Introduction to Quantum Computing Workshop

Lesson 5: Quantum Inspire and Quantum Internet

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Program today

- 75 minutes:
  - Intro / recap
  - Quantum Inspire
  - Transpilation
  - Quantum Internet
  - BBM92 protocol
- 15 minutes: break
- 75 minutes:
  - Tour by Tjeerd

Intro

- Problems with our internet
- Recap
- Quick quiz

Problems with the Classical Internet

> Main goal of the internet is **information exchange** between 👧 Alice and 👦 Bob

Limitations:

- Large quantities of data
- Latency issues
- Security by computational hardness
- Limited capabilities for distributed tasks

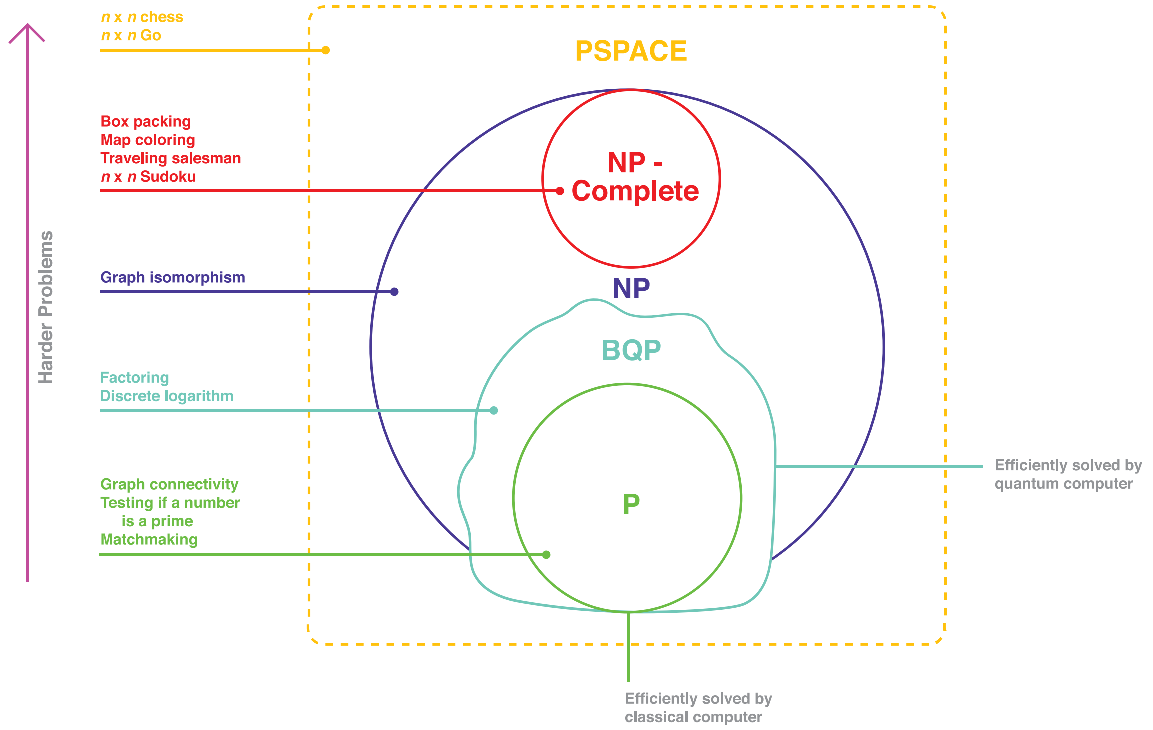
> Main goal of the *quantum* internet is ***secure* information exchange** between 👧 Alice and 👦 Bob

Limitations:

- Large quantities of data
- Latency issues ($> c$ not allowed)
- Security by ~~computational hardness~~ laws of physics
- ~~Limited capabilities~~ Some potential for distributed tasks

Problems with RSA

- Based on computational hardness assumptions (e.g., factoring large numbers).
- Vulnerable to quantum attacks (e.g., Shor's algorithm).



