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QUANTUM INFORMATION SCIENCE @ UNIPR

Quantum Compiling

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Quantum Computers @ Parma 28 October 2019

Outline

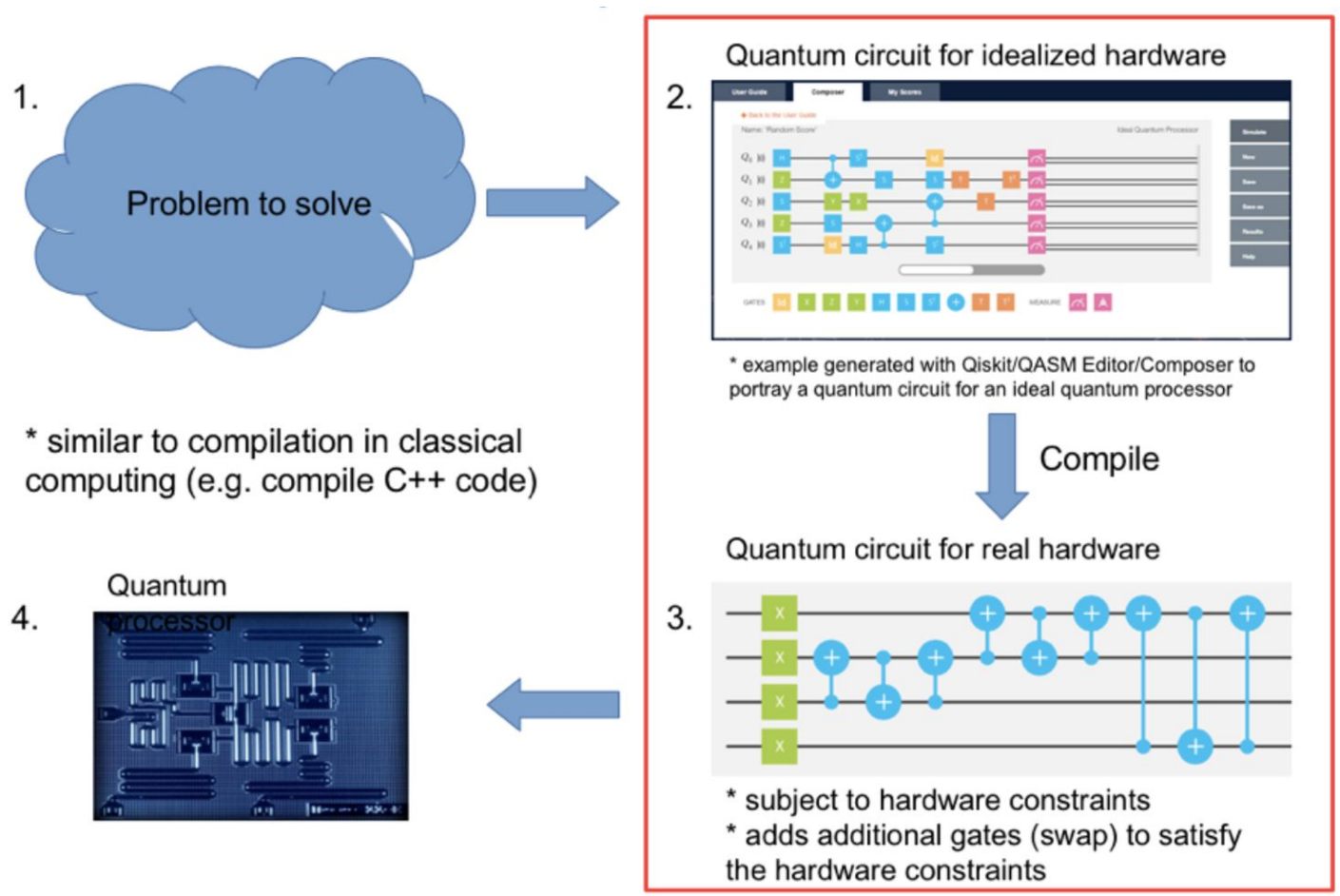
- **Quantum Compilation Problem**
- State of the Art
- Quantum Software @ UniPr

Quantum Compilation Problem

Fast, device-aware implementation of quantum algorithms

A good quantum compiler must translate an input program into the most efficient equivalent of itself, getting the most out of the available hardware.

The quantum compilation problem in general is **NP-Hard**.



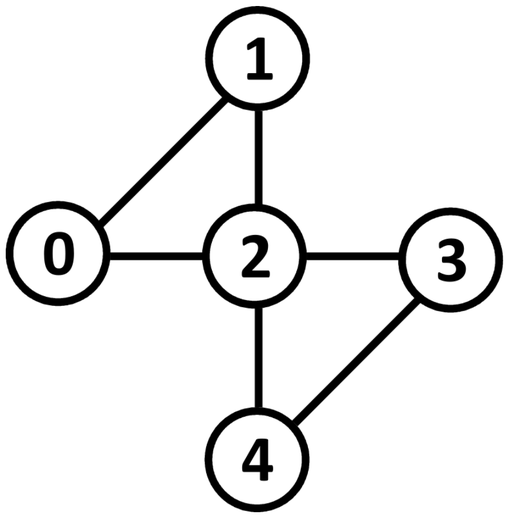
Quantum Compilation Problem

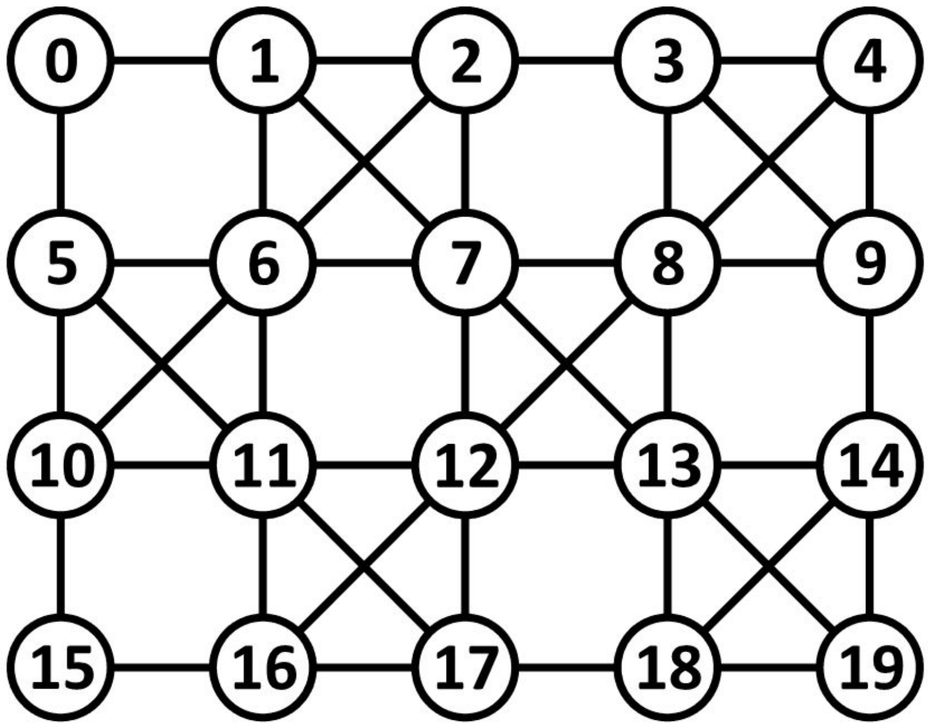
On noisy intermediate-scale quantum (NISQ) devices:

- **Gate synthesis** = decomposition of an arbitrary unitary operation into a sequence of gates from a discrete set
- Compliance with the **coupling map**
- Noise awareness

Quality indicators:

- Circuit **depth**
- **Gate count**
- **Fidelity** of quantum states





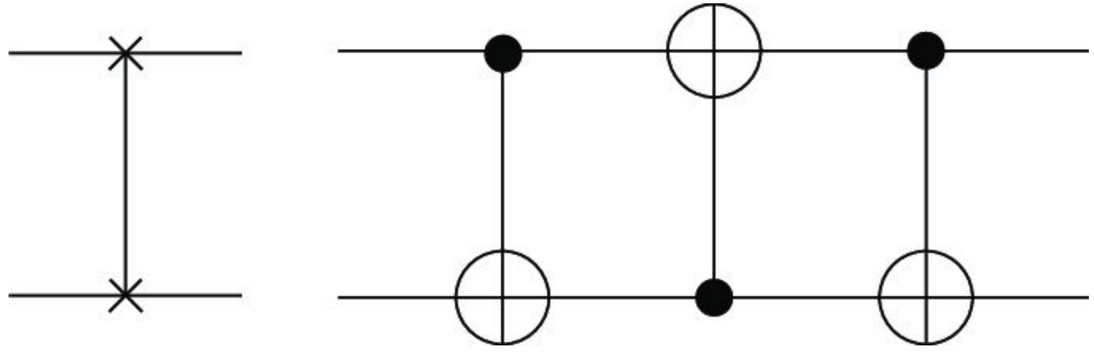
Quantum Compilation Problem

- Initial mapping of logical qubits to physical ones

  → Necessary but not sufficient

- Exchange of qubit states using SWAP gates

  → Increment of circuit depth



Example: GHZ State

The Greenberger-Horne-Zeilinger state for ***n*** qubits:

