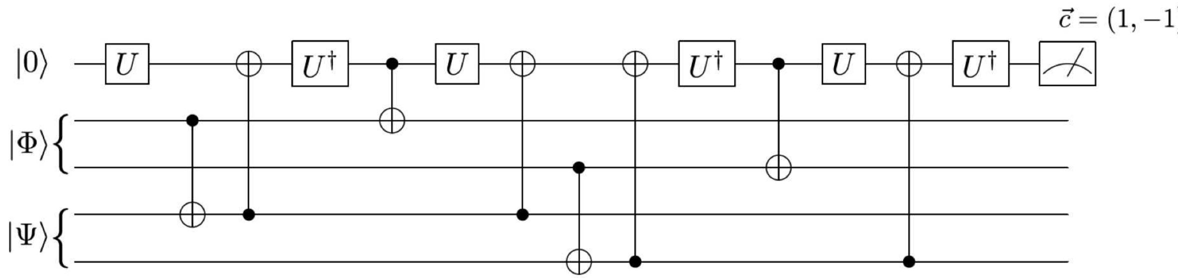
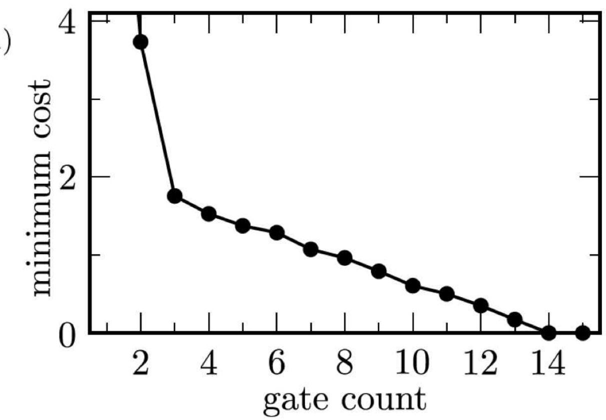
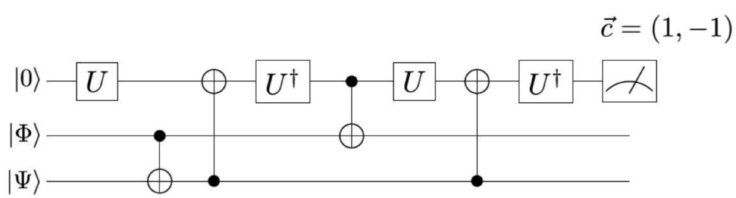


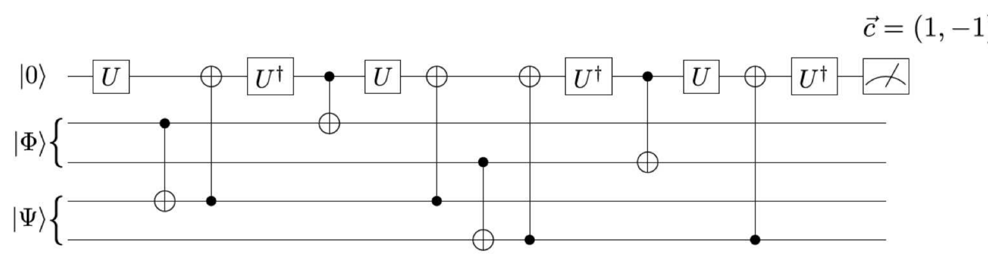


- look for patterns

one-qubit



two-qubit



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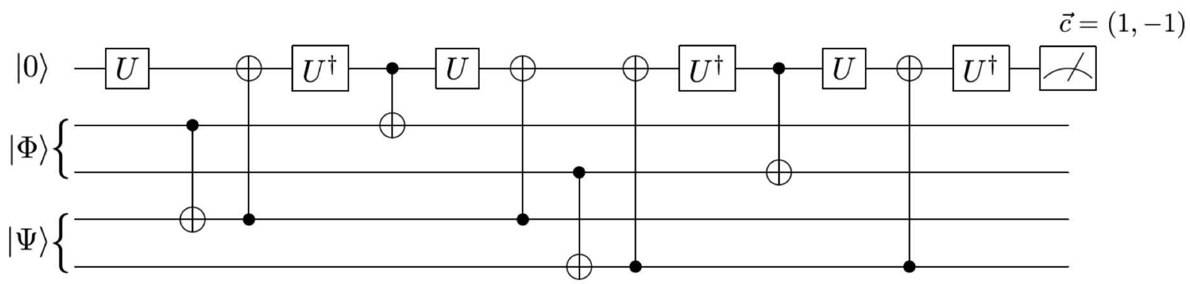