Recap: last week

- mutiple qubits
  - $|01\rangle = |0\rangle \otimes |1\rangle = |0\rangle_A \otimes |1\rangle_B =$ "1st qubit is 1 and 2nd qubit is 0"
  - $|\phi\rangle_A \otimes |\psi\rangle_B =$ "Alice has qubit in state ϕ and Bob has qubit in state ψ"
- entanglement, e.g. $\frac{1}{\sqrt{2}}(|0_A 0_B\rangle + |1_A 1_B\rangle)$
  - not decomposible: $\frac{1}{\sqrt{2}}(|0\rangle_A \otimes |0\rangle_B + |1\rangle_A \otimes |1\rangle_B) \neq |\phi\rangle_A \otimes |\psi\rangle_B$
- multiple qubit gates, e.g. CNOT
  - not decomposible: $\mathrm{CNOT} \neq U_A \otimes U_B$

Quick quiz

Quick quiz: question 1

Consider a CNOT gate where the first qubit is the control qubit and the second qubit is the target qubit. If the control qubit is in the state $\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$ and the target qubit is in the state $|0\rangle$, what is the state of the two-qubit system after the CNOT operation?

A. ✅ $\frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$
B. ❌ $|00\rangle$
C. ❌ $\frac{1}{2}(|00\rangle + |11\rangle)$
D. ❌ $\frac{1}{2}(|00\rangle + |01\rangle + |10\rangle + |11\rangle)$

Quick quiz: question 2

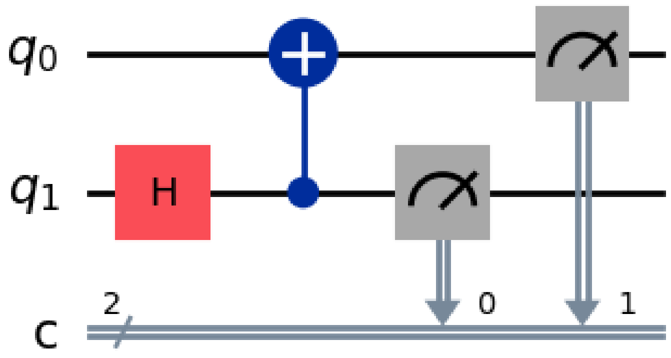
Assume we have a perfect quantum computer at our disposal. Consider the following possible outcomes of the circuit below. What outcomes are possible?