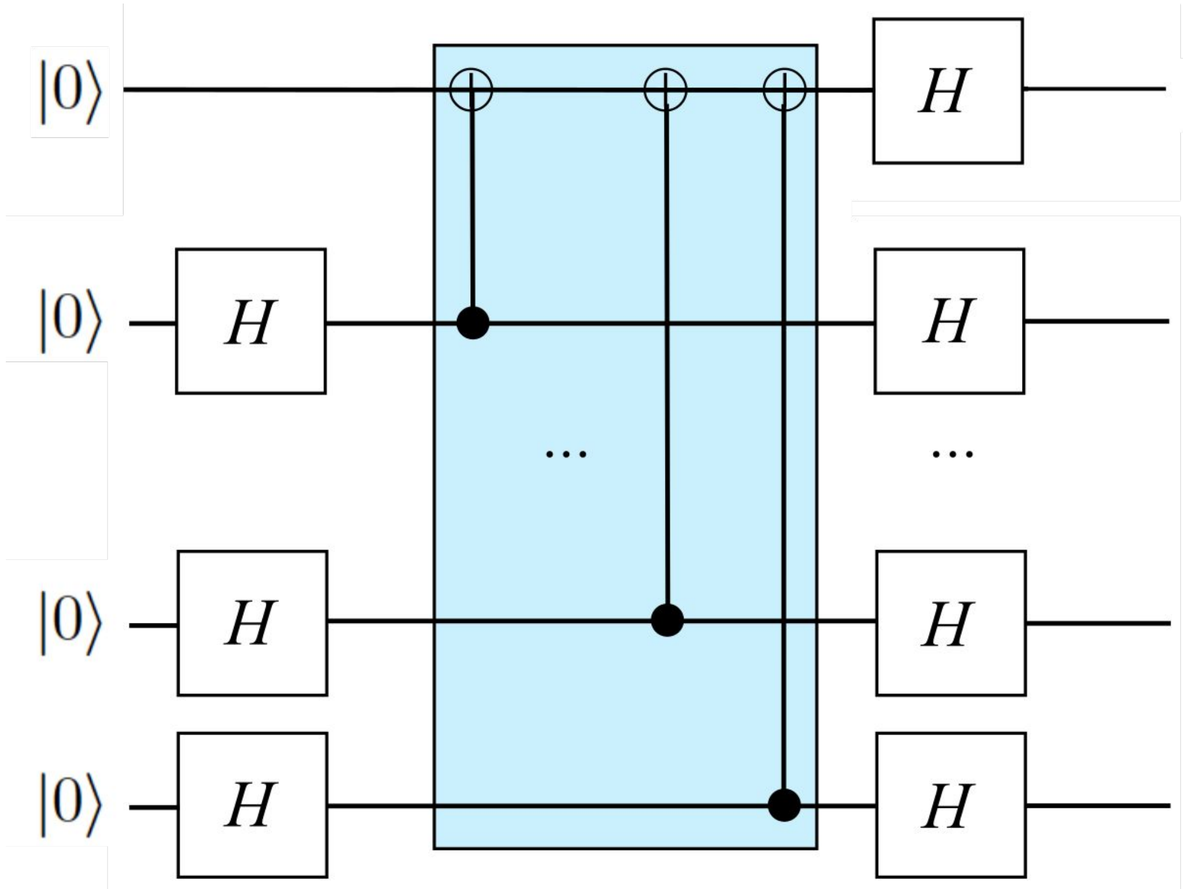
$$\frac{|0\rangle^{\otimes n}+|1\rangle^{\otimes n}}{\sqrt{2}}$$

It is an entangled quantum state that plays a prominent role in several quantum algorithms.

D. M. Greenberger, M. A. Horne, A. Zeilinger, Going Beyond Bell's Theorem, in ‘Bell's Theorem, Quantum Theory, and Conceptions of the Universe', M. Kafatos (Ed.), Kluwer, Dordrecht, 69-72 (1989)

Example: GHZ State

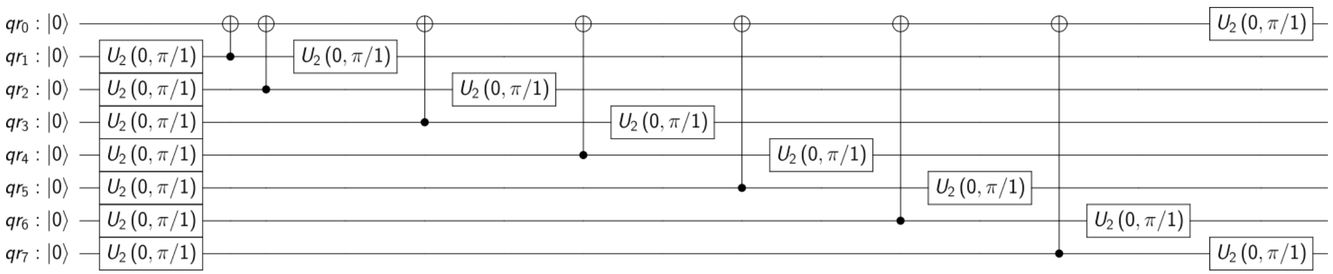
The ideal quantum circuit that generates the GHZ state requires only H and CNOT gates

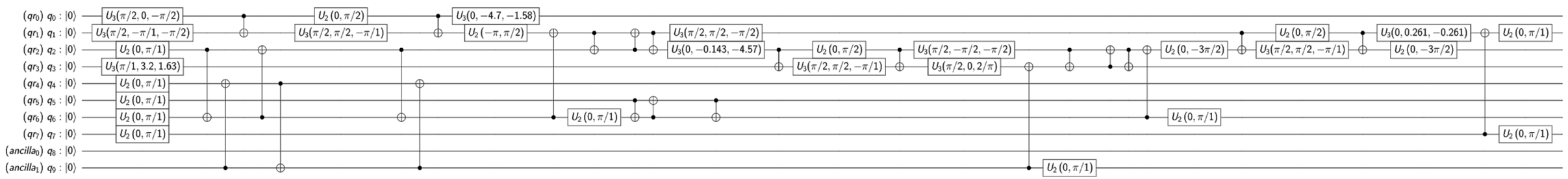


$$\frac{|0\rangle^{\otimes n} + |1\rangle^{\otimes n}}{\sqrt{2}}$$

Example: GHZ State

Ideal vs. compiled 8-qubit GHZ circuit (Qiskit v.0.12)





