Quantum Computing

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*80. Geburtsdag Prof.Dr. F. Hossfeld und 30 Jarhe HLRZ/NIC

This talk

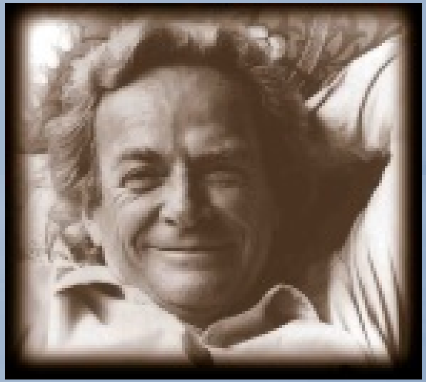
Content

- Quantum computing: the idea
  - History
  - Conflicting views
  - Two-slit experiment with electrons
- Quantum computing: in theory
- Quantum computing: technology
  - Universal gate-based QC (IBM, Google, Rigetti,…)
  - D-Wave quantum annealer

Birth of the idea of quantum computation

“…nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical…

→ build a computer that operates according to the laws of quantum theory



Richard Feynman

Richard Feynman, *Simulating Physics with Computers,* International Journal of Theoretical Physics 21, 467 (1982)

I think

I can safely say that

nobody understands

quantum mechanics.

Richard Feynman

Richard Feynman, *in The Character of Physical Law (1965)*

Father of quantum theory

There is no quantum world.
There is only an abstract physical description.

It is wrong to think that the task of physics is to find out how Nature is.

Physics concerns what we can say about nature...

Niels Bohr

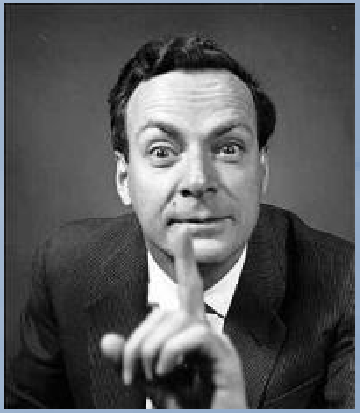
Niels Bohr, in "The philosophy of Niels Bohr" by Aage Petersen, in the *Bulletin of the Atomic Scientists* Vol. 19, No. 7 (September 1963)

CONFLICTING VIEWS

The observation that the interference pattern is built up event-by-event is impossible, absolutely impossible to explain in any classical way and has in it the heart of quantum mechanics. In reality it is the only mystery.

Classical = classical Newtonian mechanics

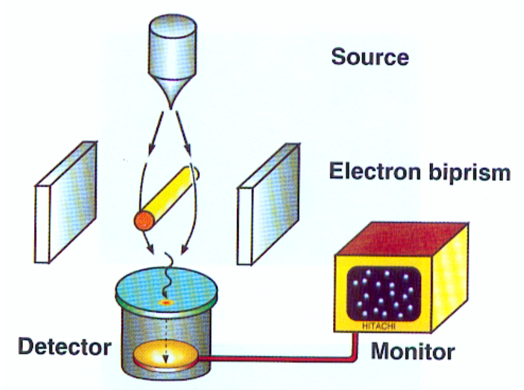
Not classical → must be quantum



Richard Feynman

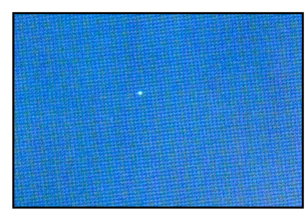
Richard Feynman, *in The Character of Physical Law (1965)*

The most beautiful physics experiment*
Single-Electron Two-Slit Experiment



- In this experiment, at any given time, only one electron travels from the source to the detector.

- Only after many (about 50000) electrons have been recorded a kind of pattern emerges



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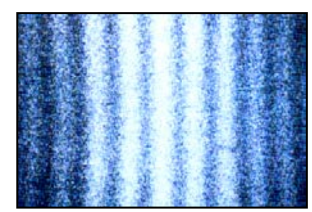
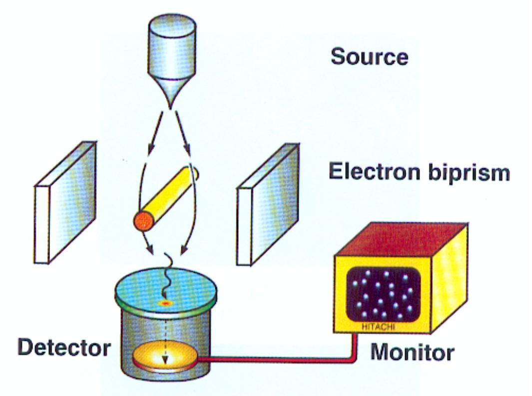