A. ❌ 50 times 0, 50 times 1

B. ❌ 10 times 0, 90 times 1

A. ✅ **50 times 00, 50 times 11**

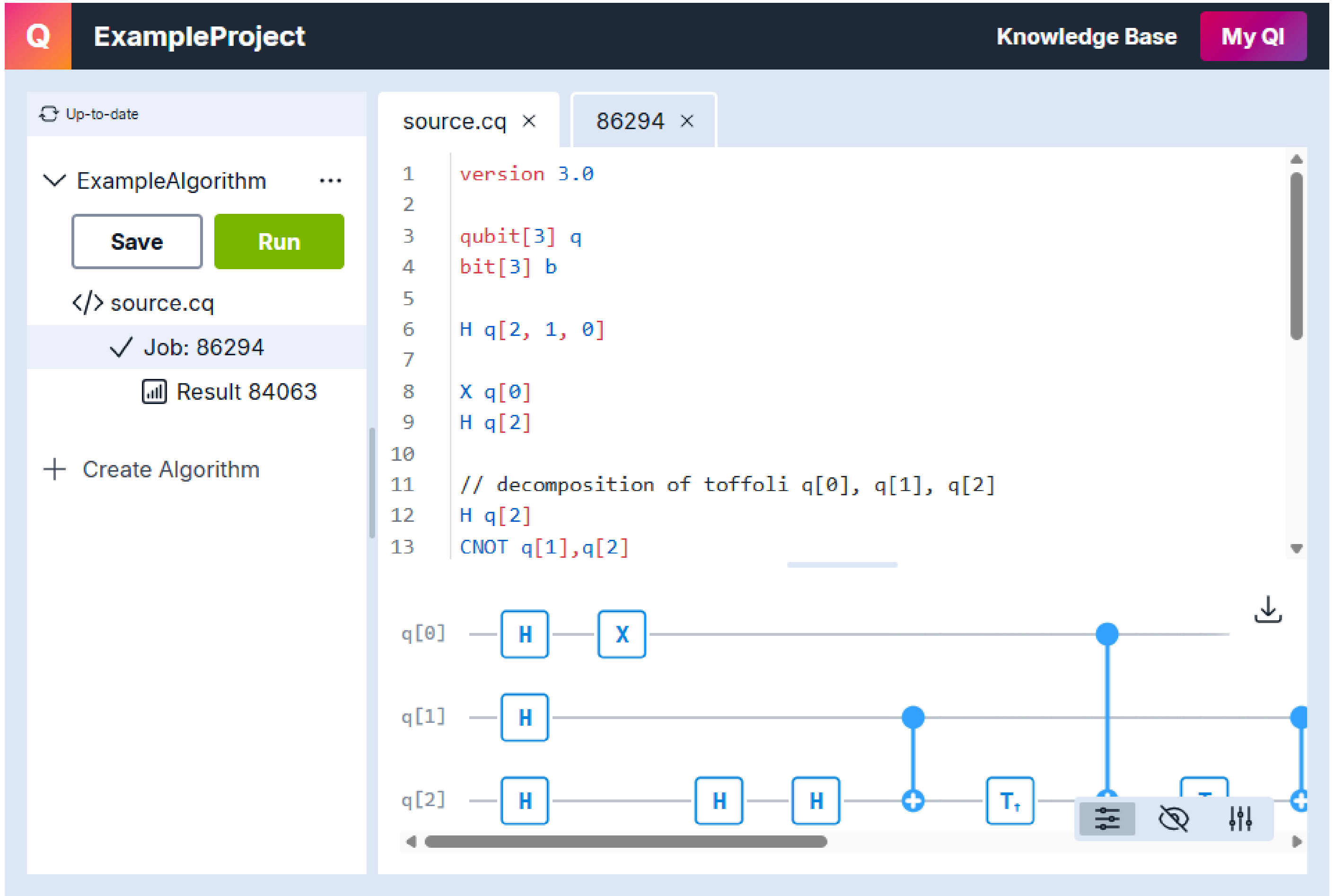
B. ✅ **10 times 00, 90 times 11**



Quantum Inspire

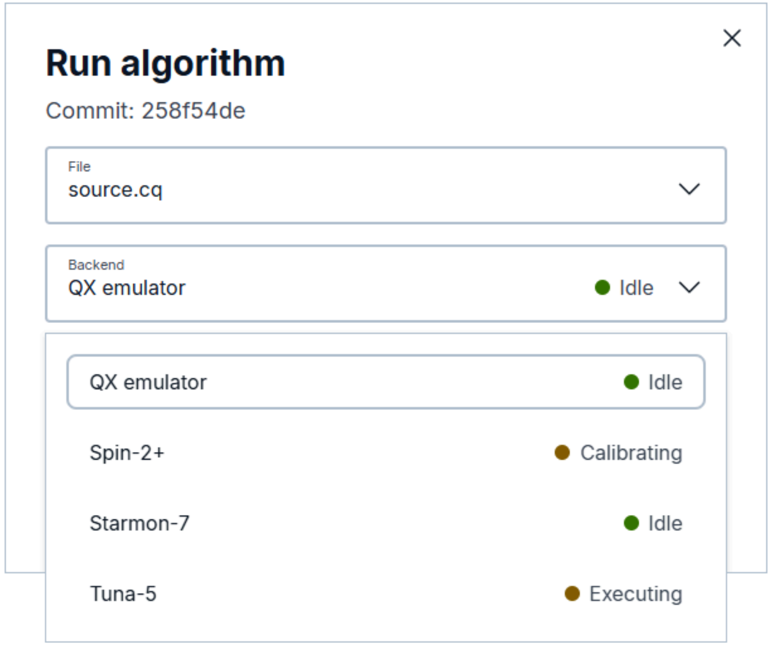
- Quantum Inspire website
- Quantum Inspire with Qiskit