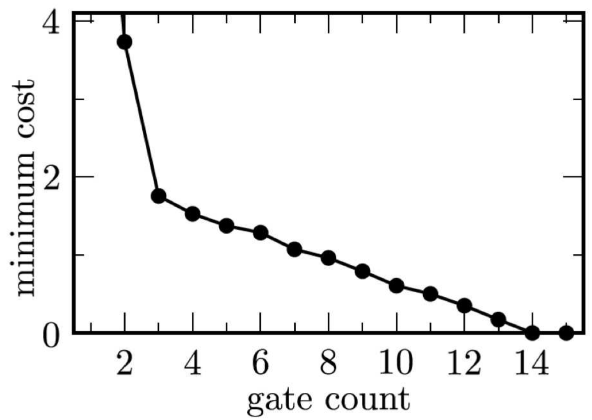

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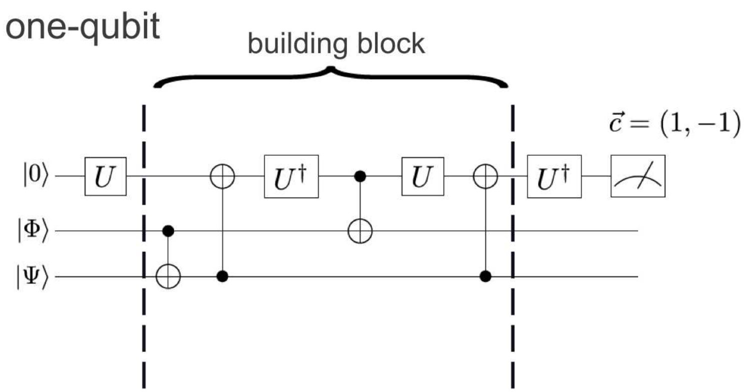
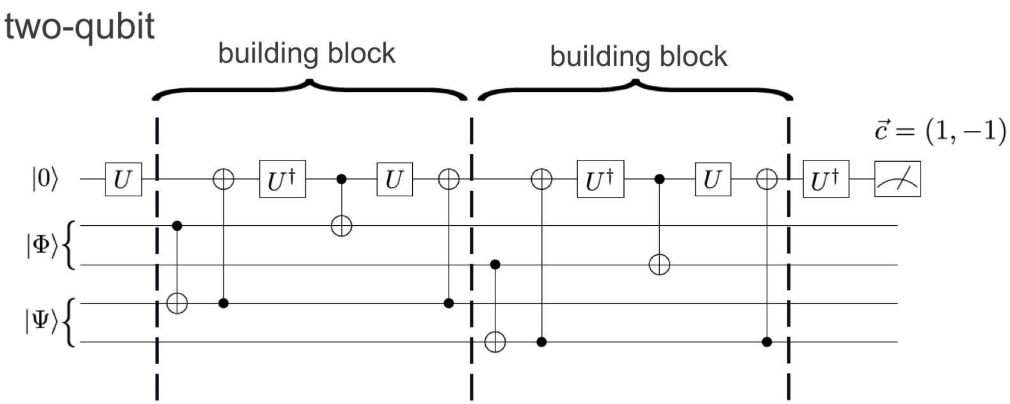
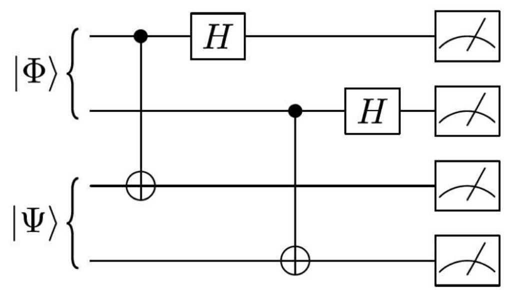


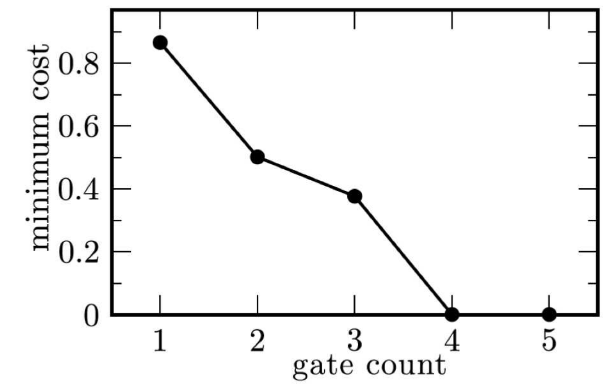


discover the scaling: Bell-Based algorithm

- solve larger problem

$\vec{c} = (1, 1, 1, -1)^{\otimes 2}$





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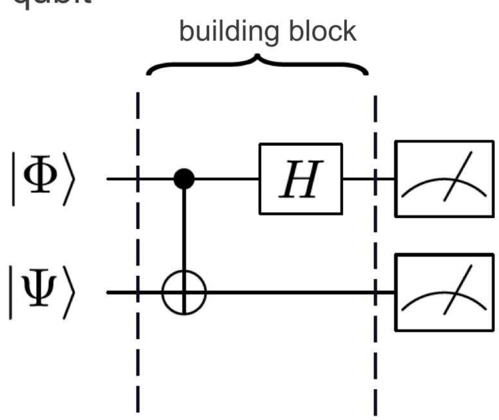
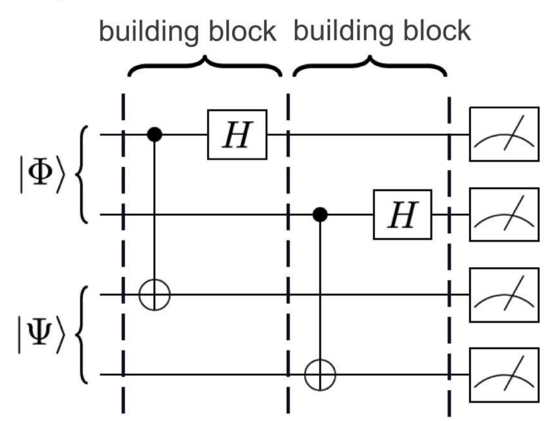
one-qubit



$\vec{c} = (1, 1, 1, -1)$

two-qubit



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discover the scaling: Bell-Based algorithm

