IFIP 60 Virtual Event Series

# Quantum Computing for DB

## Future Trends in Databases: from Data Science through Artificial Intelligence to Quantum Computing

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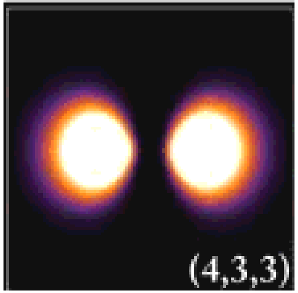
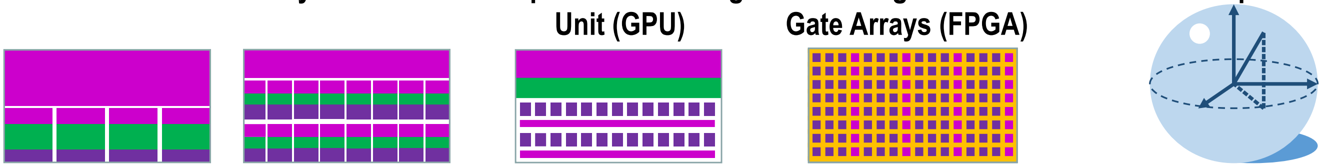
# Quantum Mechanics

- Very small particles and light behave differently from objects in normal life
- Mechanics of light and matter at the atomic and subatomic scale are described by quantum theory
  - forming the underlying principles of chemistry and most of physics
- Quantum theory has brought us the information age with its disruptive technologies of
  - transistors,
  - lasers,
  - nuclear power, and
  - superconductivity...
  - **...and now also quantum computers!**




Wavefunctions of the electron in a hydrogen atom at different energy levels. Brighter areas represent a higher probability of finding the electron.

# Architectures of Emergent Hardware

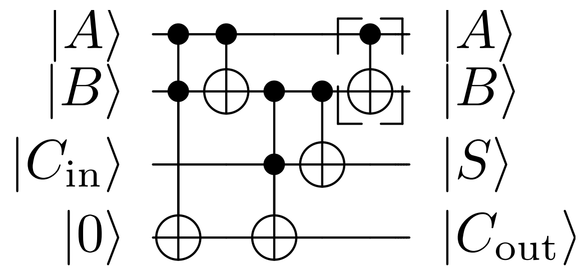


| | Multi-Core CPU | Many-Core CPU | Graphics Processing Unit (GPU) | Field Programmable Gate Arrays (FPGA) | Quantum Computer/Annealer |
|---|---|---|---|---|---|
| Cores | ~10 | ~100 | ~1000 | ~100 000 | ~50 / ~5000 qubits |
| Core Complexity | Complex (optimized for single thread performance) | | | Simple | Complex |
| Computational Model | MIMD + SIMD | | SIMD | Data-Flow | Universal/Adiabatic Quantum computing |
| Parallelism | Thread and Data Parallel | | Data Parallel | Arbitrary | Quantum Logic Gates/ Fluctuation (glob. Min.) |
| Memory Model | Shared | Distributed | | | Quantum Superposition |
| Power | 150 W | 200 W | 250 W | 50 W | 25 KW |
| Database Op. | Query Optimization (Enumeration of Plans), Concurrency Control | | | | |
| | Efficient Processing Of | | | | |
| | Query Processing | | | | |

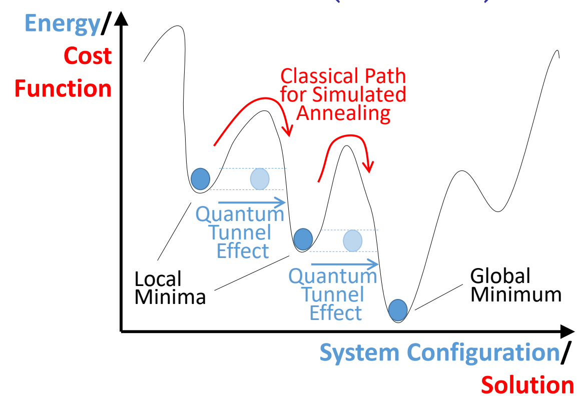
**Legend:** Computational Unit, Execution Controller, Interconnection Network, On-Chip Memory