50000

A. Tonomura, *The quantum world Unveiled by Electron Waves*, World Scientific (1998)

*Ranked 1 in a 2002 poll among physicists

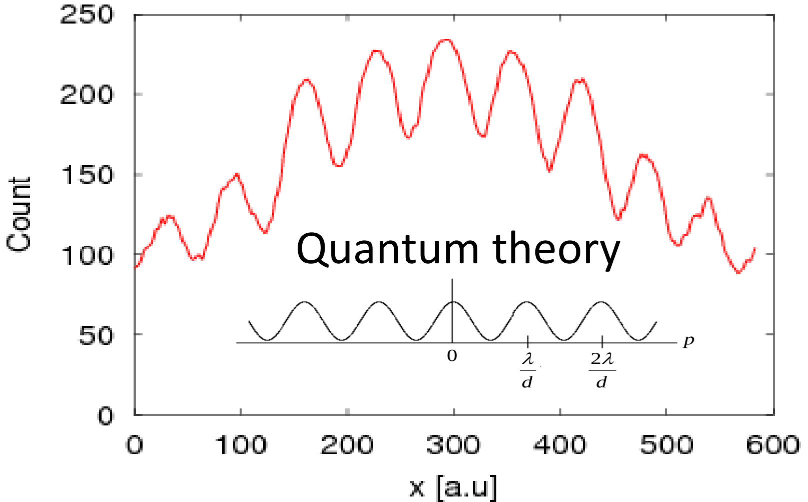
Many-electron experiment: Electron holography

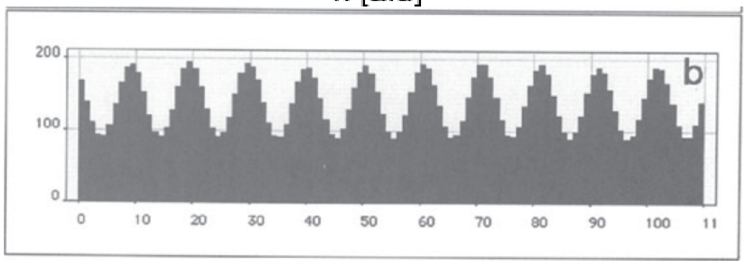


- The experimental setup is the same as before but the electron current is much larger

- After a few seconds, the CCD camera shows an interference pattern

Tonomura experiment



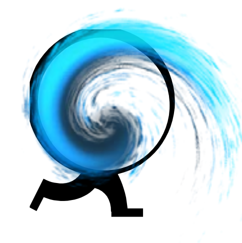


Fringe visibility of about 38%

D.J. Smith and M.R. McCartney, PRACTICAL ELECTRON HOLOGRAPHY, in Introduction to Electron Holography, E. Völkl, L. F. Allard, and D.C. Joy (Kluwer, New York 1999)

The wave function

- During the actual experiment, we see individual spots
  ➔ particle-like behavior (sensory experience)