- solve larger problem

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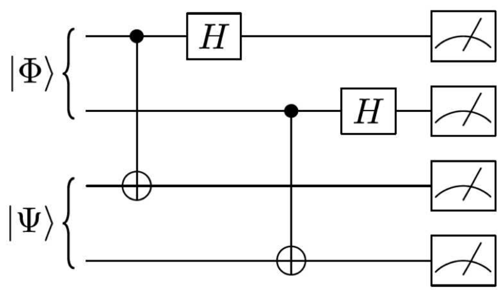
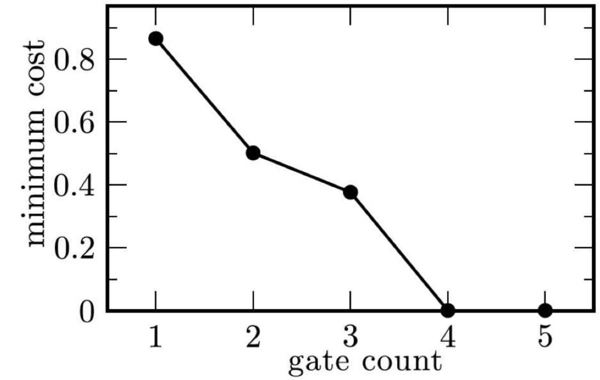
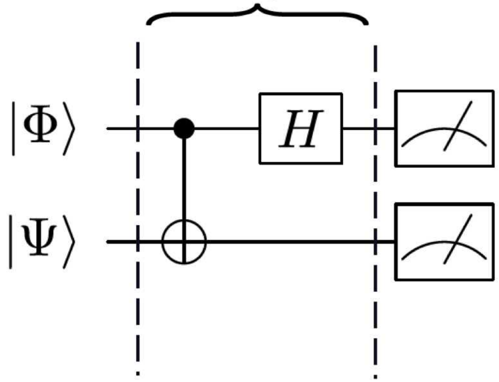