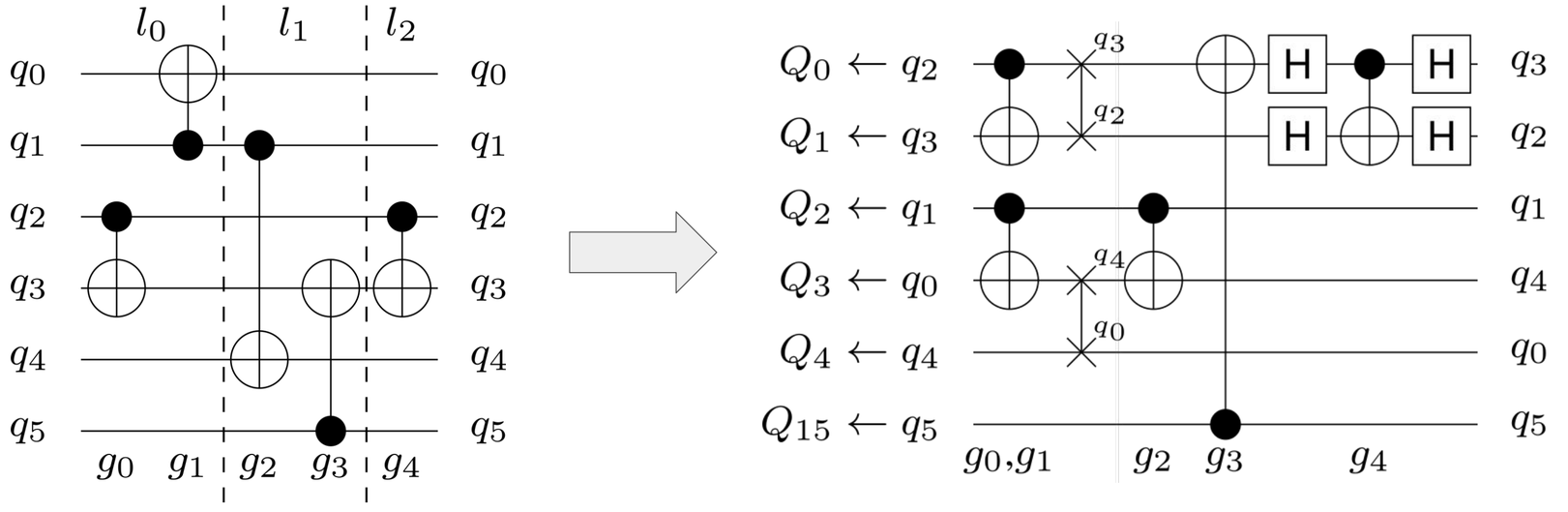
Outline

- Quantum Compilation Problem
- **State of the Art**
- Quantum Software @ UniPr

State of the Art

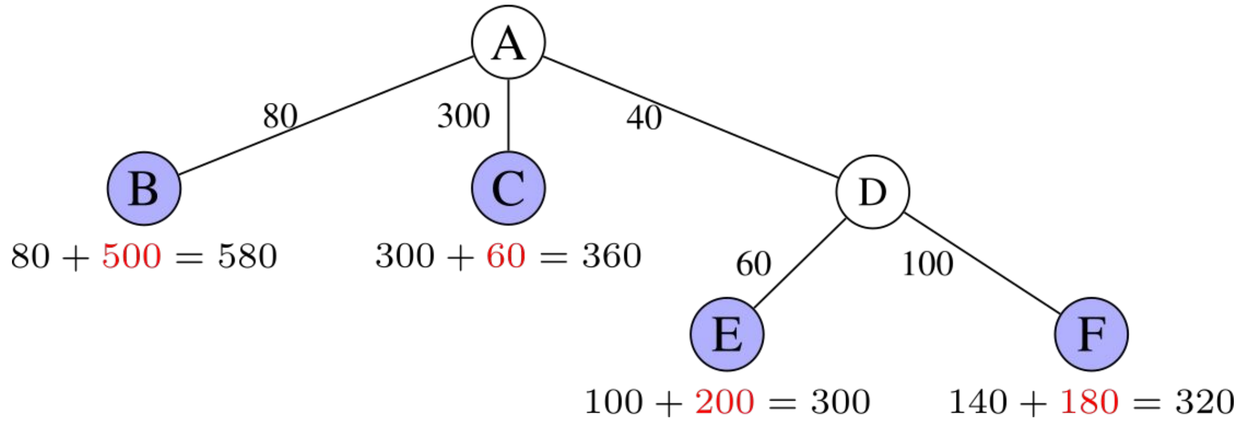
Zulehner *et al.*, An Efficient Methodology for Mapping Quantum Circuits to the IBM QX Architectures, IEEE TCAD vol.38 no.7, 2019

- Partition circuit into layers
- For each layer find a CNOT compliant mapping
  - $m!/(m-n)!$ possible mappings with m physical qubits and n logical qubits
  - A* search algorithm
  - minimize additional operations to switch between subsequent mappings



State of the Art

Zulehner *et al.*, 2019



A* search algorithm:

- start from current layer mapping
- explore possible subsequent mappings employing combinations of parallel SWAPs
- each node x_i represents a partial mapping
- expand node x_i that minimizes cost function $f(x_i) = g(x_i) + h(x_i)$
  - $g(x_i)$ is the fixed cost of current node as $f(x_{i-1}) + 7 * \#SWAPs$
  - $h(x_i)$ is a heuristic to estimate the distance from a goal node
  - enhance with lookahead capabilities

State of the Art

Childs *et al.*, *Circuit Transformations for Quantum Architectures*, TQC 2019

Architecture: $G(V,E)$

Circuit: directed acyclic graph, set of qubits Q ($|Q| \leq |V|$), size $|C|$

1) **Greedy swap circuit transformation**: Time complexity $O(|C||E|diam(G))$
   Best approach for minimizing circuit size

2) **Architecture-aware circuit transformation**:
- qubit movement: addressed by a SWAP-based *permuter*, time complexity $< t_p$
- qubit placement: addressed by a *mapper*, time complexity $< t_m$

  Time complexity $O(|C|(t_m + |V| + t_p))$

  Best approach for minimizing depth on grid architectures

State of the Art

Jandura, 2018 (LookaheadSwap in Qiskit)

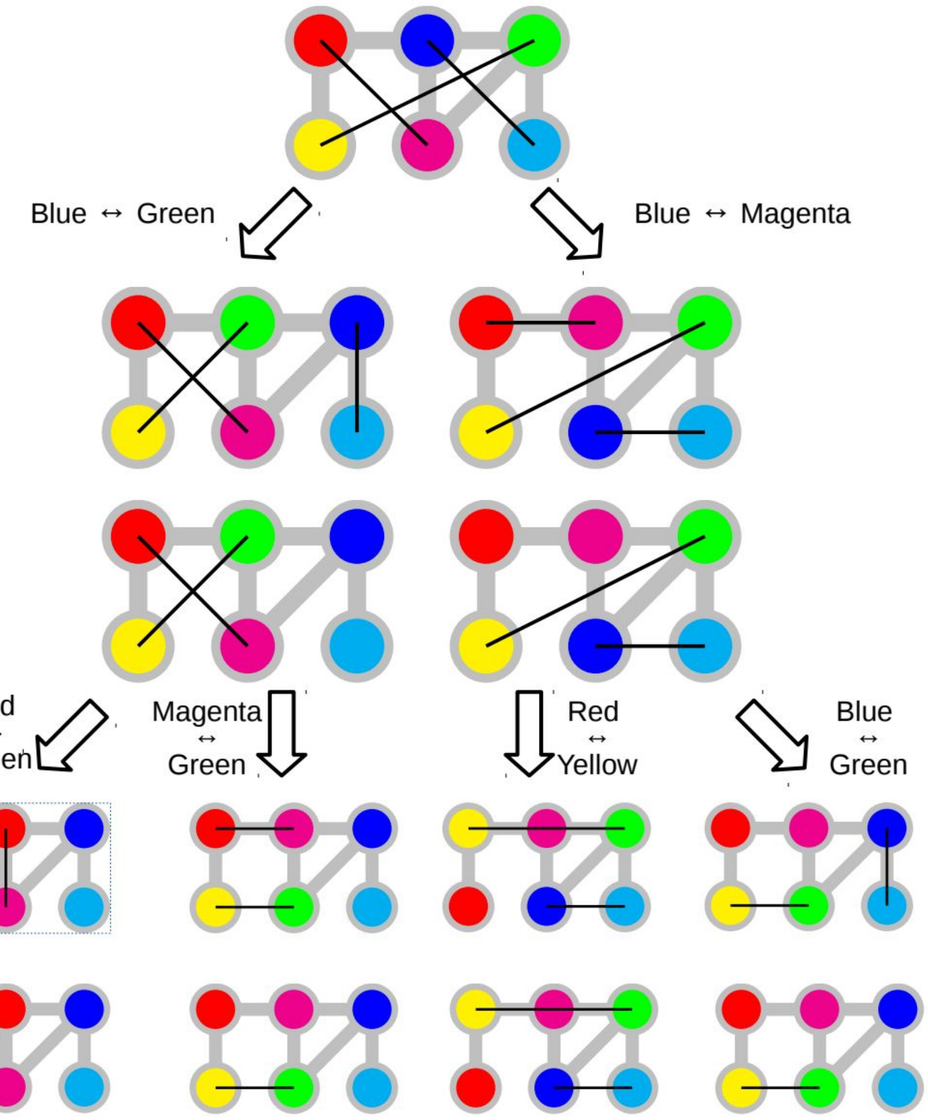
Mapping = logical qubits ↔ physical qubits

Given a mapping and a list of upcoming CNOTs, repeat 4 times:

1. Find 4 most promising swaps and calculate new mapping for each of them
2. For each mapping count how many CNOTs can be executed and remove them from the list

From the 4^4=256 final mappings, choose the one that allowed for the most CNOTs to be executed and execute the fist swap on the path to this mapping.

Then start the whole algorithm again, until the circuit is completed.

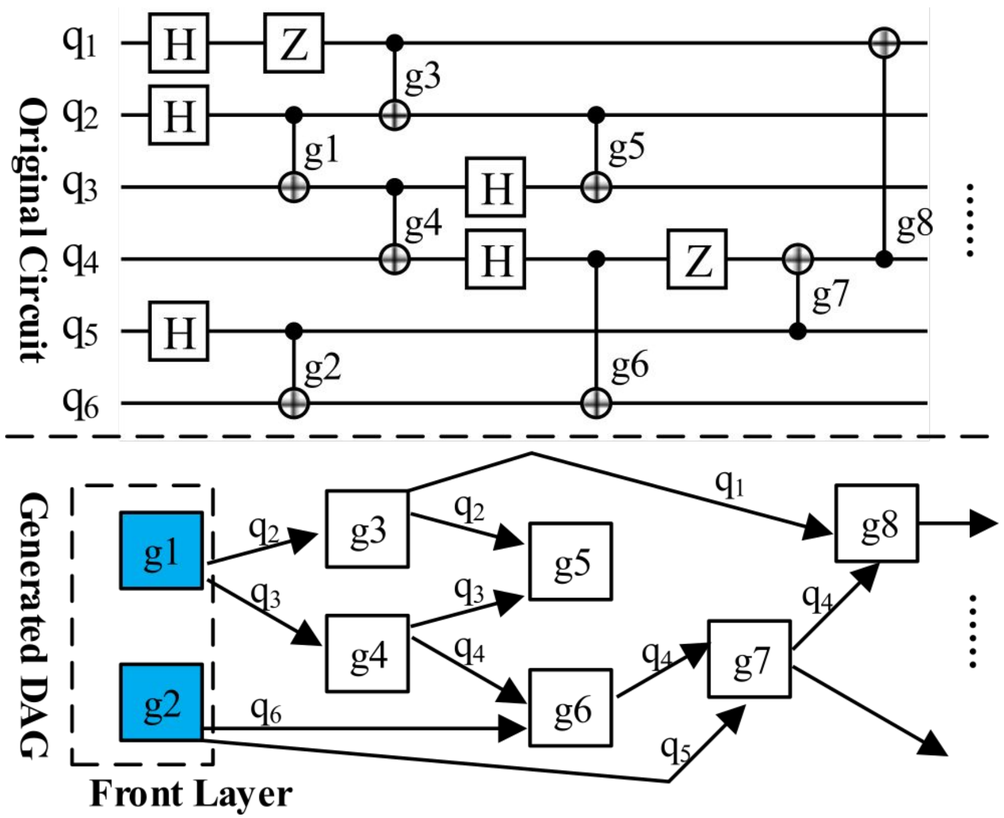


State of the Art

Li et al., Tackling the Qubit Mapping Problem for NISQ-Era Quantum Devices, ASPLOS '19, 2019