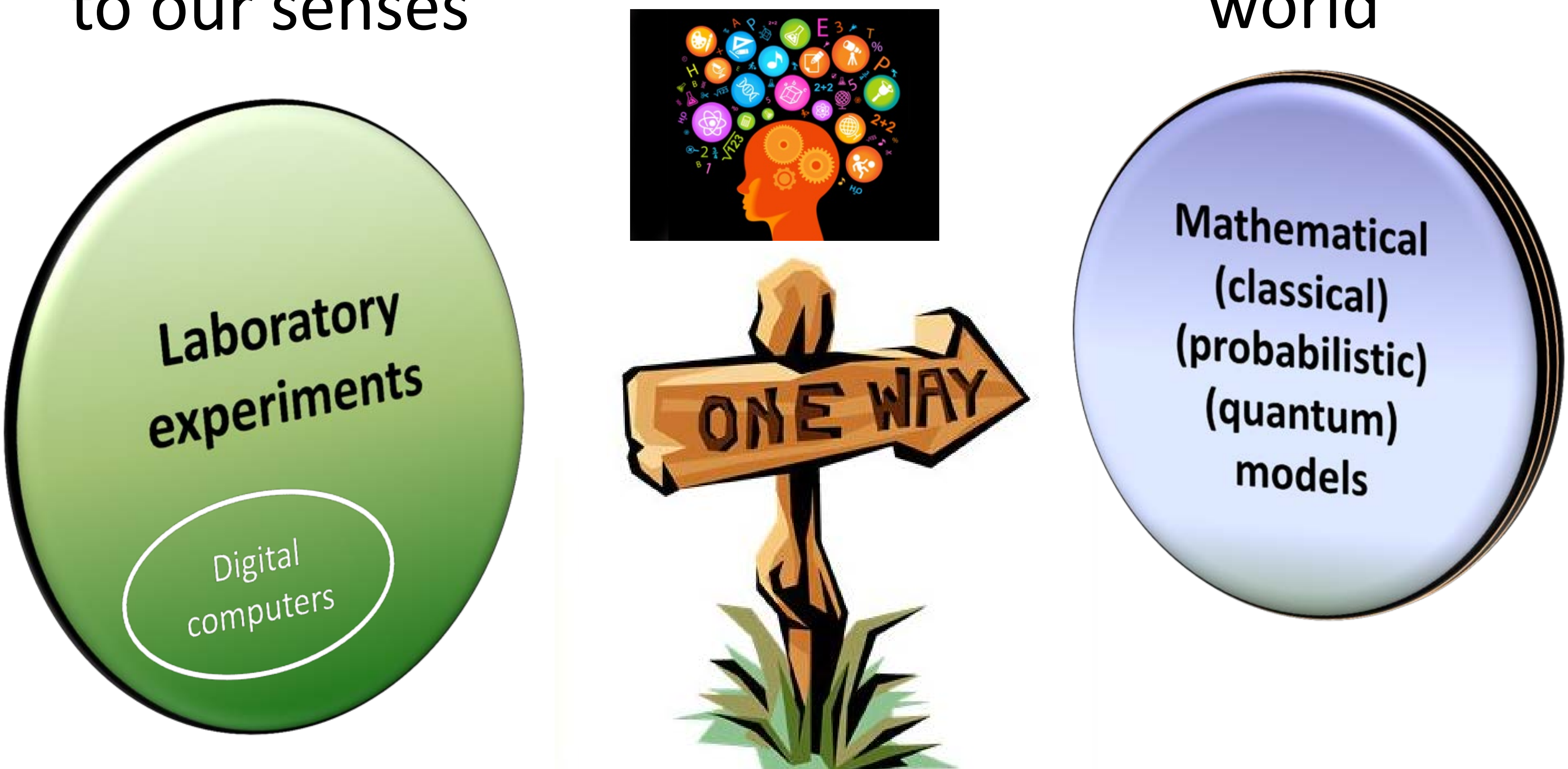
- After collecting many spots, stripes appear
  ➔ by analogy with e.g. water waves in a pond
  ➔ interference pattern ➔ wave-like behavior (description)

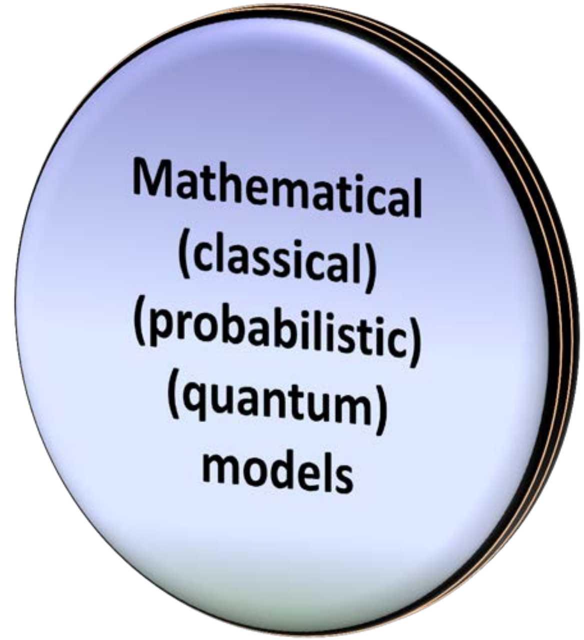
- Experiments that cannot detect the individuals only see the collective
  ➔ interference pattern ➔ wave-like behavior, consistent with 

- Summary: the behavior of the collective, NOT of the individuals, may be described by a wave function
  ➔ quantum theory (Schrödinger wave equation)
  ➔ a mathematical axiomatic framework to compute probabilities for individual events to occur
  - E. Schrödinger about the interpretation of his wave function: “I don't like it, and I'm sorry I ever had anything to do with it.”