- look for patterns

one-qubit

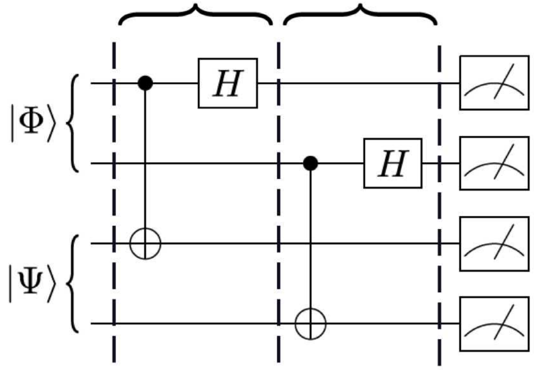
building block



$\vec{c} = (1,1,1,-1)$

two-qubit

building block building block

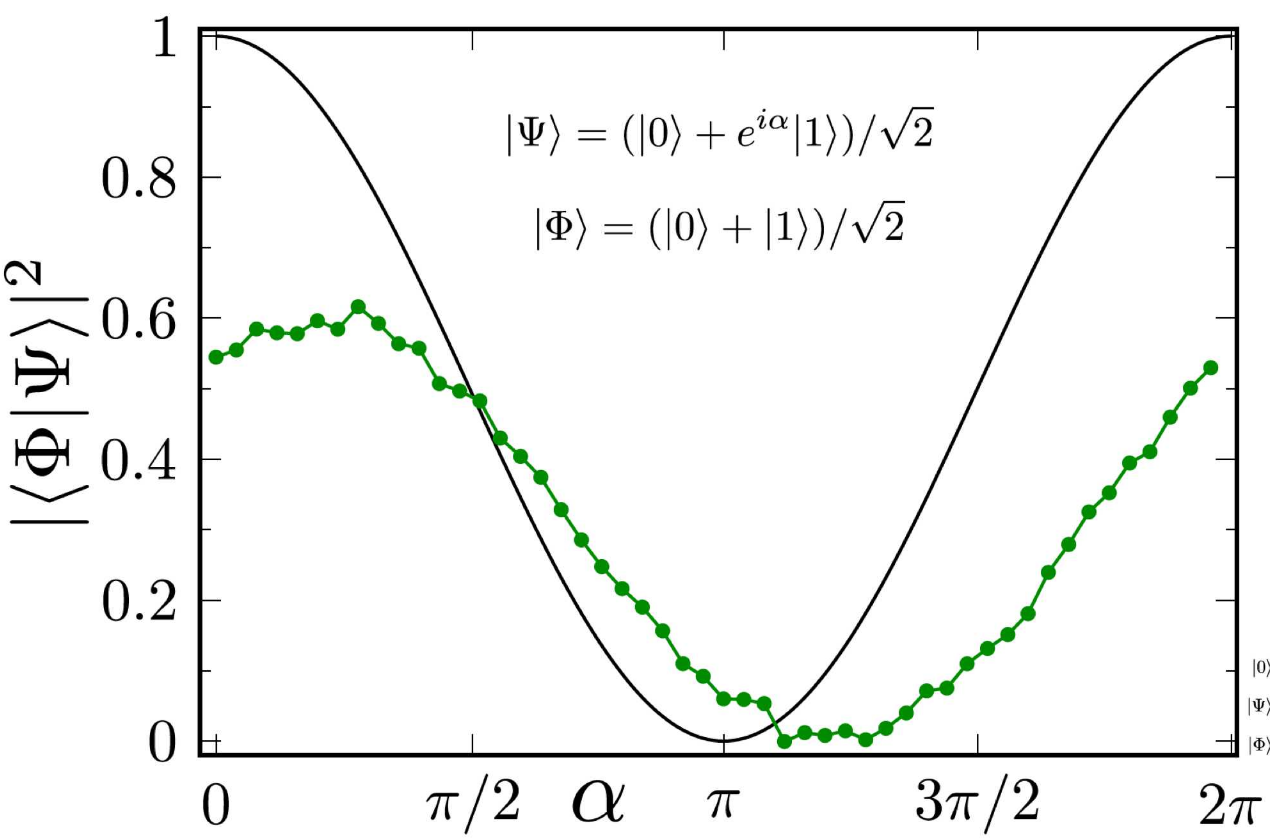


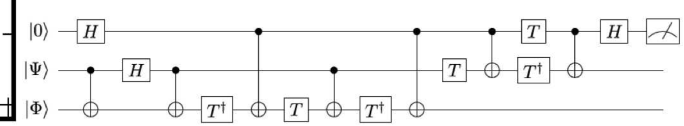
$\vec{c} = (1,1,1,-1)^{\otimes 2}$

can be used to compute Renyi entropies,

Y. Subaşı, L. Cincio, P. Coles, J. Phys. A **52**, 044001 (2019)

comparison on IBMQX4





L. Cincio, Y. Subaşı, A. Sornborger, P. Coles, New J. Phys. **20**, 113022 (2018)

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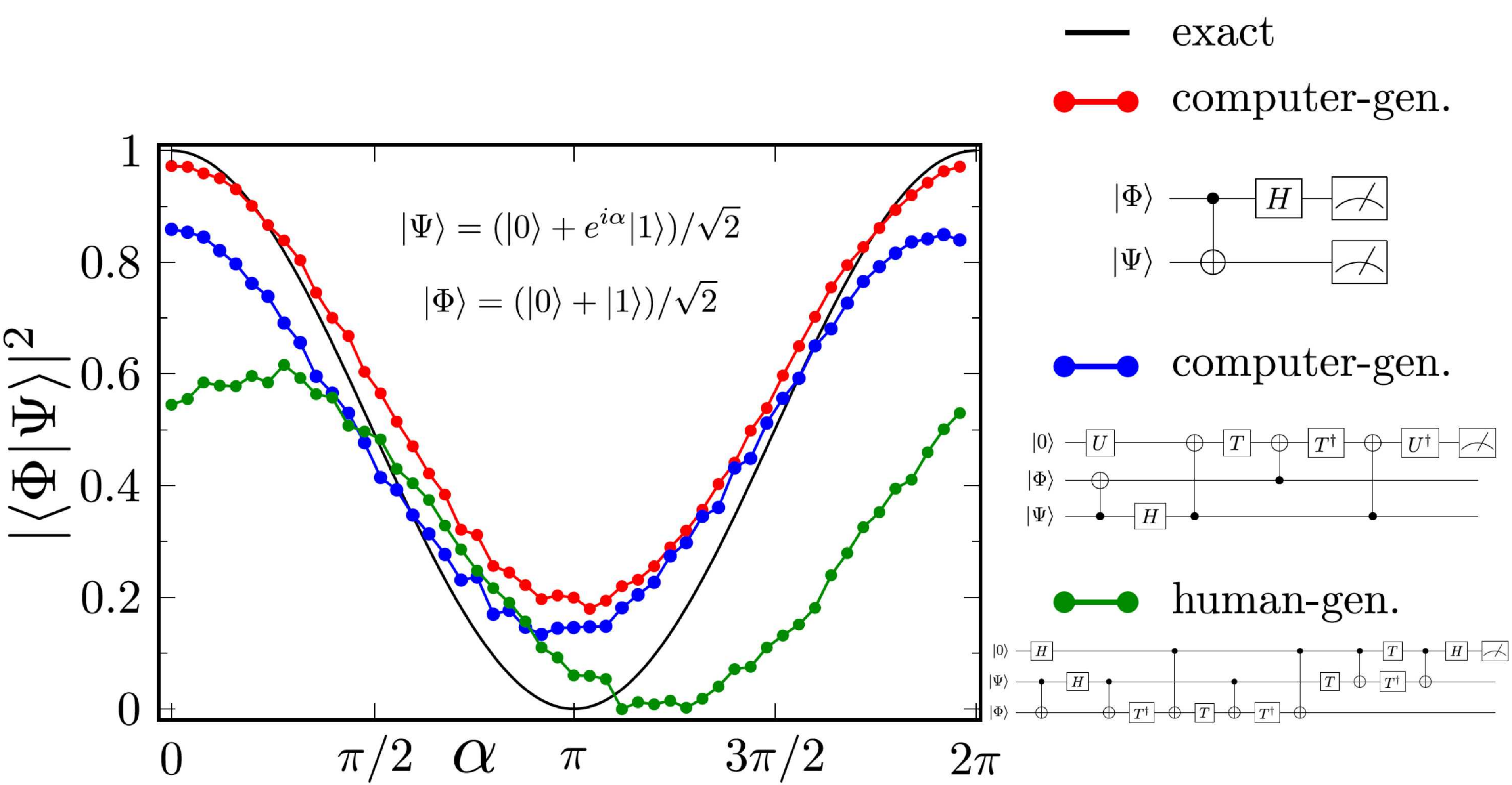