# Quantum Computer

- use of quantum-mechanical phenomena such as superposition and entanglement to perform computation
- Different types of quantum computer, e.g.
  - Universal Quantum Computer
    - uses quantum logic gates arranged in a circuit to do computation
    - measurement (sometimes called observation) assigns the observed variable to a single value
  - Quantum Annealing
    - metaheuristic for finding the global minimum of a given objective function over a given set of candidate solutions
    - i.e., some way to solve a special type of mathematical optimization problem




Quantum Circuit (Full Adder)

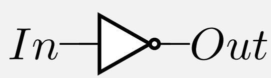



Simulated versus Quantum Annealing

# Classical versus Quantum Computing

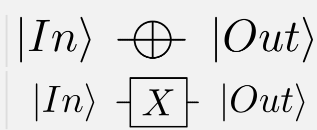
| | Classical | Quantum |
|---|---|---|
| **Information Unit** | **Bi**nary Digi**t** (Bit):<br>• basis of a 2-level system<br>• can be in state $0$ or $1$ | **Quantum Bit** (Qubit):<br>• basis of a 2-level quantum system<br>• can be in state $\|0>$, $\|1>$ or in a linear combination of both states |
| **Operation** | Logic Gate:<br>• performs on 1 or more bits to produce a single bit output | Quantum Logic Gate:<br>• performs on 1 or more qubits to change the quantum state of a single qubit |
| **Example Operation** | NOT/Inverter: | NOT/Pauli$_x$-Gate: |

**Classical** — Digital Circuit:



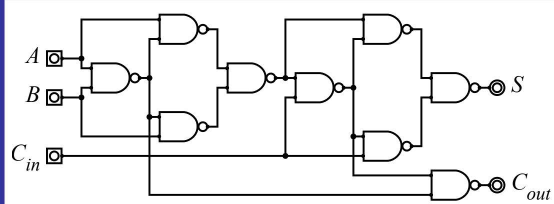
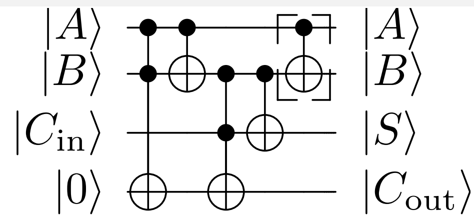

| $In$ | $Out$ |
|---|---|
| $0$ | $1$ |
| $1$ | $0$ |

**Quantum** — Quantum Circuit / Alternatively:




| $In$ | $Out$ |
|---|---|
| $\|0>$ | $\|1>$ |
| $\|1>$ | $\|0>$ |
| $\frac{1}{\sqrt{2}}(\|0> + \|1>)$ | $\frac{1}{\sqrt{2}}(\|0> + \|1>)$ |
| $\frac{3 \cdot i}{5}\|0> + \frac{4}{5}\|1>$ | $\frac{4}{5}\|0> + \frac{3 \cdot i}{5}\|1>$ |

# Digital versus Quantum Circuits

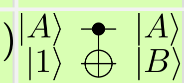
| | Digital Circuit | Quantum Circuit |
|---|---|---|
| **Building Blocks** | Logic Gates | Quantum Logic Gates |
| **Full Adder Example** |   consists of NAND gates |   consists of Toffoli and CNOT gates[1] |
| **In- and Output Full Adder** | see digital truth table below | see quantum text and table below |

**In- and Output Full Adder – Digital Circuit:**

| Inputs | | | Outputs | |
|---|---|---|---|---|
| A | B | $C_{in}$ | $C_{out}$ | S |
| 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 1 | 0 | 1 |
| 0 | 1 | 0 | 0 | 1 |
| 0 | 1 | 1 | 1 | 0 |
| 1 | 0 | 0 | 0 | 1 |
| 1 | 0 | 1 | 1 | 0 |
| 1 | 1 | 0 | 1 | 0 |
| 1 | 1 | 1 | 1 | 1 |