SW**A**P-based **B**idi**RE**ctional heuristic search (**SABRE**)

- Preprocessing
  - Compute distance matrix D over the coupling map
  - Generate DAG from circuit to represent two-qubit gates dependencies
  - Initialize the front layer F as the set of two-qubit gates without unexecuted predecessors
  - Generate random initial mapping



State of the Art

Li et al., Tackling the Qubit Mapping Problem for NISQ-Era Quantum Devices, ASPLOS '19, 2019

SWAP-based heuristic

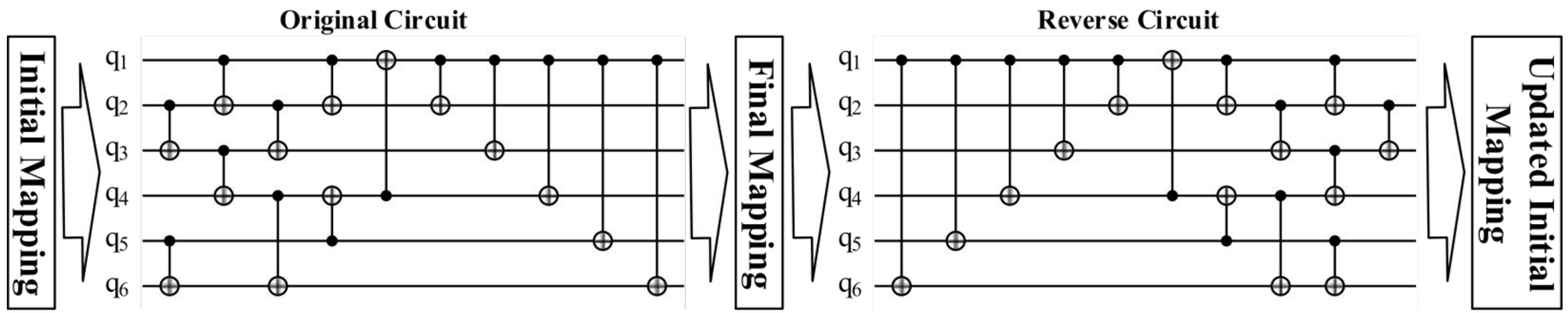
- Iterate over front layer F
  - Remove executable gates from F and add their successor to F
  - For those gates in F that cannot be executed, search for SWAPs to insert and update mapping
  - Select best SWAP to insert using an heuristic cost function based on distance matrix D
- Stop when F is empty

State of the Art

Li et al., Tackling the Qubit Mapping Problem for NISQ-Era Quantum Devices, ASPLOS '19, 2019

Reverse traversal for bidirectional mapping

- From the original circuit generate a reverse circuit
- Use the final mapping of the first SWAP-based compilation as the initial mapping to compile the reverse circuit
- Use the final mapping of the reverse compilation to recompile the original circuit
- This initial mapping has the quality of taking into account all the gates information



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DIPARTIMENTO DI INGEGNERIA E ARCHITETTURA

Team

- Michele Amoretti (PhD, associate professor)
- Davide Ferrari (PhD student)

Topics

- high performance computing (classical and quantum)
- quantum compiling
- quantum networking (protocols for distributed monitoring, anonymity, leader election, etc.)

Source code: https://github.com/qis-unipr

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Quantum Software @ UniPr

Research related to IBM Q

International Journal of Quantum Information
Vol. 16, No. 8 (2018) 1840006 (15 pages)

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World Scientific
www.worldscientific.com

Efficient and effective quantum compiling for entanglement-based machine learning on IBM Q devices

Davide Ferrari*,†,‡ and Michele Amoretti*,†,§

Efficient Quantum Compiling for Quantum Chemistry Simulation on IBM Q

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Quantum Computers @ Parma, 28/10/2019

Deterministic Pattern-Oriented Quantum Compiler (DPQC)

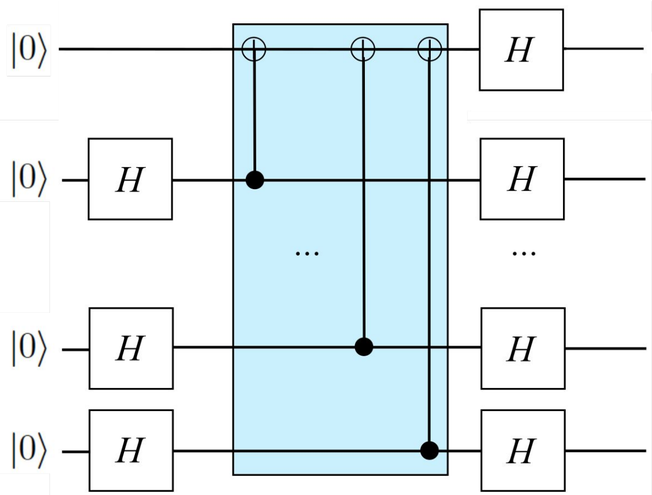
The DPQC software is the implementation of **efficient and deterministic strategies** for the compilation of quantum circuits characterized by peculiar sequences (patterns) of two-qubit operators.

By compilation we mean the transformation of abstract quantum circuits into circuits suited to the characteristics of the available hardware device, preserving their correctness and trying to maximize their efficiency.

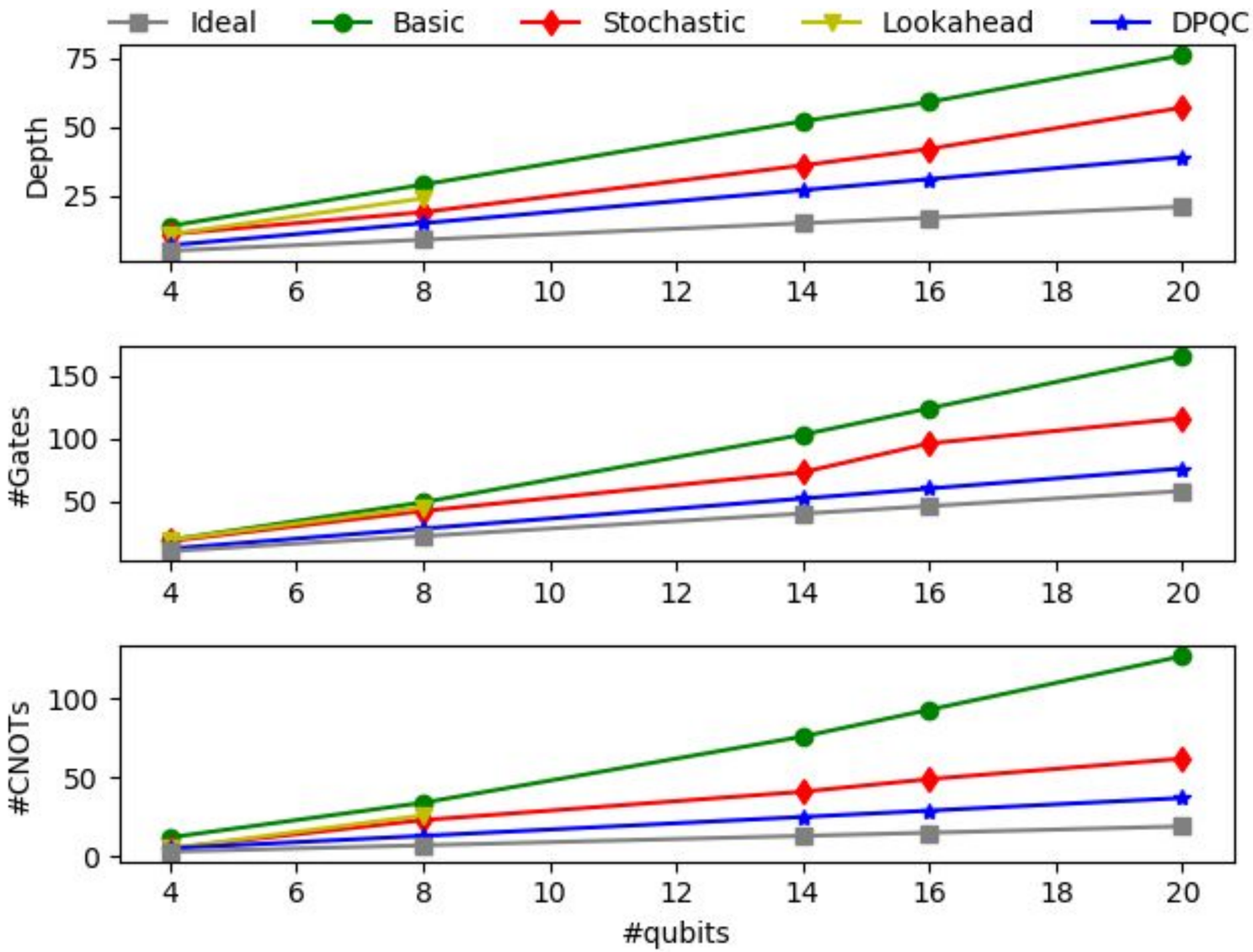
Among the possible characteristics of a quantum computer, the DPQC software considers the coupling map and tries to **minimize circuit depth and gate count**.