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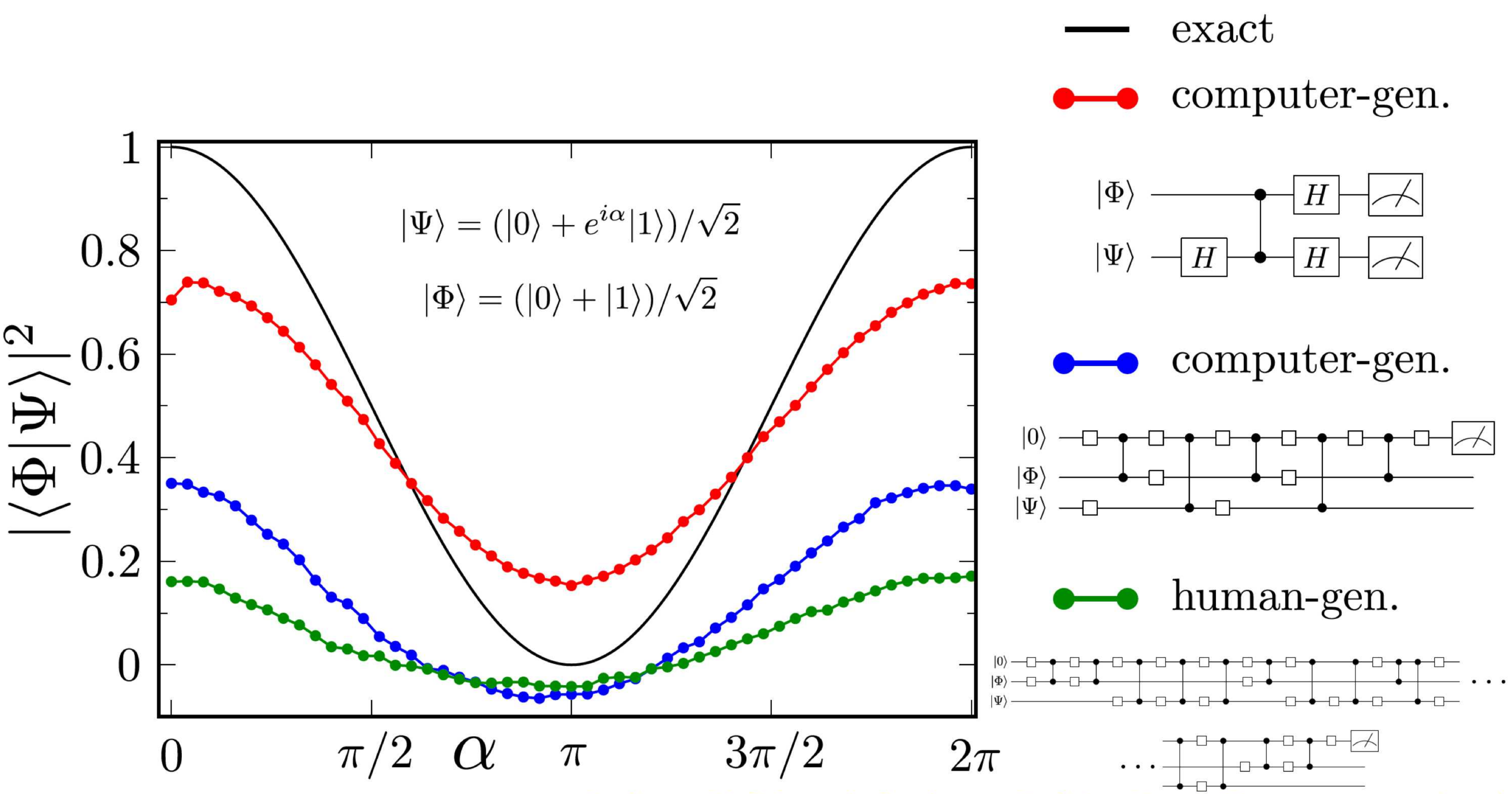
comparison on Rigetti

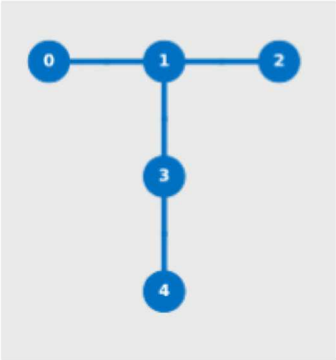


L. Cincio, Y. Subaşı, A. Sornborger, P. Coles, New J. Phys. **20**, 113022 (2018)

example: Quantum Fourier Transform (*machine specific*)

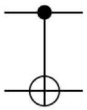
- given state $|\Psi\rangle$, compute $U_{\mathrm{QFT}}|\Psi\rangle$

- target IBM Ourense (5-qubit)



- basis gate set

$$-\boxed{P}- \;=\; \text{“pulse”} = e^{-i\pi X/4}$$



$$-\boxed{R_z(\theta)}-$$

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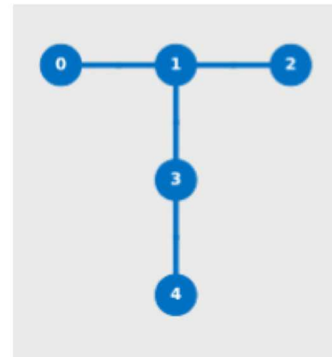
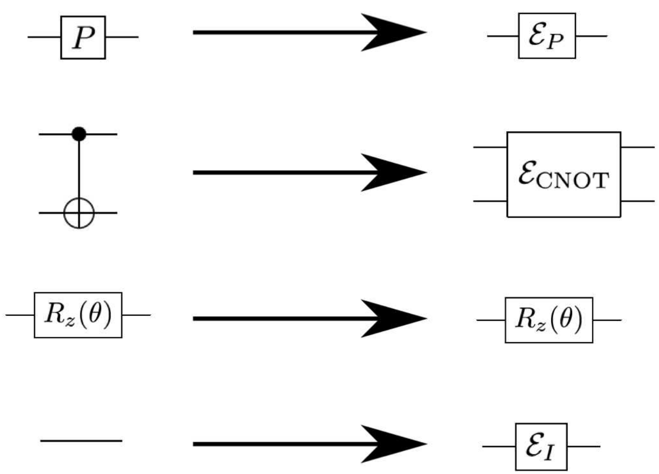


- basis gate set, error model



- evaluate cost function using noisy gates

example: Quantum Fourier Transform (*machine specific*)

