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Programming quantum computers

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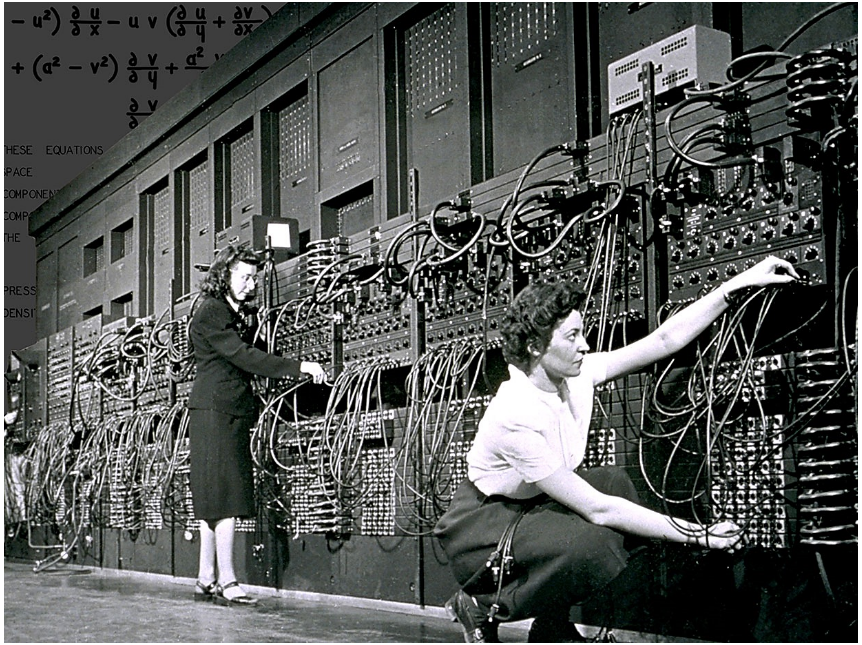
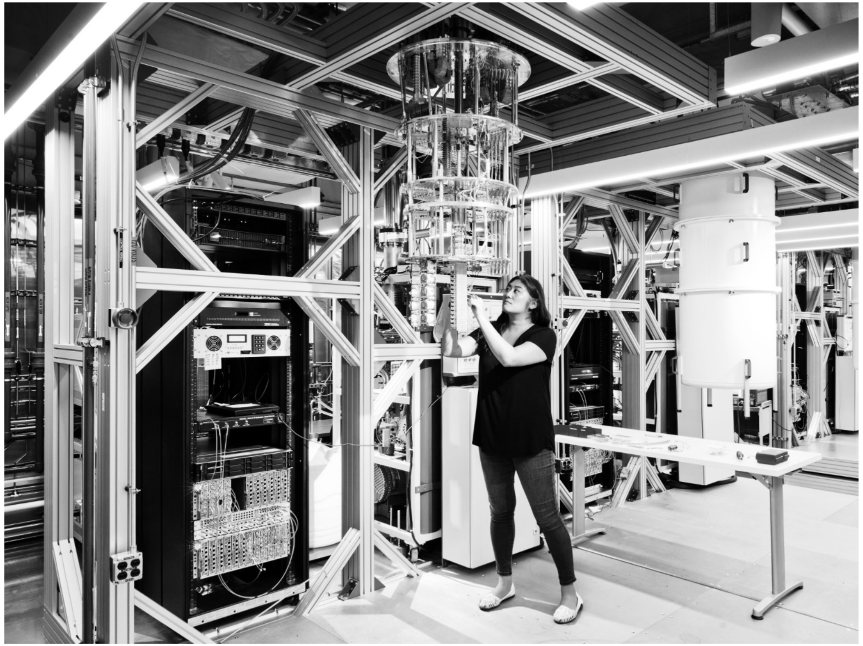
Quantum algorithms and software / VTT