SIAE filing n.2019002328, 11/9/2019

GHZ Results



$$\frac{|0\rangle^{\otimes n} + |1\rangle^{\otimes n}}{\sqrt{2}}$$



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Quantum Chemistry Circuits

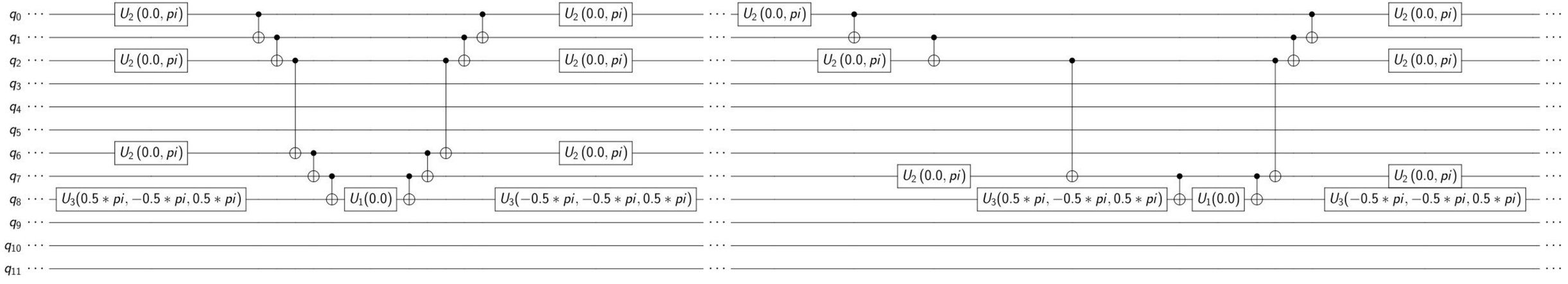
Used to compute the ground state wave function of simple molecular systems such as:

- Hydrogen **H_2 with 4 qubits**
- Lithium Hydride **LiH with 12 qubits**
- Water **H_2O with 14 qubits**

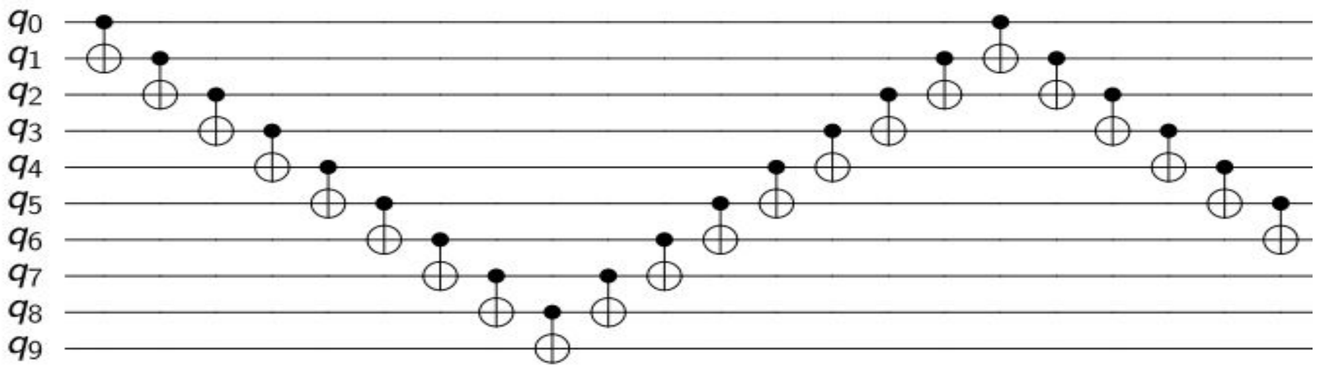
Ivano Tavernelli
Theoretical Quantum Computing @ IBM Research - Zurich

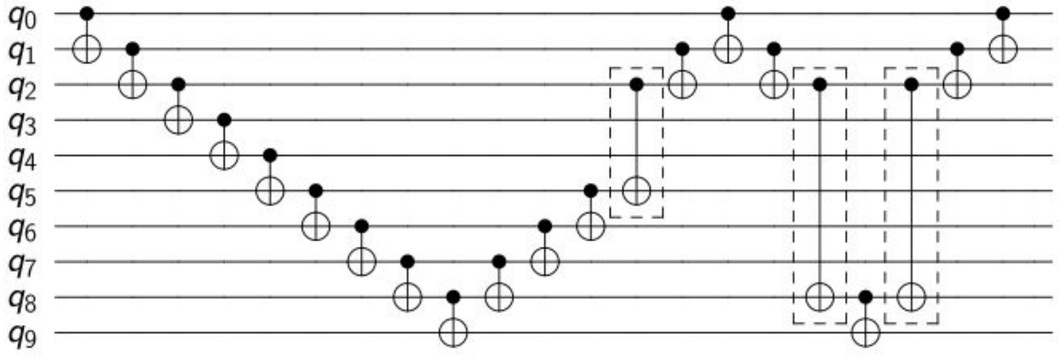
Quantum Computers @ Parma, 28/10/2019

UCCSD



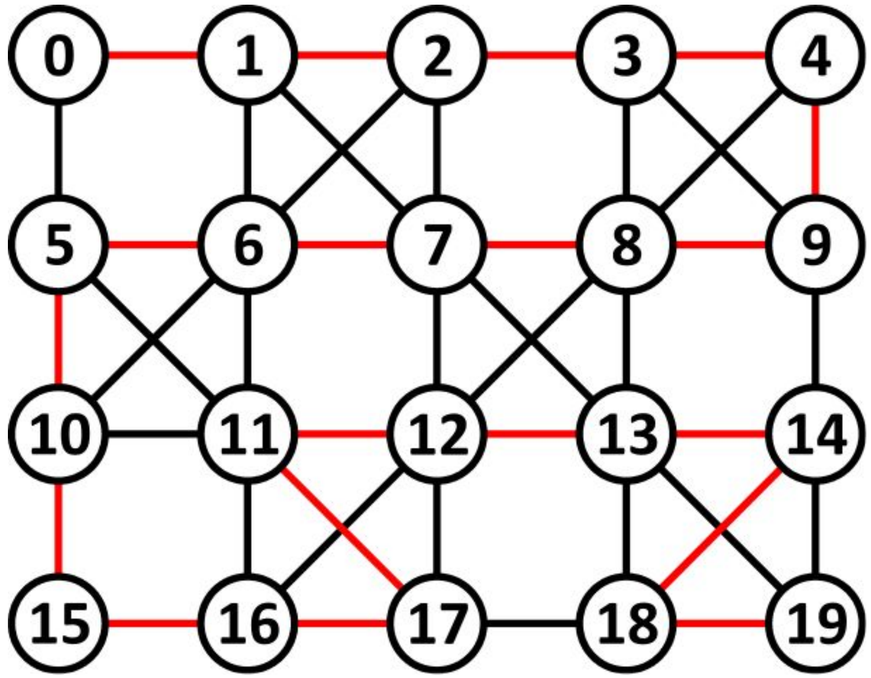
Characterized by repeated sequences of CNOTs