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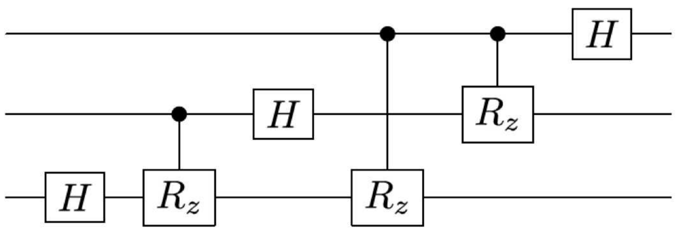
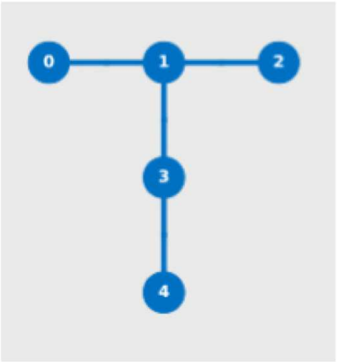
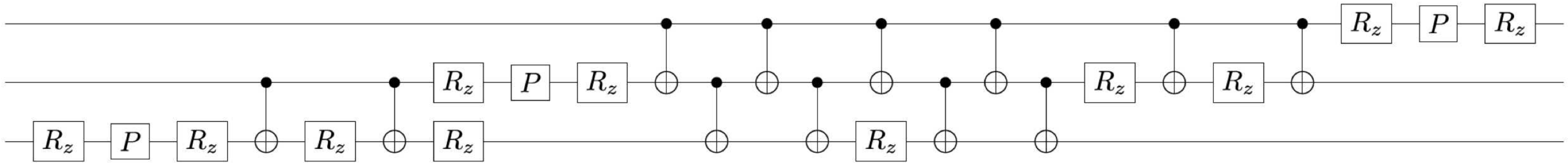
- textbook version



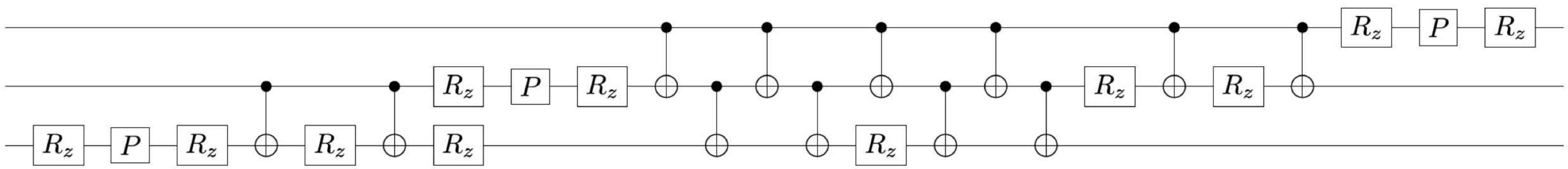


- textbook version using available gates

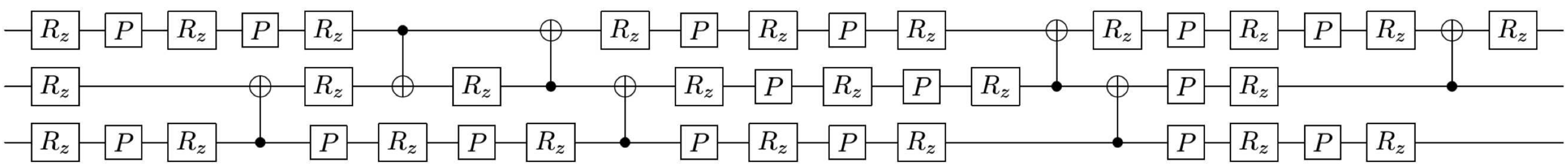


example: Quantum Fourier Transform (*machine specific*)

- textbook (human generated)



- computer generated



- less CNOTs: 12 $\longrightarrow$ 7
- more noise-free $\boxed{R_z(\theta)}$ gates with variational parameters

L. Cincio, K. Rudinger, M. Sarovar, P. J. Coles, *in preparation*

example: Quantum Fourier Transform (*machine specific*)

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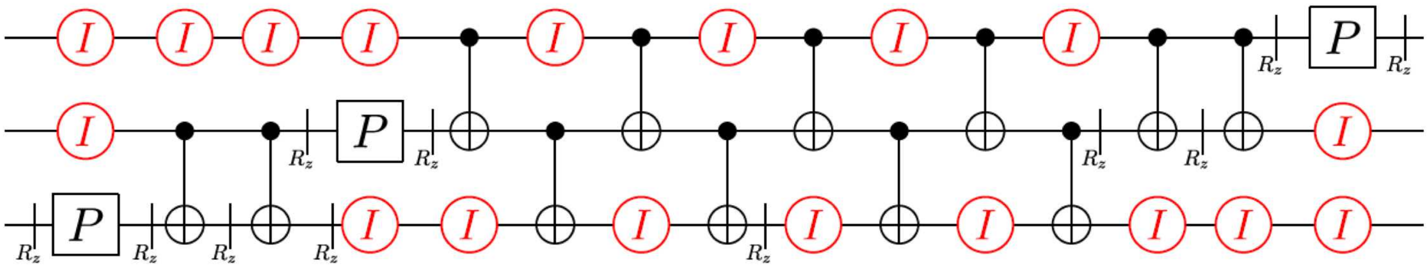