World accessible to our senses

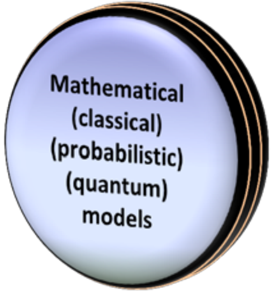
Mathematical world





QUANTUM COMPUTING: THEORY

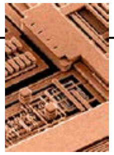
Bit versus qubit



- Bit: 0 or (exclusive) 1
- Elementary operations:

  $$0 \rightarrow 0\,,\quad 0 \rightarrow 1$$
  $$1 \rightarrow 0\,,\quad 1 \rightarrow 1$$

  – Boolean algebra
- Read out:
  – Either 0 or 1
- Mechanical, electronic, … , realizations
  – Logical operation does not depend on realization

- Qubit:

  $$\Psi = \begin{pmatrix} a_0 \\ a_1 \end{pmatrix} \begin{matrix} \leftarrow \text{state } 0 \\ \leftarrow \text{state } 1 \end{matrix}$$
- Elementary operations:

  $$\Psi_{\text{out}} = U \Psi_{\text{in}}$$

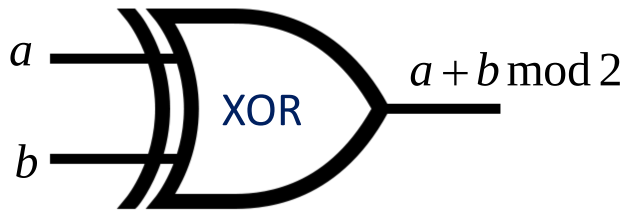
  – Linear algebra (matrix * vector)
- Read out: Probability to observe state 0 (1) is

  $$P_i = |a_i|^2 \quad , \quad i = 0,1$$
- QC theory: Nature performs U in one (1) step, with infinite precision
  – Postulated intrinsic parallelism

Computation: Add 2 (qu)bits

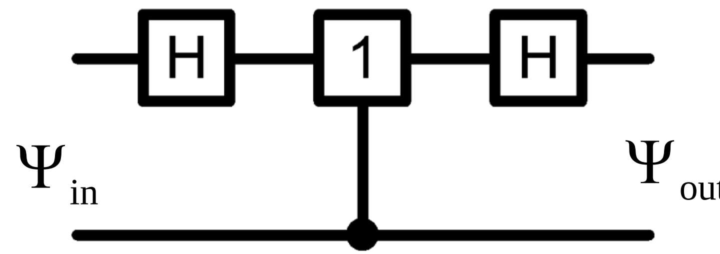
Mathematical
(classical)
(probabilistic)
(quantum)
models

- 2-bit adder



- For given (a,b), gate computes a+b mod 2
- 0+0 ➔ 0 , 1+0 ➔ 1
  0+1 ➔ 1 , 1+1 ➔ 0

- 2-qubit adder (CNOT)



$$\Psi_{\text{in}} = \begin{pmatrix} a_{00} \\ a_{10} \\ a_{01} \\ a_{11} \end{pmatrix} \quad \boxed{H} = \frac{1}{2}\begin{pmatrix} +1 & +1 & 0 & 0 \\ +1 & -1 & 0 & 0 \\ 0 & 0 & +1 & +1 \\ 0 & 0 & +1 & -1 \end{pmatrix} \quad \boxed{1} = \begin{pmatrix} +1 & 0 & 0 & 0 \\ 0 & +1 & 0 & 0 \\ 0 & 0 & +1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