CNOT Sequences Without Gaps

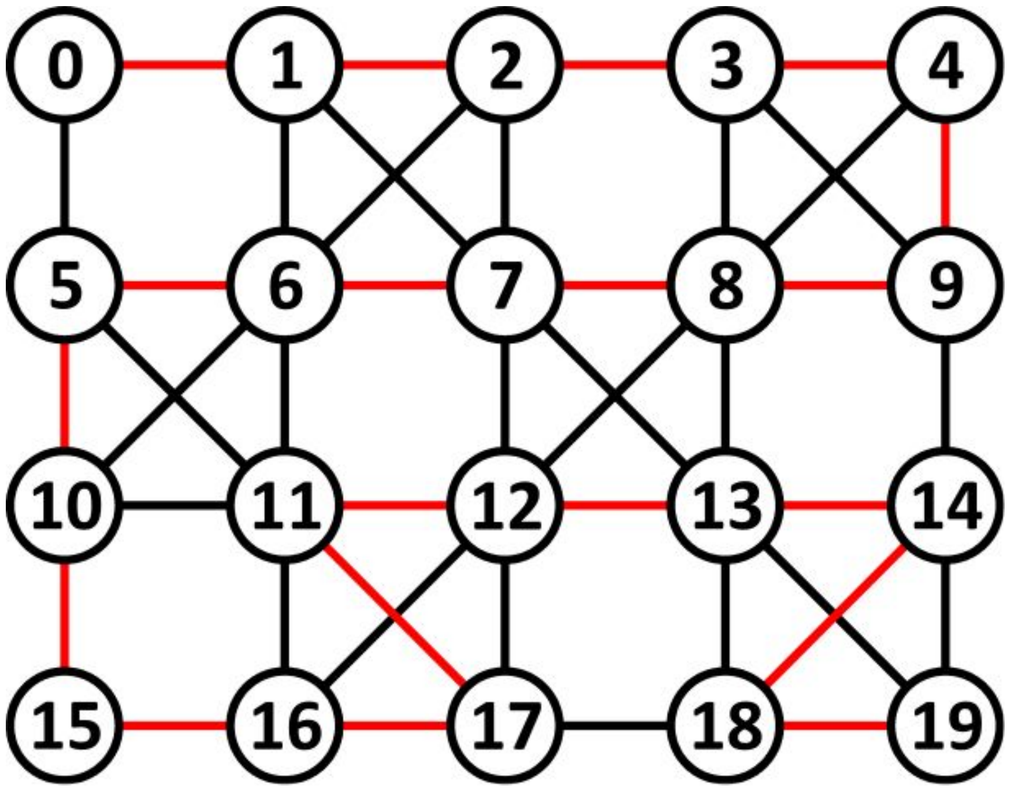
- Algorithm ***chain_layout()*** analyzes the coupling map and orders the qubits in a *chain*
- Every logical qubit $\mathbf{q_i}$ is associated with the **i-th** physical qubit in the chain
- Initial mapping satisfies all CNOTs



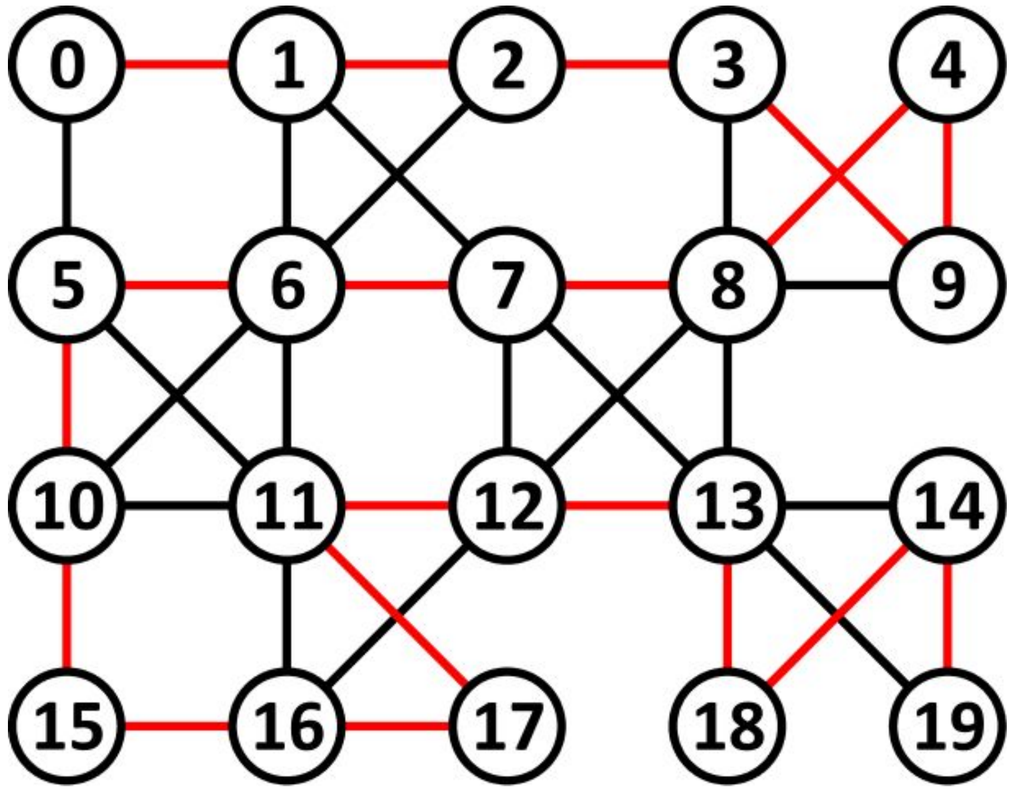
- In general, the problem of finding a path that visits every node only once is NP-complete
- *chain_layout()* exploits the qubit indexing and the graph structure to find a path with a deterministic and efficient approach
- Computational complexity ***O(m)***, where *m* is the number of physical qubits

CNOT Sequences Without Gaps

IBM Q20 Ideal



IBM Q20 Tokyo



CNOT Sequences With Gaps

- Initial mapping is not enough
- Algorithm ***path()*** moves the qubits q_1 and q_2 involved in a remote CNOT close to each other:
  - iteratively computes the SWAP path between q_1 and q_2 neighbors
  - evaluates the distance between q_x and q_y as $|x - y|$ with x and y being their physical qubit indices in the coupling map
  - uses a cost function to choose which qubit to add to the path

$$f(x, y) = |x - y| * SWAP\_DEPTH$$

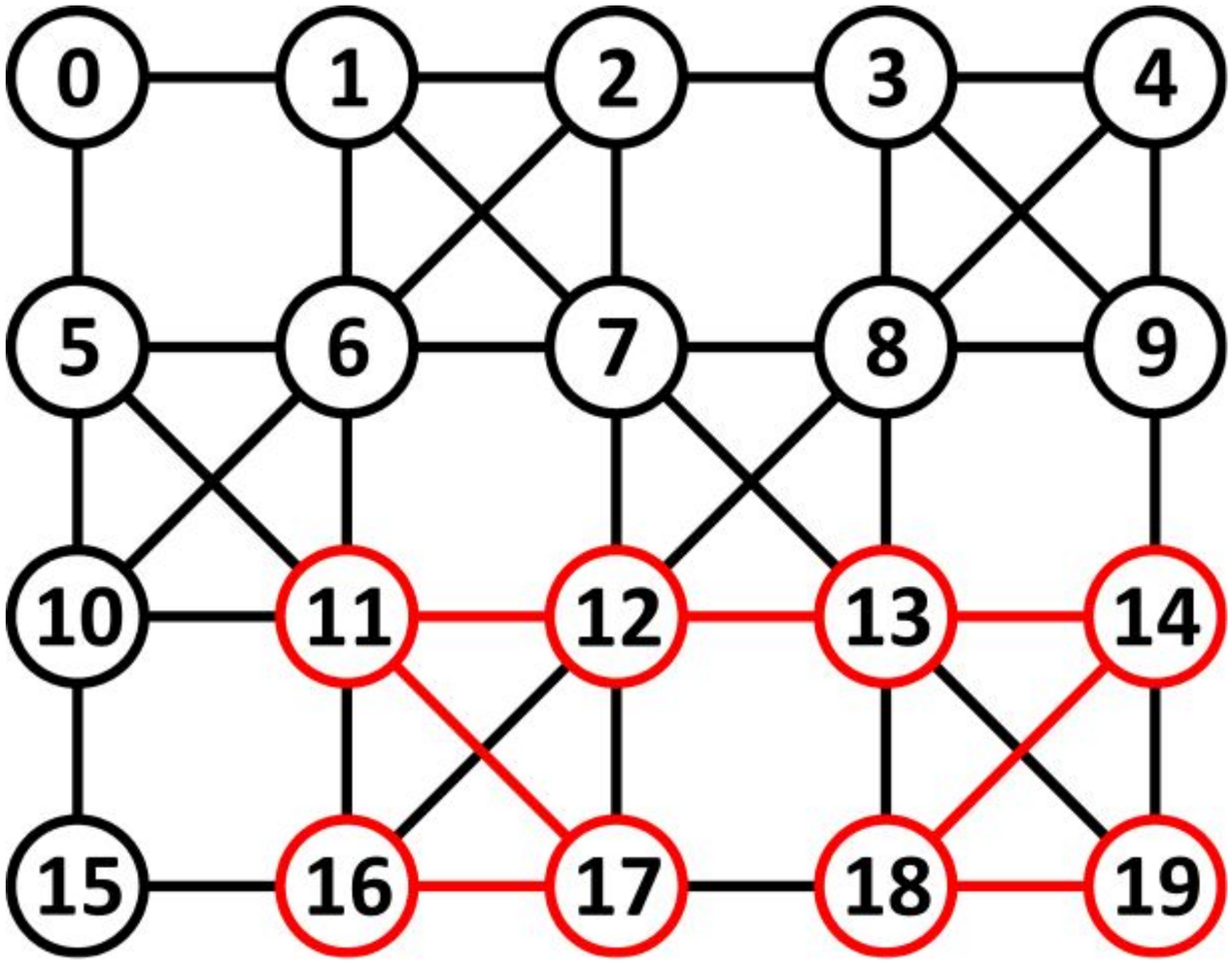
  - updates q_1 and q_2 mapping after every iteration
- Computational complexity ***O(m)***

UCCSD Results

IBM Q20 Tokyo	**Circuit Depth**				
Circuit Name	Input Circuit	DPQC	Basic	Stochastic	Lookahead
H2_UCCSD	82	71	71	71	71
LiH_UCCSD	8845	8065	10989	10820	n.a.
H2O_UCCSD	15388	16647	16143	18116	n.a.
Random20_UCCSD	125638	146686	163516	n.a.	n.a.