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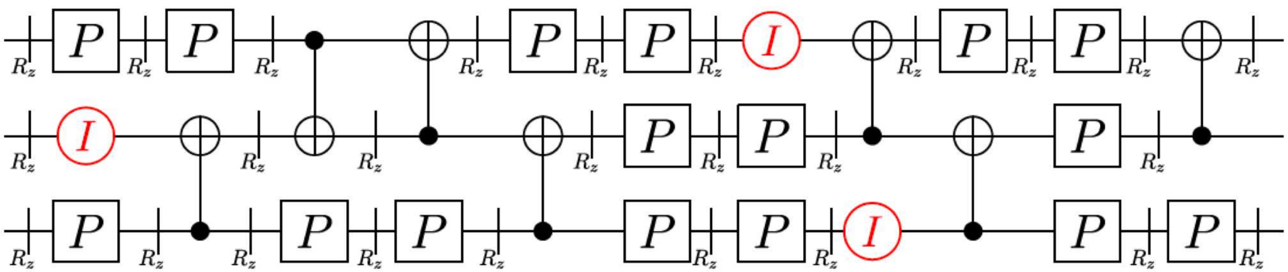
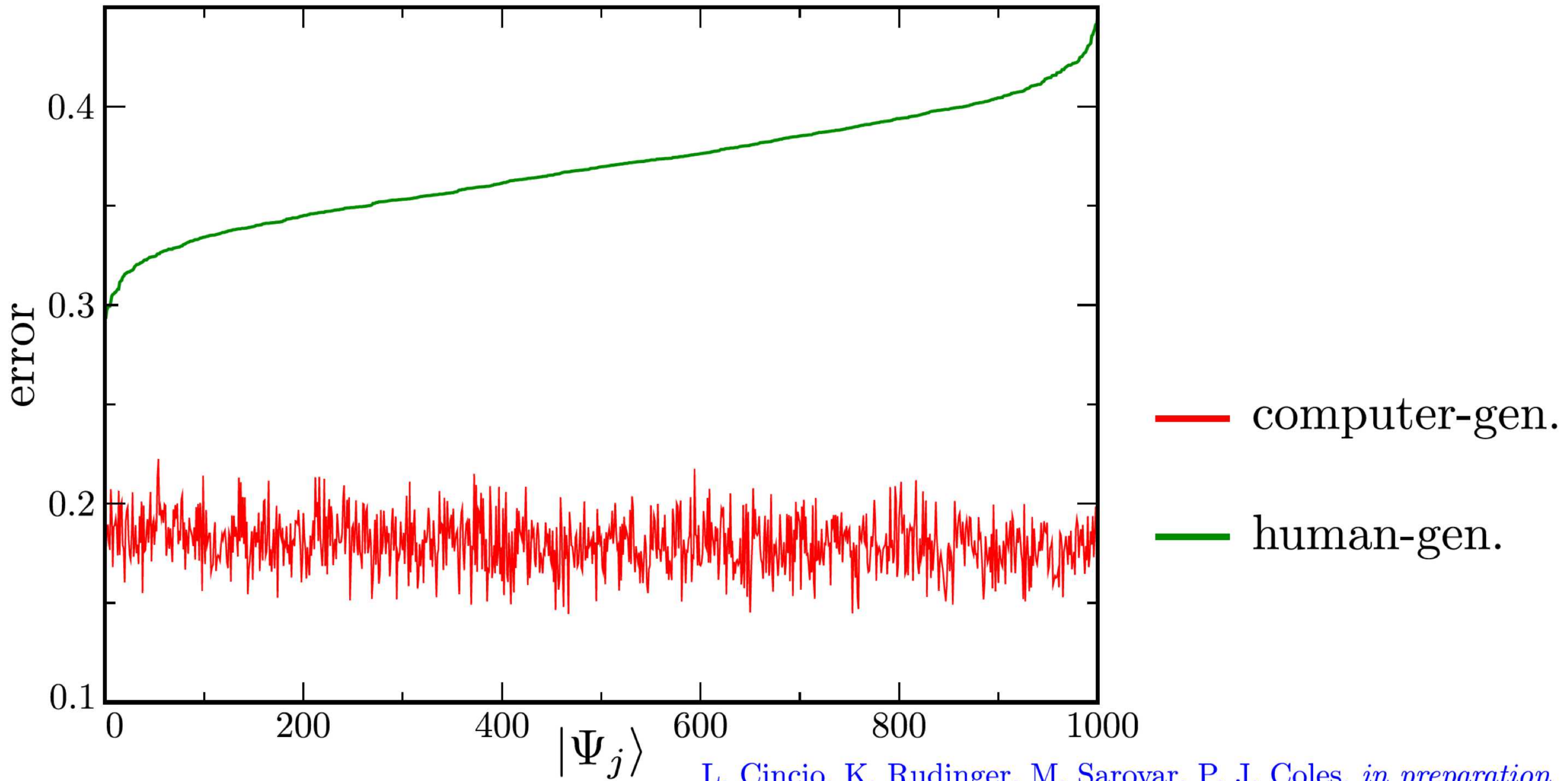


  - less CNOTs: 12 $\longrightarrow$ 7
  - more noise-free $\boxed{R_z(\theta)}$ gates with variational parameters
  - less qubit idling: 18 x I $\longrightarrow$ 3 x I

L. Cincio, K. Rudinger, M. Sarovar, P. J. Coles, *in preparation*

comparison on noisy simulator

- 1000 random states $|\Psi_j\rangle$
- error $= \| \rho_j - |\Psi_j^{\mathrm{ex}}\rangle\langle\Psi_j^{\mathrm{ex}}| \|$, where $|\Psi_j^{\mathrm{ex}}\rangle = U_{\mathrm{QFT}}|\Psi_j\rangle$