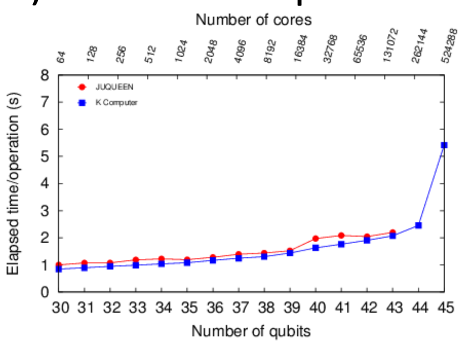
$$\Psi_{\text{out}} = \frac{1}{4}\begin{pmatrix} +1 & +1 & 0 & 0 \\ +1 & -1 & 0 & 0 \\ 0 & 0 & +1 & +1 \\ 0 & 0 & +1 & -1 \end{pmatrix}\begin{pmatrix} +1 & 0 & 0 & 0 \\ 0 & +1 & 0 & 0 \\ 0 & 0 & +1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}\begin{pmatrix} +1 & +1 & 0 & 0 \\ +1 & -1 & 0 & 0 \\ 0 & 0 & +1 & +1 \\ 0 & 0 & +1 & -1 \end{pmatrix}\begin{pmatrix} a_{00} \\ a_{10} \\ a_{01} \\ a_{11} \end{pmatrix}$$

- By postulate, a QC can perform a matrix-vector multiplication in 1 operation

Where does the power of the pen-and-paper (PaP) QC comes from?

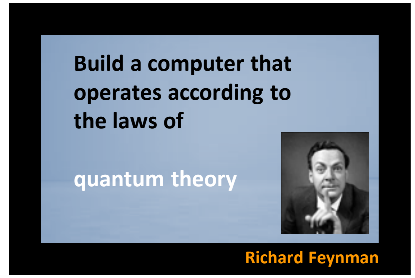
- The PaP-QC follows the laws of quantum theory
  - The state of a PaP-QC is encoded in the wave function
- For a system of N qubits, the wave function represents 2^N complex numbers
- An operation of a PaP-QC amounts to multiplying the wave function with a unitary matrix
  - It is believed, without any empirical evidence, that Nature knows how to do each such operations in 1 step
- It follows that the PaP-QC is a superb parallel computer that multiplies a $2^N \times 2^N$ matrix and a 2^N vector in 1 step
  - In theory: exponential speed-up (order of 1 instead of 2^{2N} operations) for algorithms that can exploit this parallelism, e.g. Shor's number factoring algorithm
- For N up to 43(45) qubits, JUQUEEN (K-computer) beats the exponential growth, not only in theory but also in practice*

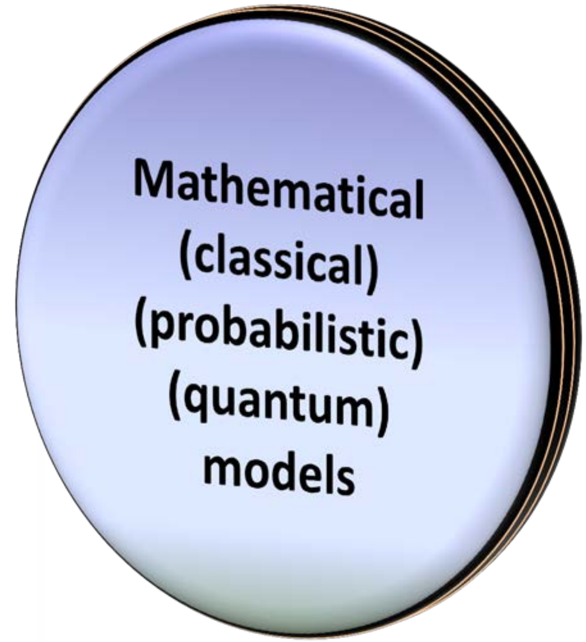
*N. Yoshioka, H. Watanabe, N. Ito, F. Jin, K. Michielsen, H. De Raedt, Massively parallel quantum computer simulator, ten years later, in preparation



World accessible to our senses

Mathematical world



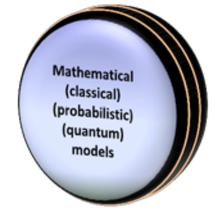


Homework: show that it is possible to actually build a device that can work with "real" real numbers (not floating-point numbers!) such as π, e , $\sqrt{2}$, …