Quantum Inspire: the website



Quantum Inspire: in Jupyter Notebook

Quantum Inspire: screenshots



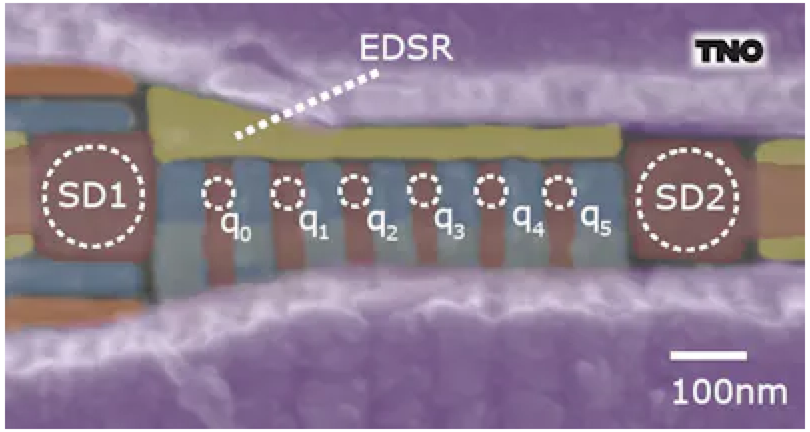
Transpilation

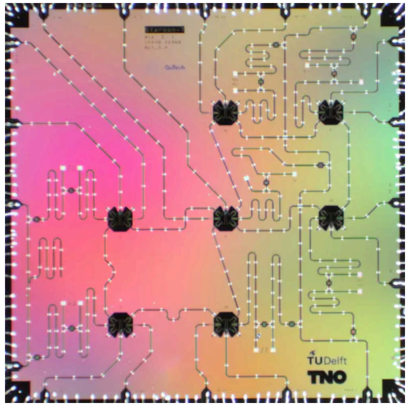
- Backends
- Quantum chip architectures
- Transpilation steps
- Universality quantum gates

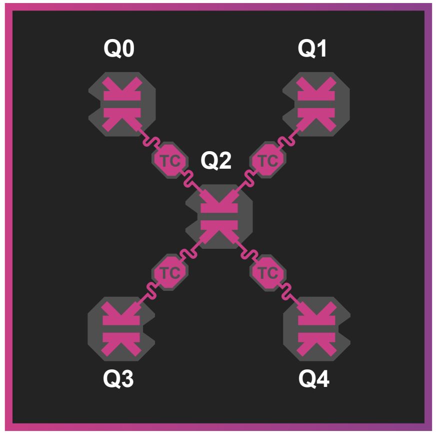
Quantum Inspire: backends

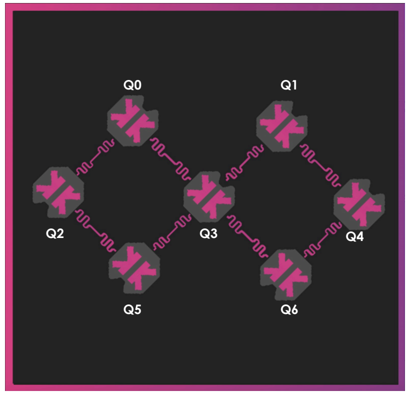
- Tuna-5: a 5-qubit processor based on superconducting transmon qubits with flux tunable qubit couplers
- SPIN-2: a 2-qubit processor based on single electron spin qubits in Silicon
- STARMON-7: a 7-qubit processor based on superconducting transmon qubits
- QX-26: Programmable quantum computer simulator up to 26 qubits
- QX-31: Programmable quantum computer simulator up to 31 qubits
- QX-34-L: Programmable quantum computer simulator up to 34 qubits

Quantum chip architectures









Compilation on architectures

Exception `ExperimentFailed`

Let's do something illegal:

```
qc = QuantumCircuit(5, 2)
qc.h(0)
qc.cx(0, 1)
qc.measure(0, cbit=0)
qc.measure(1, cbit=1)
```

> **Compilation error**: the following qubit interactions in the circuit prevent a 1-to-1 mapping: `{(0, 1)}`

Successful compilation

```
qc = QuantumCircuit(5, 2)
qc.h(0)
qc.cx(0, 1)
qc.measure(0, cbit=0)
qc.measure(1, cbit=1)
```

Transpilation steps

- parsing
- gate decomposition, e.g. $\mathrm{CNOT} = (I \otimes H)\mathrm{CZ}(I \otimes H)$
- mapping (logical to physical qubits), minimizing routing
- routing (SWAP's)
- optimization (gate cancellation / merging / fusion / commutation, noise, etc.)
- scheduling (time optimization by parallelization, gate delays, etc.)