IBM Q20 Tokyo	**Compilation Time (s)**			
Circuit Name	DPQC	Basic	Stochastic	Lookahead
H2_UCCSD	10.18	10.91	10.82	11.97
LiH_UCCSD	246.52	495.37	1346.79	n.a.
H2O_UCCSD	346.32	774.08	3803.04	n.a.
Random20_UCCSD	2351.45	6626.03	n.a.	n.a.

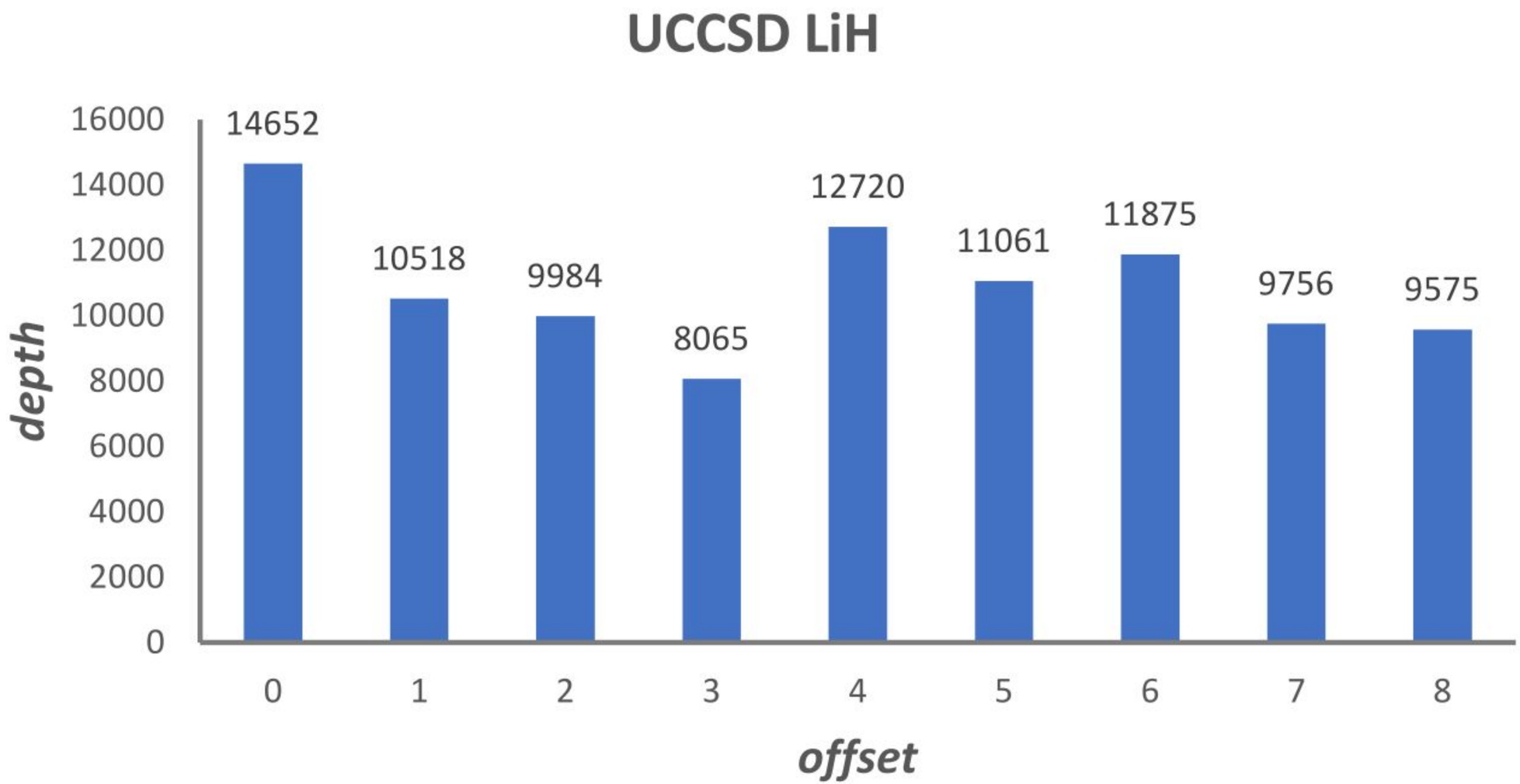
Sequence Offset



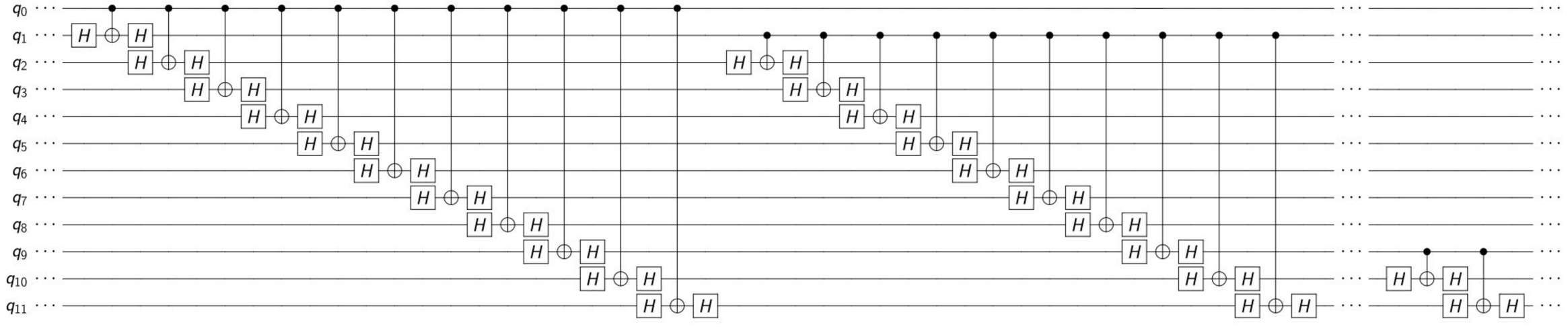
8 qubits chain with *offset*=12

- $0 \leq \boldsymbol{offset} < (m\text{-}n)$
- Used to map the qubits in the circuit to the qubits in the chain in the interval {0,..,*n* + *offset*} instead of {0,..,*n*}

Sequence Offset

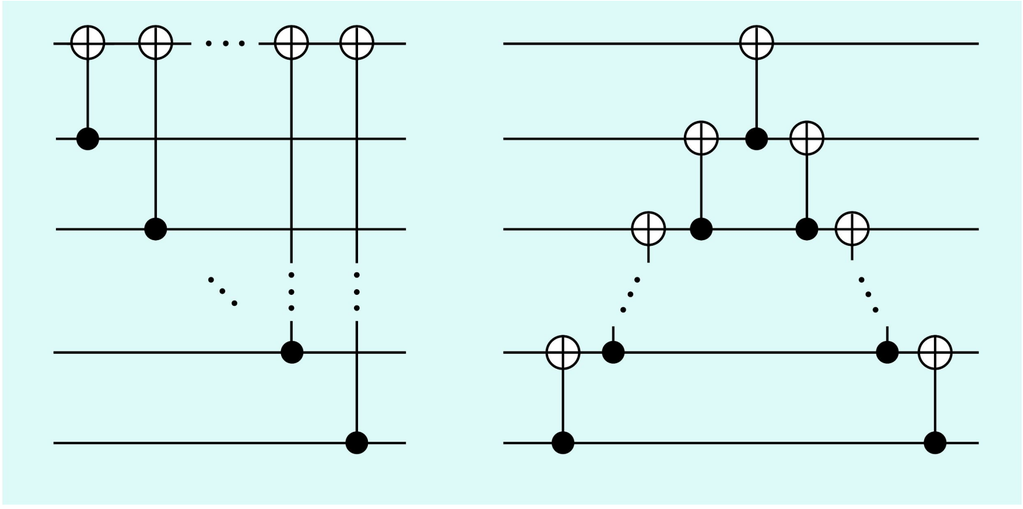


RyRz



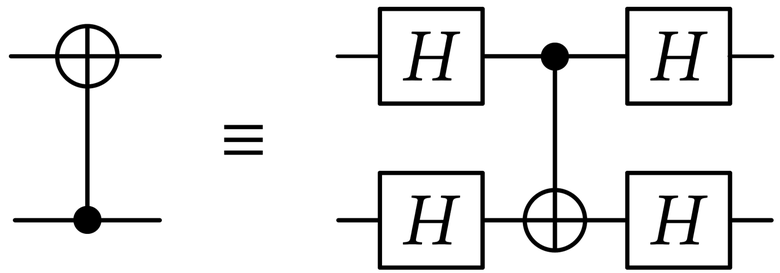
Repeated sequences of inverted CNOT cascades

