Quantum Computing

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Leve De Wiskunde! 19 April 2024
Quantum Physics
Solvay conference Brussels 1927

Dirac  Schrödinger  Pauli  Heisenberg

Planck  Curie  Lorentz  Einstein  Bohr
Quantum Physics

• Niels Bohr:
  “If quantum physics hasn’t profoundly
  shocked you, you haven’t understood it yet.”

• Albert Einstein:
  “God does not play dice.”

• Richard Feynman:
  “I think I can safely say that nobody understands
  quantum physics.”
Quantum Physics

1. Superposition:
   • Of different states

2. Interference:
   • Of states

3. Entanglement:
   • Of two or more physical systems
Quantum Physics

1. Superposition:
   • Of different states

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Superposition

- An object in **different states simultaneously**:
  - A photon can be at **two positions** at the same time
  - Schrödinger’s cat: **dead and alive**

- Experimentally verified:
  - Small systems, such as photons
  - Bigger systems, molecules...

April 2023: Fat quantum cats at **ETH Zurich**: 16 micrograms!
“About your cat Mister Schrödinger...
I’ve got good and bad news.”
Superposition:
An experiment
Quantum Bit: Polarization of a Photon
Qubit: Rectilinear/Computational Basis

|1⟩_+  |0⟩_+  |1⟩_+
Detecting a Qubit

No photons: 0
Measuring a Qubit

Measurement: with prob. 1 yields 1

No photons: 0
Photons: 1
Diagonal Basis

Measurement:
\[ \frac{\leftrightarrow + \uparrow}{\sqrt{2}} = \uparrow \]
with prob. ½ yields 0
with prob. ½ yields 1
Video
Measuring Collapses the State

Measurement:

\[
\frac{\left\langle \uparrow \mid \downarrow \right\rangle + \left\langle \downarrow \mid \uparrow \right\rangle}{\sqrt{2}} = \frac{1}{2}
\]

with prob. \( \frac{1}{2} \) yields 0
with prob. \( \frac{1}{2} \) yields 1
Measuring Collapses the State

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Quantum Physics

1. Superposition:
   - Of different states
   - Observation: collapse of the superposition

2. Interference
   - Of an object in superposition

3. Entanglement
   - Of two or more physical systems
no superposition but: beamsplitter reflects 50% and transmits 50%?
Mach-Zehnder interferometer

When you perform the experiment

detector 0

ALWAYS !!!

detector 1

mirror

mirror

When you perform the experiment

DuSoft
Research Center for Quantum Software
According to quantum mechanics, the clicks will always be detected by detector 0.
Quantum Physics

1. Superposition
   • Of different states
   • Observation: collapse of the superposition

2. Interference:
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Quantum Computers
Quantum Physics + Computer Science = Quantumcomputer

Sources:
- Alan Turing
- Alonzo Church
- Emile Post
- Feynman
- Deutsch
Quantum Bit

- Classical bit: \(0\) or \(1\)
- Quantum bit: superposition of \(0\) and \(1\)
More qubits

- 1 qubit superposition of 2 states
- 2 qubits superposition of 4 states
- 3 qubits superposition of 8 states
- 4 qubits superposition of 16 states
- 5 qubits superposition of 32 states
- 6 qubits superposition of 64 states
- 300 qubits superposition of $2^{300}$ states
Quantum software: fundamentally different

- Qubit: superposition of 0 and 1
- 300 qubits: astronomical amount of parallel computation
- How to get the answer out??
  - Measuring destroys computation!!
- Quantum Program
  - Use interference to cancel undesired computations
- Does not always work!

Our focus: how can we optimally use the extra power!
Quantum Programming is like Composing

• Music
  - Sound waves interfere
  - Composer creates ‘beautiful’ interference of sound waves

• Quantum Computer
  - Qubits in superposition interfere
  - Quantum programmer ensures useful interference of qubit states
What can you do with it?

- Factor big numbers [Shor]
  - Breaks frequently used cryptography

- Quantum cryptography [Bennett-Brassard-Ekert]
  - Quantum-proof cryptography

- Efficient communication
  - Quantum internet, entanglement etc.

- Simulation of nature
  - Chemistry, material design, new medicines..

- ??????
### Progress in Building Qubits

<table>
<thead>
<tr>
<th>More general</th>
<th>More specialized</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Universal Quantum Computer</strong></td>
<td><strong>Quantum Annealer</strong></td>
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<tr>
<td>Mostly: gate-based</td>
<td></td>
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<tr>
<td><strong>Fault-tolerant</strong></td>
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<tr>
<td>Uses error correction</td>
<td>Subject to errors</td>
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<tr>
<td>Should run any quantum algorithm</td>
<td>Can simulate a certain class of molecules/materials</td>
</tr>
<tr>
<td><strong>Noisy</strong></td>
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<tr>
<td>Subject to errors</td>
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<td>Runs only short programs</td>
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</tbody>
</table>

#### Hardware manufacturers by qubit type:

<table>
<thead>
<tr>
<th>Superconducting</th>
<th>IBM (433 qubits)</th>
<th>Google (72)</th>
<th>Rigetti (80)</th>
<th>D-Wave (5000 qubits)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trapped Ions</td>
<td>Quantinuum (32)</td>
<td>IonQ (32)</td>
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<tr>
<td>Ultracold Atoms</td>
<td>Pasqal (100)</td>
<td>ColdQuanta Atom Computing</td>
<td>QuEra (256 qubits)</td>
<td>Pasqal (196)</td>
</tr>
</tbody>
</table>

Version: Aug 2023
The Future is Quantum

• 2015: Launch research center for quantum software
• 2020: launch network organization
• 2021: 615M€ for 7y for
• 2024/25: start of UvA MSc Quantum Computer Science
• 2027: new UvA quantum building
About the MSc programme

Research-based programme
• Very strong connection with **active research** in QuSoft
  - All lecturers are QuSoft members!
• Much of industry is research based as well

Focus on Theoretical Aspects
• **Not** an engineering programme!
• No practical lab sessions
• Focus on theoretical physics, mathematics, algorithms and programming

Interdisciplinary

**Recommended BSc program**: BSc mathematics!
Questions?

- Nationale Quantum Cursus: https://quantum-cursus.nl/
- Quantum Quest: https://www.quantum-quest.org/
- The Professional’s guide to Quantum Technology: https://www.quantum.amsterdam/guide-to-quantum/