

On Qubit Routing

in Quantum Computer Architectures

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USI

May 22, 2025

Universal Quantum Computer

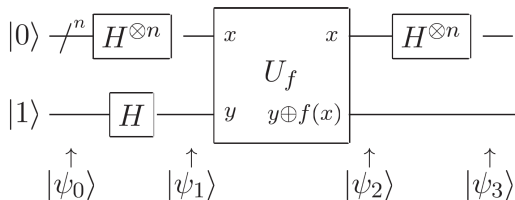


David Deutsch

Definition

The tape (t) of Deutsch's Turing machine $\mathcal{U}$ consists of an infinite sequence of qubits and its finite control consists of a finite sequence of qubits (m). $\langle \dots \rangle$ (Gruska 2000)

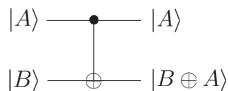
Circuit Model



Circuit for Deutsch-Josza algorithm (Nielsen and Chuang 2010)

Two-Qubit Gates

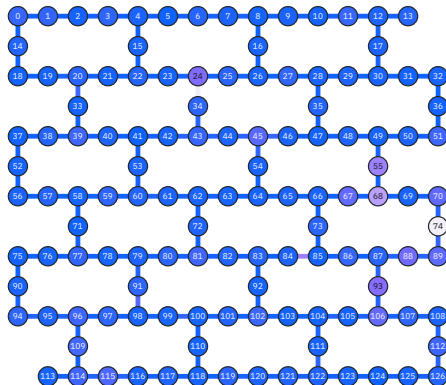
controlled-NOT



$$U_{CN} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

A CNOT gate (Nielsen and Chuang 2010)

Quantum hardware connectivity

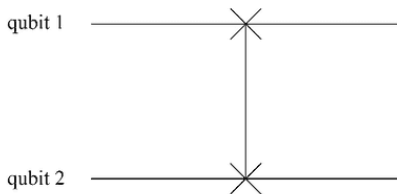


IBM Brisbane connectivity (*The IBM Quantum Heavy Hex Lattice* | *IBM Quantum Computing Blog* 2025)

SWAP Gate

A swap gate SWAPs two qubit states, "moving" the state along the physical entities.

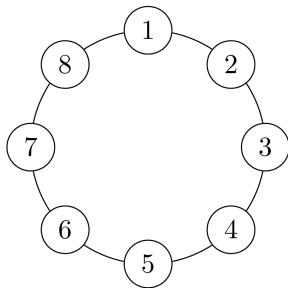
$$\text{SWAP}(|\phi_1\rangle \otimes |\phi_2\rangle) = |\phi_2\rangle \otimes |\phi_1\rangle.$$



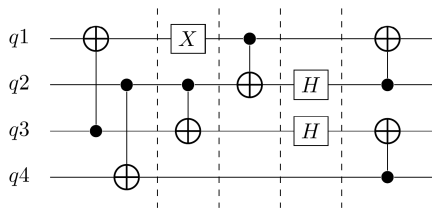
A SWAP gate symbol (Bergholm et al. 2022)

Qubit routing

We'd like to execute the circuit on a given hardware topology



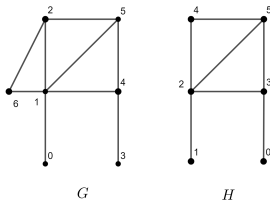
Hardware topology



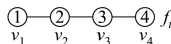
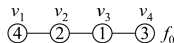
Routed circuit (Cowtan et al. 2019)

NP hardness

Subgraph isomorphism (initial mapping) and token swapping (qubit routing)



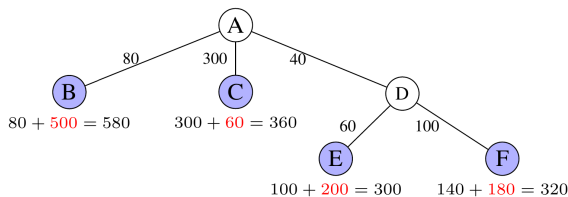
Graph isomorphism



Token swapping (Yamanaka et al. 2015)

Example solution (Zulehner, Paler, and Wille 2018)

- 1 Slicing the circuit into **incompatible** timesteps
- 2 For every timestep:
 - 1 Getting all the hardware compliant permutations
 - 2 Use $\mathcal{A}^*$ algorithm for finding the way to the compliant permutation from the starting point



$\mathcal{A}^*$ search algorithm

Possible outcomes

- Reduce the qubit routing problem to a known NP hard problem
- Derive an approximation algorithm with a known ratio
- Analyse the influence of the hardware graph characteristics to the hardness of the solution
- And many more

Wrap up

- Qubit routing is a hardware problem, haunting the execution of the quantum circuits on the NISQ devices
- The problem is believed to be NP hard
- Biggest trend is to solve it heuristically, however the approximation algorithms are also possible

Thank you

Bibliography I

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