07/07/2022 VTT – beyond the obvious

Where we stand with current QPUs



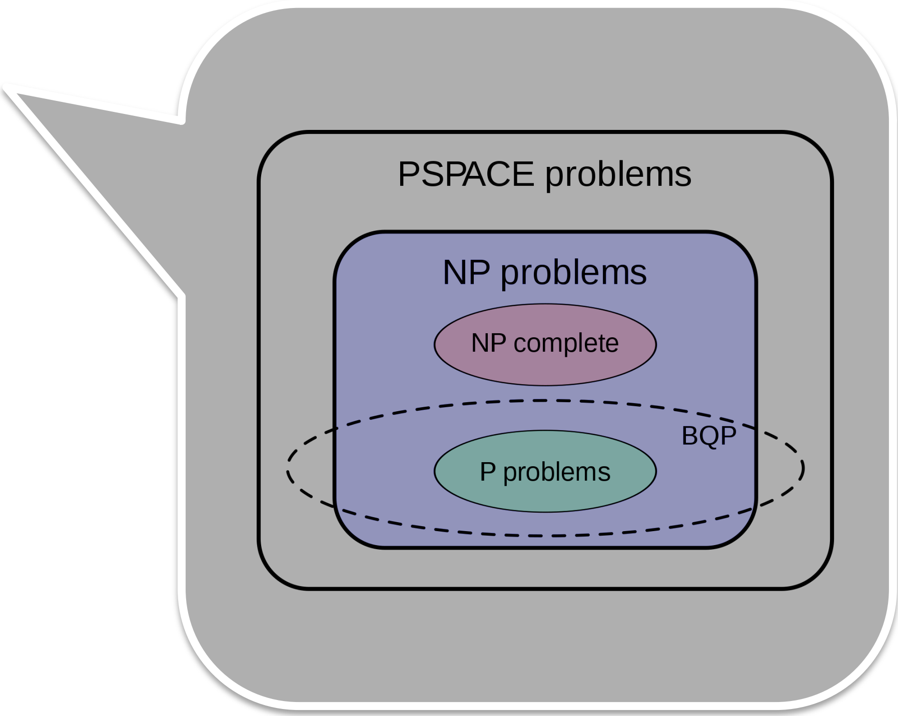


NISQ era = Noisy Intermediate-Scale Quantum

High-level programming workflow

Programing quantum computers workflow

1. Identify problem to be solved
2. Choose suitable platform and vendor
3. Prepare quantum program
4. Transpile
5. Submit



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- Quantum simulations (chemistry, material science, etc.) are suitable for adiabatic computers
- Quantum algorithmic tasks work well on gate-based platforms (superconductive, ion-based, optical, etc.)
- Optimization problems might benefit from various platforms

- Vendors may vary in quality in price and might offer also free computational time

Programing quantum computers workflow

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- Different vendors have their own libraries:
  - IBM: Qiskit
  - Google: Cirq
  - Xanadu: Strawberry Fields
  - Etc.
- Usually Python-based
- Many times offer wide variety of approaches to quantum computing
  - Simple gate-based
  - Hybrid (VQE, QAOA, etc.)
  - Supplemented by AI
  - Etc.

Programing quantum computers workflow

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- Important optimization task for efficient computation
- Many times hands-on
- Roughly composed of three main tasks:
  - routing: fitting the circuit to chosen device
  - decomposition: replacing gates with the native set
  - optimization: reducing the complexity of fitted circuit
- if we will want to get the most out of the QPU, we have to consider QPU's architecture, quality and (potentially) speed.

Programing quantum computers workflow

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- After transpilation quantum compilation transforms submission to some lower level language (OpenQASM2, etc.) and then to basic instruction set of QPU electronics
- These might have various bottlenecks
- Demand for
  - Quality
  - Fast access
  - Precompilation
  - Classical control
  - Intermediate measurements
  - Etc.

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Quantum teleportation → gate-based (superconductive) → IBMQ

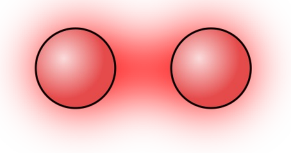
Let's have a look at Jupyter notebook

Quantum teleportation

Quantum teleportation

- With shared entanglement and 2 classical bits of information we can “teleport” a quantum state

$$|\Psi_+\rangle$$



C. H. Bennett, G. Brassard, C. Crépeau, R. Jozsa, A. Peres, W. K. Wootters – Teleporting an Unknown Quantum State via Dual Classical and Einstein–Podolsky–Rosen Channels, Phys. Rev. Lett. 70, 1895–1899 (1993)

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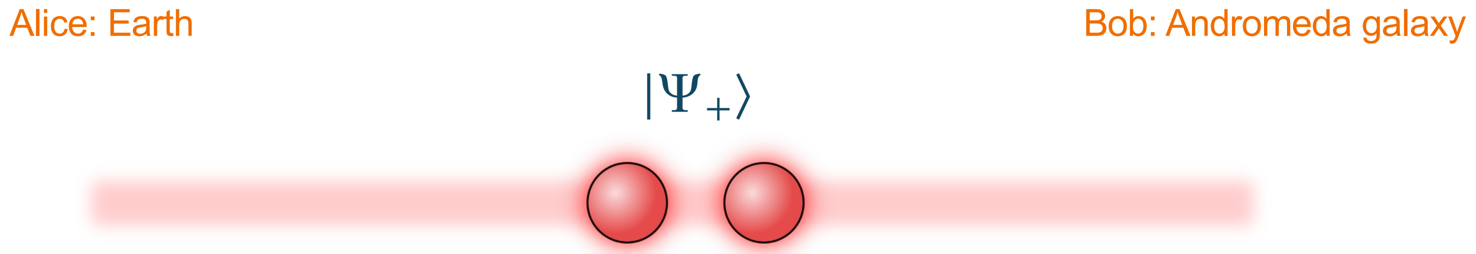