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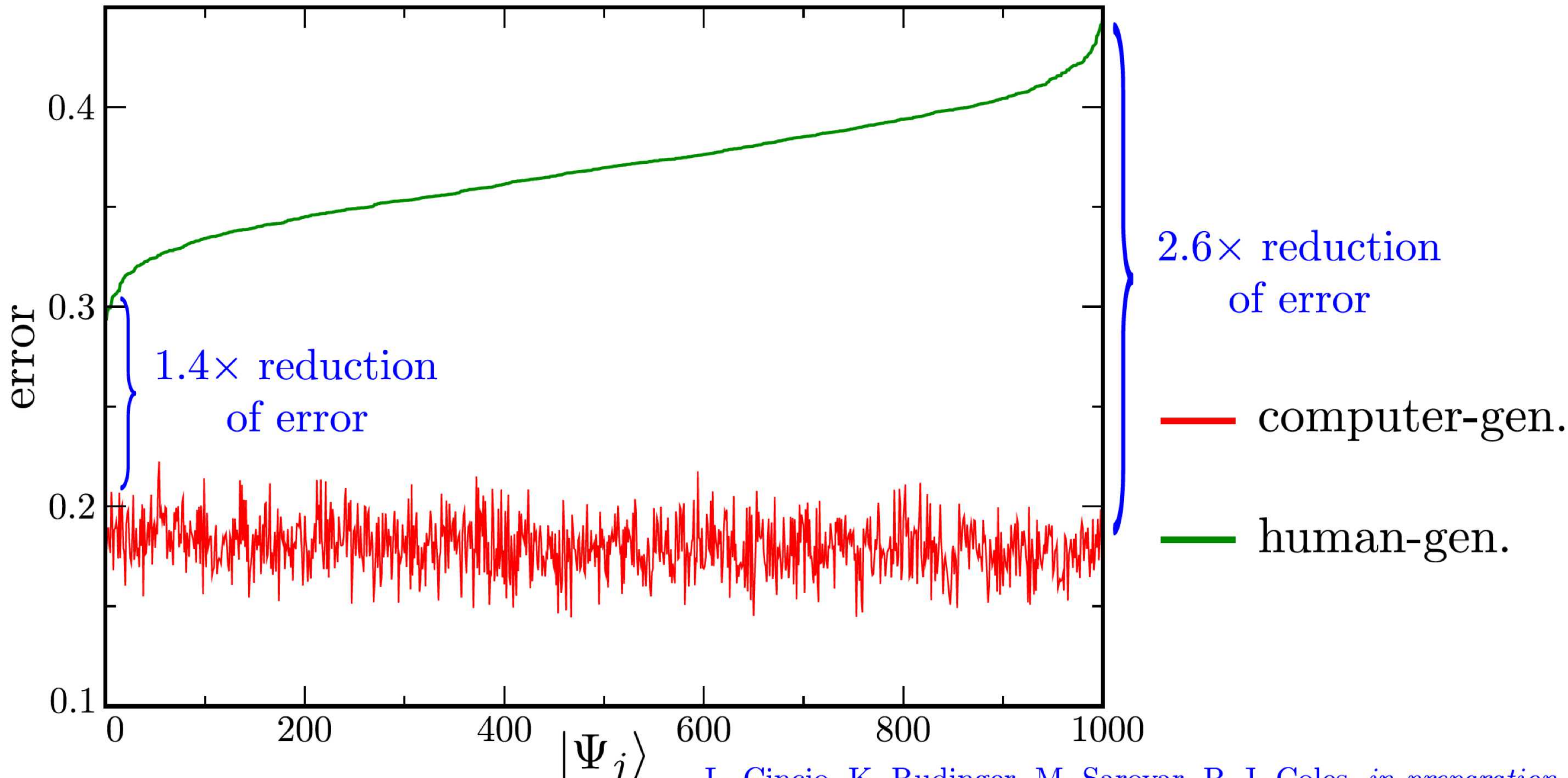
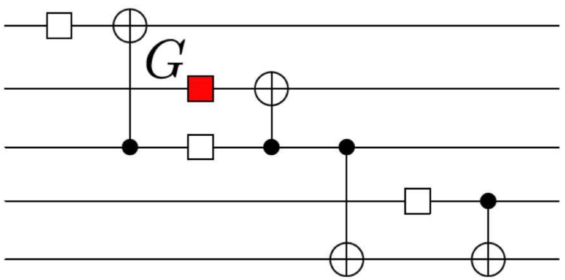


L. Cincio, K. Rudinger, M. Sarovar, P. J. Coles, *in preparation*

summary



- this is not a compiler!

- framework for automated algorithm discovery
  - optimize structure of an algorithm and continuous gates
  - optimize over classical post-processing

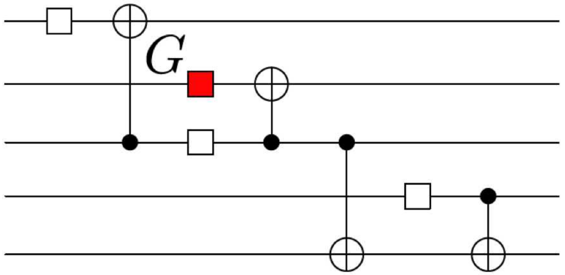
- algorithm structure optimization also used in
  - Variational Quantum Linear Solver

    C. Bravo-Prieto, R. LaRose, M. Cerezo, Y. Subasi, L. Cincio, P. J. Coles, arXiv:1909.05820
  - Variational Quantum State Diagonalization

    R. LaRose, A. Tikku, E. O'Neel-Judy, L. Cincio, P. J. Coles, npj Quant. Inf. **5**, 8 (2019)
  - Quantum-assisted Quantum Compiling

    S. Khatri, R. LaRose, A. Poremba, L. Cincio, A. T. Sornborger, P. J. Coles, Quantum **3**, 140 (2019)

summary



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THANK YOU!

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    C. Bravo-Prieto, R. LaRose, M. Cerezo, Y. Subasi, L. Cincio, P. J. Coles, arXiv:1909.05820

  - Variational Quantum State Diagonalization

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