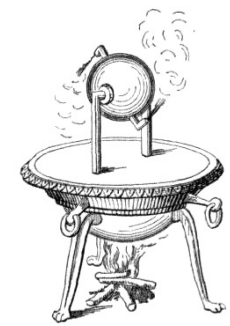
Laboratory experiments

QUANTUM COMPUTING TECHNOLOGY

Technology ⇔ delivers devices that can do useful "work" for us



- The operation of devices does not depend on features of mathematical models
- Example: rudimentary steam engine (Hero of Alexandria, 1 century AD), constructed long before "modern theory" was developed
  - Independent of any "physical laws", it works
    - Physical laws(⇔ descriptions) may change with time…
    - Until the late 1500's, everyone "knew" that heavy objects fall faster than lighter ones because Aristotle had said so… Then Galileo demonstrated that this is not the case…
    - Max Planck ($\hbar$): We have no right to assume that any physical laws exist, or if they have existed up until now, that they will continue to exist in a similar manner in the future.



- Mathematical models facilitate technological progress a lot

World of realizable devices

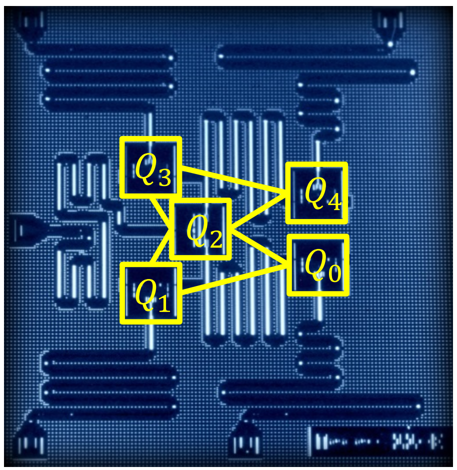
Quantum computer technology

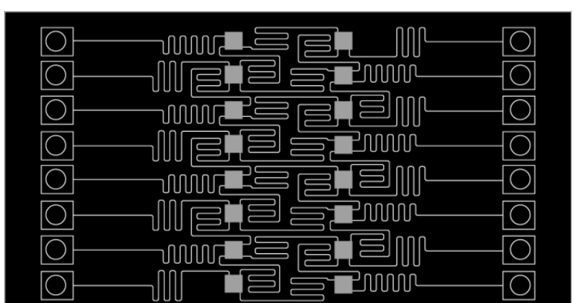
- The power of quantum computer technology should NOT depend on features of quantum theory
  - Niels Bohr: quantum theory is ONLY an abstract description…
  - It is NOT because quantum theory describes atomic phenomena very well, it also tells Nature how to behave
    - Why would Nature care about the mathematical models that humans invent?

World of realizable devices

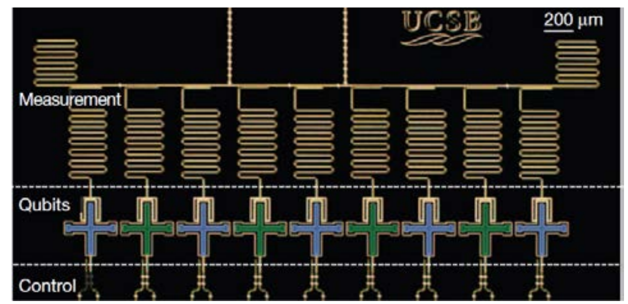
Universal gate-based QC technology

- **IBM:**
  Transmon qubits (5,16)





- **Google**
  Xmon qubits (9)



- **Rigetti Computing**
  Transmon qubits (3-8)