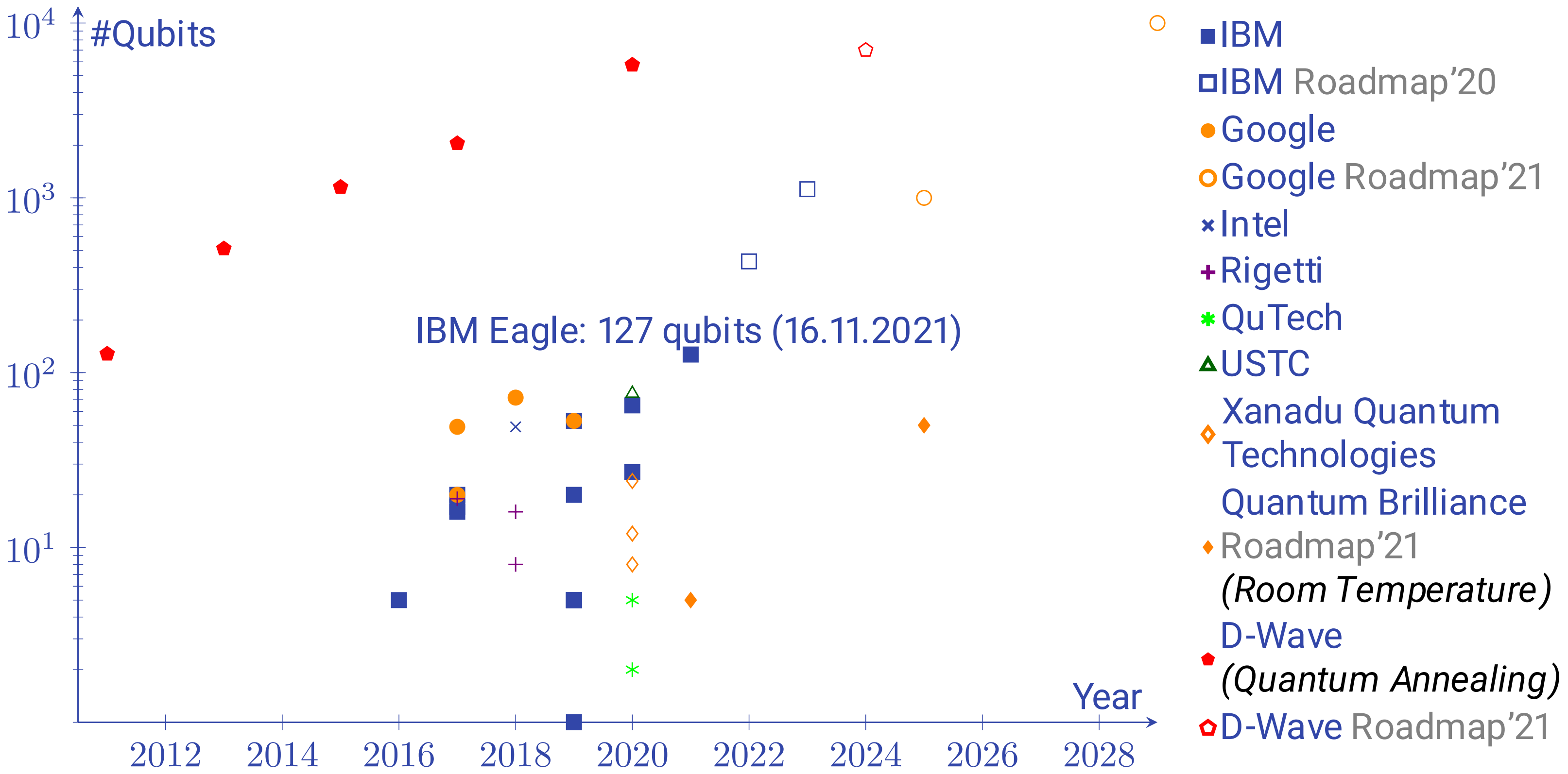
**In- and Output Full Adder – Quantum Circuit:**

$|0>$ **and** $|1>$ **as input:** Output is $|0>$ and $|1>$ analogous to digital circuit.
**Superpositions as input:** Superpositions as output with corresponding probabilities for basic quantum states, e.g.:

| A | B | $C_{in}$ | $C_{out}$ | S |
|---|---|---|---|---|
| $\frac{1}{\sqrt{2}}(\|0>+\|1>)$ | 0 | 0 | $ABC_{out}S$: $\frac{1}{\sqrt{2}}(\|0000>+\|1001>)$ | |
| $\frac{1}{\sqrt{2}}(\|0>+\|1>)$ |   | 0 | 0 | 1 |