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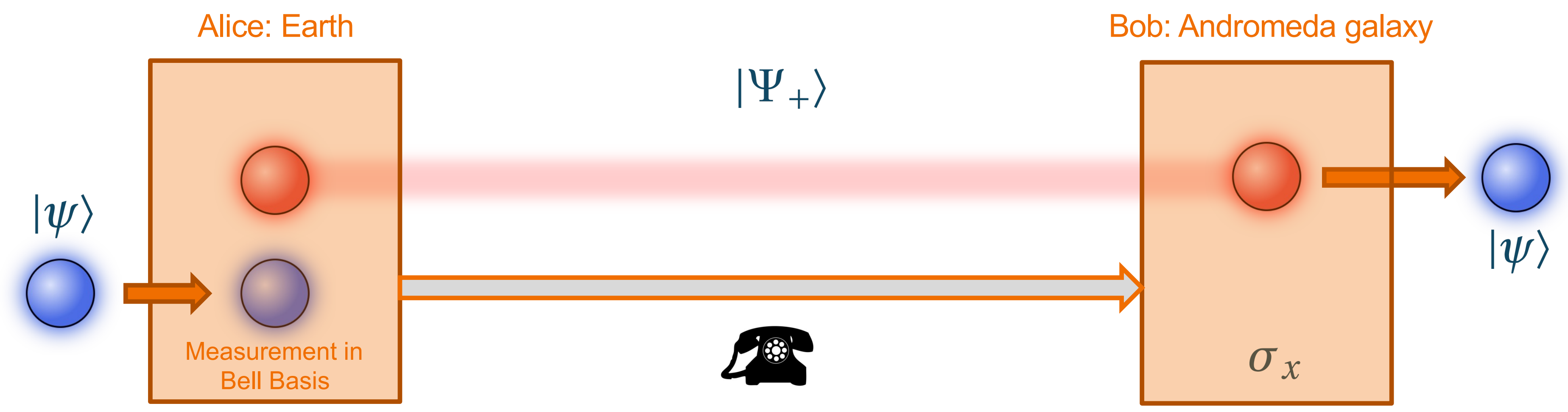

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Quantum teleportation

- How does it work? Composite state before Alice measures it is $|\Phi\rangle = |\psi\rangle \otimes |\Psi_+\rangle$
- If $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$ then $|\Phi\rangle = \frac{1}{\sqrt{2}}\left(\alpha|000\rangle + \beta|100\rangle + \alpha|011\rangle + \beta|111\rangle\right)$
- We measure in the Bell basis and use:

$$|00\rangle = \frac{1}{\sqrt{2}}(|\Psi_+\rangle + |\Psi_z\rangle) \qquad |01\rangle = \frac{1}{\sqrt{2}}(|\Psi_x\rangle + \mathrm{i}|\Psi_y\rangle)$$

$$|11\rangle = \frac{1}{\sqrt{2}}(|\Psi_+\rangle - |\Psi_z\rangle) \qquad |10\rangle = \frac{1}{\sqrt{2}}(|\Psi_x\rangle - \mathrm{i}|\Psi_y\rangle)$$

- Now

$$|\Phi\rangle = \frac{1}{2}\left[|\Psi_+\rangle \otimes |\psi\rangle + |\Psi_x\rangle \otimes \sigma_x|\psi\rangle + |\Psi_y\rangle \otimes \sigma_y|\psi\rangle + |\Psi_z\rangle \otimes \sigma_z|\psi\rangle\right]$$

Quantum teleportation

- Measuring the state

$$|\Phi\rangle = \frac{1}{2}\left[|\Psi_+\rangle \otimes |\psi\rangle + |\Psi_x\rangle \otimes \sigma_x|\psi\rangle + |\Psi_y\rangle \otimes \sigma_y|\psi\rangle + |\Psi_z\rangle \otimes \sigma_z|\psi\rangle\right]$$

in Bell basis gives each result with the same probability ¼ and gives two bits of classical information about the transformation Bob needs to make to transform his state $|\phi\rangle$ to $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$:

$$|\Psi_+\rangle \to \mathbb{1}|\phi\rangle = |\psi\rangle \qquad |\Psi_x\rangle \to \sigma_x|\phi\rangle = |\psi\rangle$$