Universality quantum gates

- A universal set of quantum gates is a set of gates that can be used to construct any quantum circuit.
- A universal set of quantum gates typically includes:
  - Single-qubit gates (e.g., X, Y, Z, H, S, T)

$$T = \begin{pmatrix} 1 & 0 \\ 0 & e^{i\pi/4} \end{pmatrix}$$

  - Two-qubit gates (e.g., CNOT, CZ)

Errors

- Types of errors:
  - **Bit-flip error**: A qubit flips from 0 to 1 or from 1 to 0.
  - **Phase-flip error**: A qubit's phase is flipped, changing the sign of its amplitude.
  - **Depolarizing error**: A qubit's state is replaced with a completely mixed state.
- Artificially introducing errors
  - In Qiskit: `noise`
  - In Quantum Inspire: `wait`
- Decoreherence
- TBC: next week error correction codes

Quantum Internet

- Requirements
- Teleportation
- Entanglement swapping

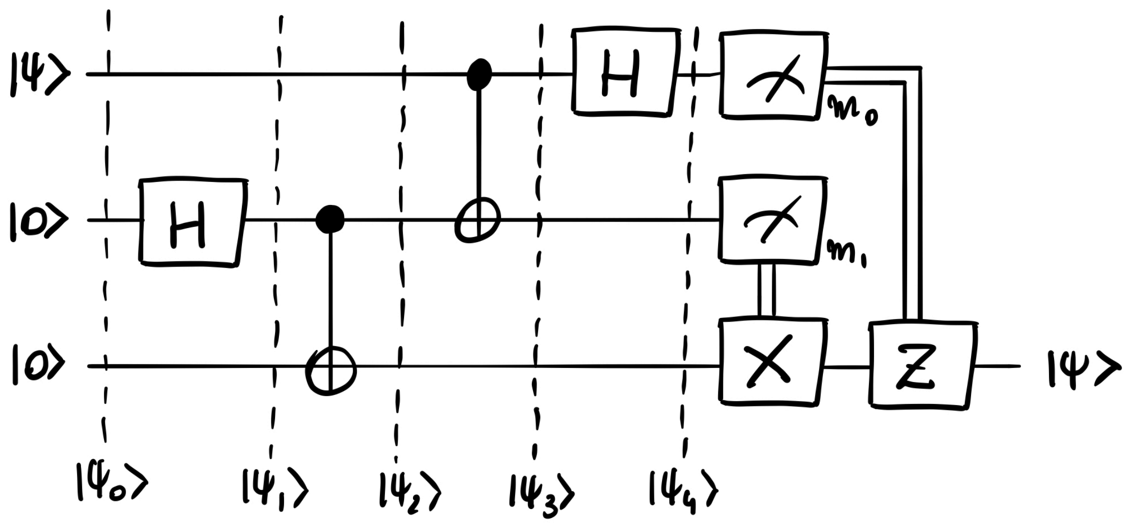
Requirements

What do we want?

- Generate entanglement
- Distribute entanglement
- Quantum storage for 'long' time
  - For synchronizing operations in a quantum network.
  - Buffering qubits in repeaters.
  - Protecting the delicate quantum state from decoherence.
- Interfacing Different Quantum Systems: Transducers
- Quantum repeaters?