[1]The dotted square marks a superfluous gate if uncomputation to restore the B output is not required. [Feynman, 1986]

# Timeline of Quantum Computers



# Potential of Quantum Algorithms

- Quantum Algorithm Zoo as example of collection of *important* quantum algorithms

| | |
|---|---|
| **Covered Years** | 1974-today |
| **#Investigated References** | 430 (visited on October 2021) |
| **#Algorithms** | **64** |
| **Speedups** | **Superpolynomial: 31**, Polynomial: 27, Constant factor: 1, Varies: 3, Various: 1, Unknown: 1 |

**Terminology:**
$\alpha$: positive constant
$C(n)$: runtime of the best known classical algorithm
$Q(n)$: runtime of the quantum algorithm
Superpolynomial Speedup: $C = 2^{\Omega(Q^{\alpha})}$
Polynomial Speedup: otherwise

# Very Important Quantum Algorithms 1/2: Shor's Algorithm[1]

- factoring integers in polynomial time
  - Depth of quantum circuit[2] to factor integer $N$: $O((log\ N)^2(log\ log\ N)(log\ log\ log\ N))$
  - superpolynomial speedup, i.e., almost exponentially faster than the most efficient known classical factoring algorithm (general number field sieve): $O(e^{1.9(log\ N)^{\frac{1}{3}}(log\ log\ N)^{\frac{2}{3}}})$
- Important for cryptography $\longrightarrow$ Post-Quantum Cryptography
- Most quantum algorithms with superpolynomial speedup like Shor's algorithm are based on quantum Fourier transforms (quantum analogue of inverse discrete Fourier transform)

[1] [Shor, 1994] [2] [Beckman et al., 1996]

# Very Important Quantum Algorithms 2/2: Grover's Search Algorithm

- Black box function (oracle) $f: \{0, \ldots, 2^b - 1\} \mapsto \{true, false\}$
- Grover's search algorithm finds one $x \in \{0, \ldots, 2^b - 1\}$, such that $f(x) = true$
  - if there is only one solution: $\frac{\pi}{4} \cdot \sqrt{2^b}$ basic steps each of which calls $f$
    Let $f'(b)$ be runtime complexity of $f$ for testing $x$ to be true:
    $\Rightarrow O(\sqrt{2^b} \cdot f'(b))$
  - if there are $k$ possible solutions: $O(\sqrt{\frac{2^b}{k}} \cdot f'(b))$
- Basis of many other quantum algorithms and applications

Lov K. Grover. A fast quantum mechanical algorithm for database search. *STOC'96*, 1996

# Algorithms (used e.g. in Query Optimization) and their Quantum Counterparts

| Query Optimization Approach | Basic Algorithm | Quantum Computing Counterpart |
|---|---|---|
| [S+79] | Dynamic Programming [E04] | [R19] [A+19] |
| [IW87], QA: [TK16] | Simulated Annealing [KGV83] | [J+11] |
| [MP18] [Y+20] [W+19] [O+19] | Reinforcement Learning [BSB81] | [S+21] [DCC05] |
| [GPK94] | Random Walk [BN70] | [ADZ93] [A+01] |
| [BFI91] | Genetic Algorithm [H92] | [W+13] |
| [TC19] | Ant Colony Optimization [CDM91] [DBS06] | [WNF07] [G+20] |

This list is not complete...

# Open Challenges for QC for Databases

- Are QC counterparts of basic algorithms used in query optimizations suitable for speeding up databases?
- What should be the properties of a quantum computer (e.g. #qubits, latencies of gates) to achieve certain speedups?
- How to combine classical and quantum computing algorithms to achieve good speedups with few qubits?
  (...for running database optimizations on current available quantum computers...)
- What other database domains besides query optimization benefit from quantum computers?
  (In short: those based on mathematical optimization problems, but also other...?)

**Please contact me for collaborations: groppe@ifis.uni-luebeck.de**