- CNOT cascades are equivalent to CNOT sequences
- Algorithm ***analyze_circuit()*** detects CNOT cascades and turns them into CNOT sequences
- Computational complexity ***O(gn)*** with *g* being the number of gates in the circuit

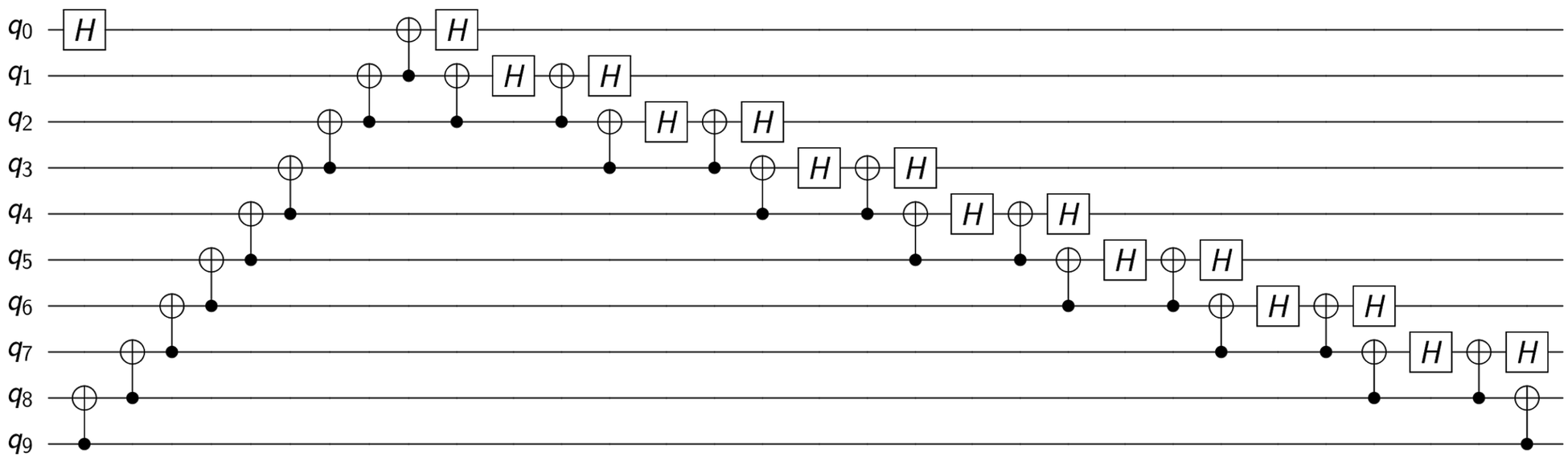


CNOT Cascade

Inverted CNOT cascade



- CNOT gates can be inverted by applying H gates before and after involved qubits
- ***analyze_circuit()*** also detects inverted CNOT cascades and turns them into CNOT cascades
- Algorithm ***gate_cancellation()*** deletes double CNOT and double H gates
- Computational complexity $\boldsymbol{O(dn^2)}$



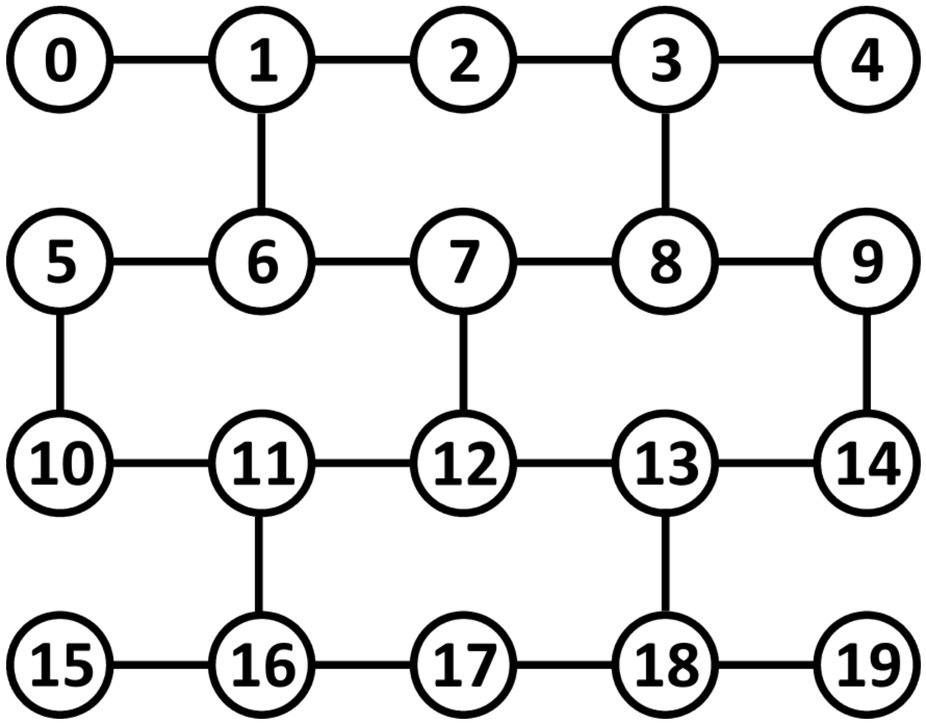
RyRz Results

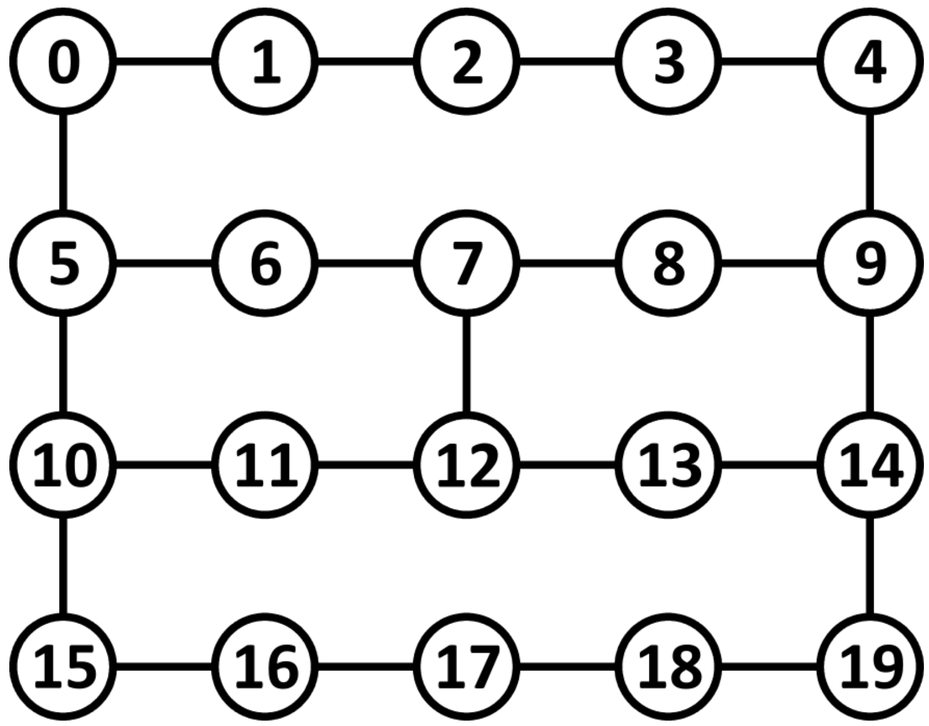
IBM Q20 Tokyo	**Circuit Depth**				
Circuit Name	Input Circuit	DPQC	Basic	Stochastic	Lookahead
H2_RyRz	73	56	161	102	n.a.
LiH_RyRz	223	216	n.a.	724	n.a.
H2O_RyRz	273	256	1517	856	n.a.
Random20_RyRz	393	376	3558	1611	n.a.

IBM Q20 Tokyo	**Compilation Time (s)**			
Circuit Name	DPQC	Basic	Stochastic	Lookahead
H2_RyRz	0.81	11.90	41.15	n.a.
LiH_RyRz	2.26	n.a.	509.83	n.a.
H2O_RyRz	3.20	159.75	514.65	n.a.
Random20_RyRz	6.10	379.84	1291.33	n.a.

Future Work

- Testing the proposed approach with the **new coupling maps**
- Using extra qubits
- Implementing an **automatic offset selection** algorithm
- Studying **other circuit patterns**





Future Work

While effective, circuit depth and gate count are only pseudo-objectives. In reality, what matters is the **fidelity** of a computation when run on actual quantum hardware.

NISQ compilers excel when more **information** is made available to them **from the device**.

IBM Q **device properties** are shared openly and can be benchmarked, resulting in a bunch of compiler innovations.

P. Murali *et al.*, Noise-Adaptive Compiler Mappings for Noisy Intermediate-Scale Quantum Computers, arXiv:1901.11054, 2019

S. Nishio *et al.*, Extracting Success from IBM's 20-Qubit Machines Using Error-Aware Compilation, arXiv:1903.10963, 2019

Thank You!

Questions?