Teleportation

- A protocol that transfers quantum states using entanglement and classical communication.
- It requires:
    - A shared entangled state.
    - Classical communication to transmit measurement results.
    - Local operations on the entangled state to reconstruct the original quantum state.
- Not faster than light

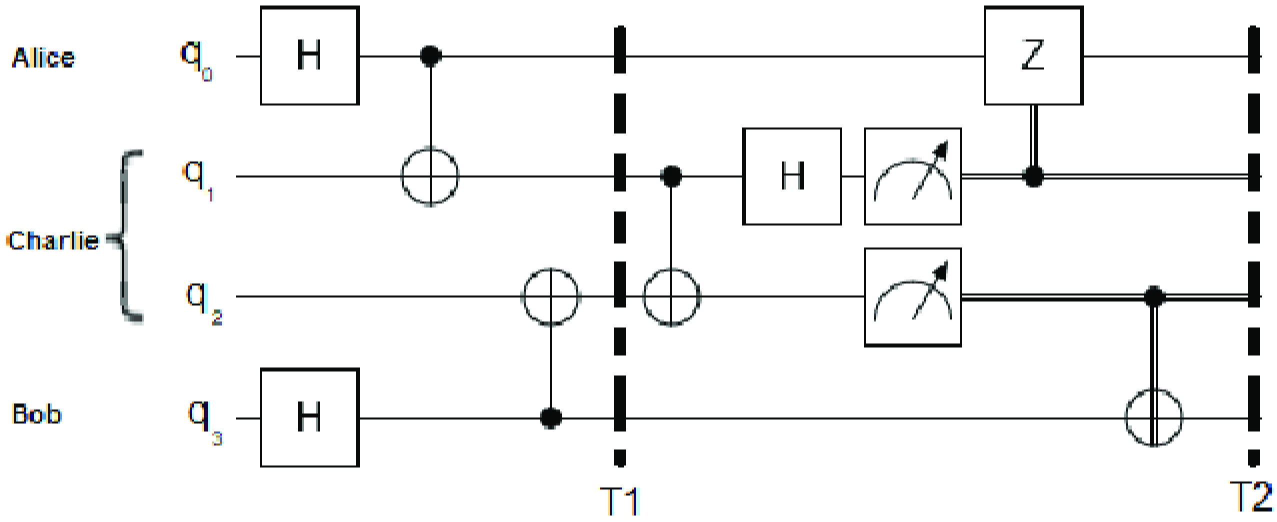


Teleportation, the math

- Initial state: $(\alpha\left|0\right\rangle_A + \beta\left|1\right\rangle_A) \otimes \frac{1}{\sqrt{2}}(\left|00\right\rangle_{BC} + \left|11\right\rangle_{BC})$
- Rewritten: $\frac{1}{\sqrt{2}}(\alpha\left|000\right\rangle_{ABC} + \alpha\left|011\right\rangle_{ABC} + \beta\left|100\right\rangle_{ABC} + \beta\left|111\right\rangle_{ABC})$
- After $\mathrm{CNOT}_{A\to B}$: $\frac{1}{\sqrt{2}}(\alpha\left|000\right\rangle_{ABC} + \alpha\left|011\right\rangle_{ABC} + \beta\left|110\right\rangle_{ABC} + \beta\left|101\right\rangle_{ABC})$
- Rewritten: $\frac{1}{\sqrt{2}}\left(\alpha\left|0\right\rangle_A(\left|00\right\rangle_{BC} + \left|11\right\rangle_{BC}) + \beta\left|1\right\rangle_A(\left|10\right\rangle_{BC} + \left|01\right\rangle_{BC})\right)$
- After H_A: ...
- Rewritten:

$$\frac{1}{2}(\left|00\right\rangle_{AB}(\alpha\left|0\right\rangle_C + \beta\left|1\right\rangle_C) + \left|01\right\rangle_{AB}(\alpha\left|1\right\rangle_C + \beta\left|0\right\rangle_C) + \left|10\right\rangle_{AB}(\alpha\left|0\right\rangle_C - \beta\left|1\right\rangle_C) + \left|11\right\rangle_{AB}(\alpha\left|1\right\rangle_C - \beta\left|0\right\rangle_C))$$

Entanglement swapping



- Useful for quantum repeaters
- Exercise in math
- Exercise in Jupyter Notebook

BBM92 protocol

- The idea
- ~~BB84~~
- Implementation in Quantum Inspire
- Listing Eve

BBM92 protocol: the idea

- Alice and Bob share entangled qubits
- Alice and Bob choose a basis to measure their qubits
- If they choose the same basis, they keep the result as a bit
- If they choose different bases, they discard the result
- **Not secure against untrusted devices**

BBM92 in Quantum Inspire