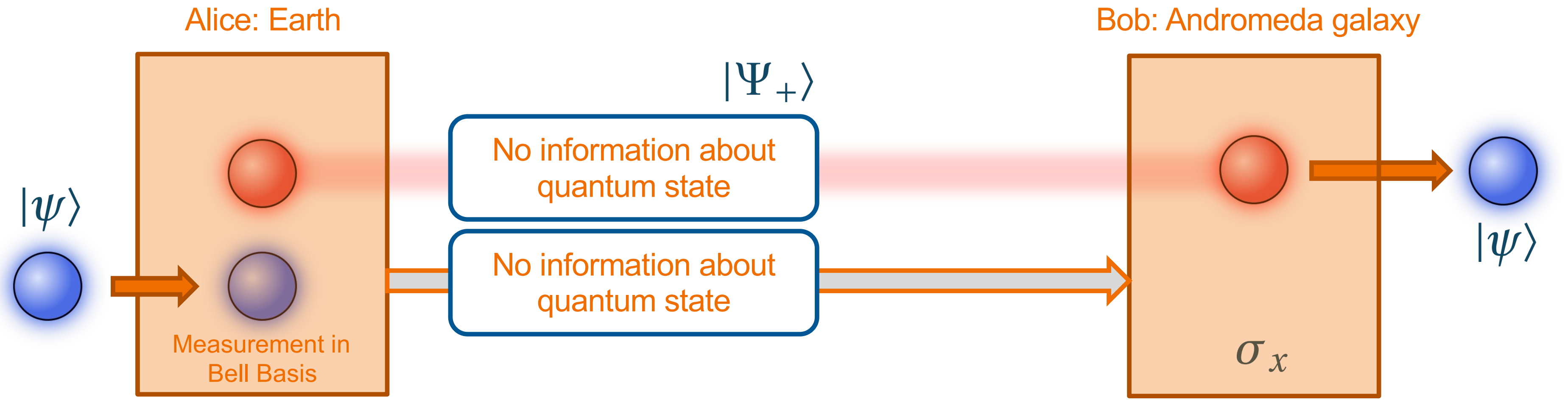
$$|\Psi_y\rangle \to \sigma_y|\phi\rangle = |\psi\rangle \qquad |\Psi_z\rangle \to \sigma_z|\phi\rangle = |\psi\rangle$$

- This holds because

$$\mathbb{1}^2 = \sigma_x^2 = \sigma_y^2 = \sigma_z^2 = \mathbb{1}$$

Quantum teleportation

- With shared entanglement and 2 classical bits of information we can “teleport” a quantum state



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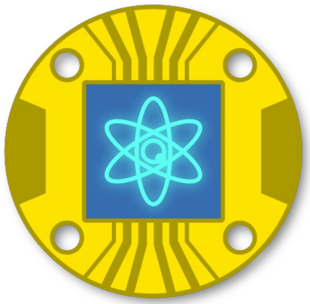
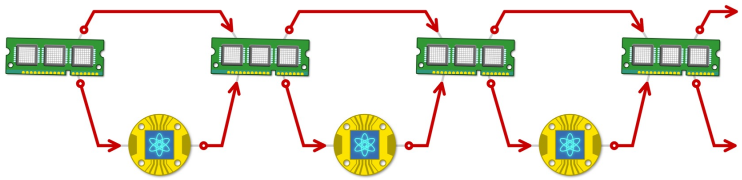
Beyond transpilation

Transpilation

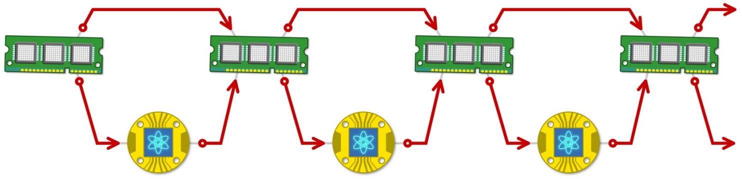
- routing: fitting the circuit to chosen device
- decomposition: replacing gates with the native set
- optimization: reducing the complexity of fitted circuit



- Current devices are noisy and small
- Useful for smaller tasks → hybrid computation
- New bottlenecks



Hybrid computations



- Current devices are noisy and small
- Useful for smaller tasks → hybrid computation
- Old bottlenecks:
  - Size – number of qubits
  - Quality (decrease noise, error correction, etc.)
- New bottlenecks:
  - Initialization speed (loading the data to the electronics)
  - Parametric circuits and pre-compilation (VQE, QAOA, etc.)
  - Fast communication buses (integration to HPC framework)
  - Active reset (decrease the measurement times)
- Practical demands: classical control, intermediate measurements, etc.

Holistic quality and speed measures:
- Quantum volume
- CLOPS
- Algorithmic qubits

Summary

- High level programming of QPUs can be simple
- But more time you put into preparations, more quality you can gain in computation (will it be enough?)
- Specifics of NISQ devices mean that alternative (hybrid) approaches are studied widely – these require new ways of quantifying the quality of the quantum resources

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