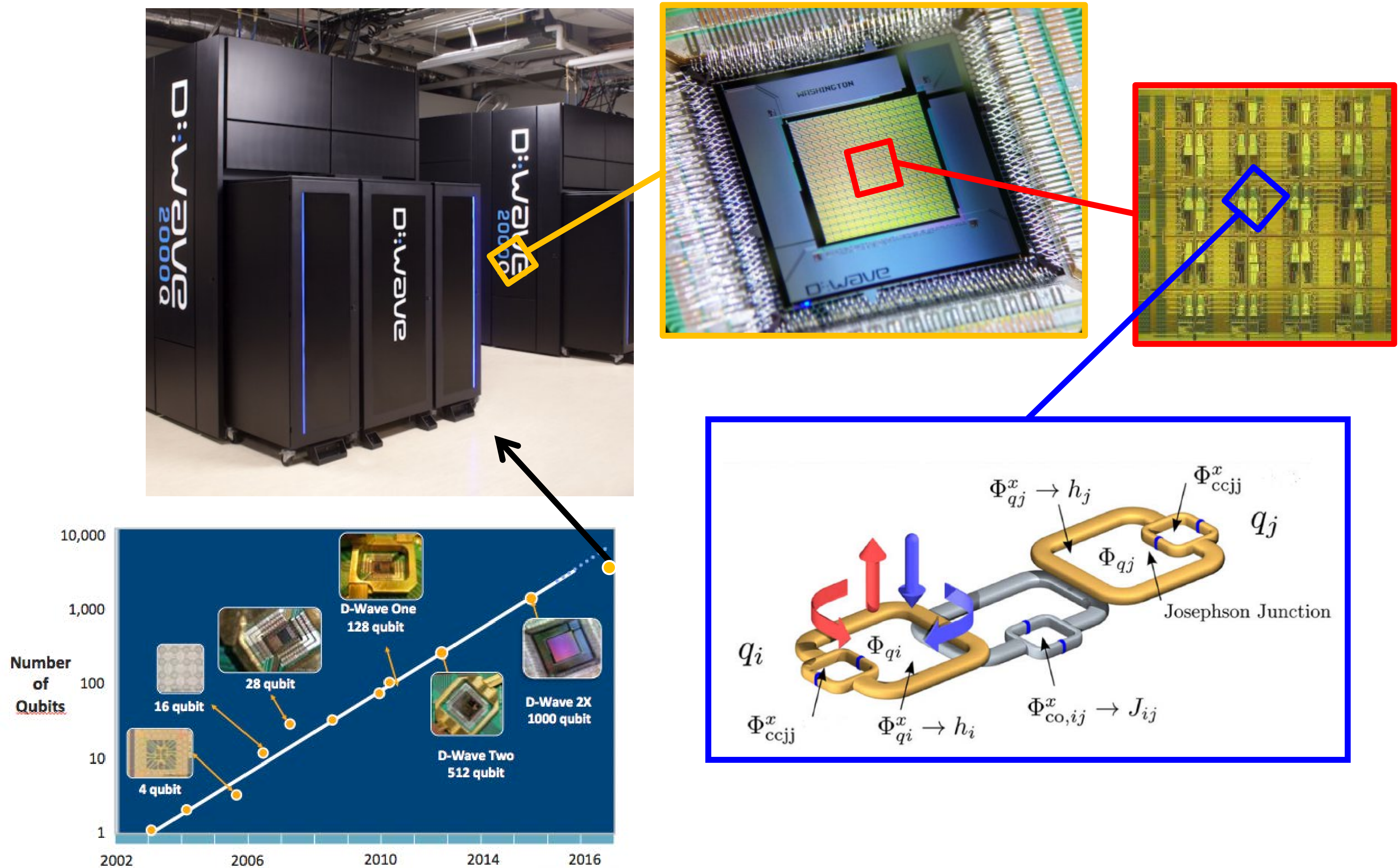
Universal gate-based QC technology

- IBM, Google, Rigetti Computing, … , QC physics community promise to build universal quantum computers based on superconducting (ion) devices
  - Individual gate control by microwave (laser) pulses
  - Experience shows that it is extremely challenging to build devices with a few qubits and force them to behave as predicted by quantum theory
    - Having one or two well-functioning qubits does not guarantee that one can put many together and construct a useful device
  - No indication for a quantum or even classical speed-up, let alone an exponential one
  - Our own benchmarks* of the IBM-QE (5 qubits) show that this device does not yet qualify as a computer

*Benchmarking gate-based quantum computers, K. Michielsen et al., Comp. Phys. Comm. (2017, in press)

World of realizable devices

D-Wave quantum annealers



World of realizable devices

D-Wave: quantum annealers built from superconducting qubits

- Can be used for
  - Solving optimization problems (QUBOs)*
  - Machine learning
  - Boltzmann sampling

- VERY fast “Ising model in a transverse field” real-time-dynamics simulators
  - Orders of magnitude faster (in real time) than equivalent algorithms running on digital (parallel) computers
  - Programming ⇔ specify the parameters of the Ising model
  - Annealing ⇔ slowly changing the parameters keeps the physical system close to the state with minimum energy ⇔ solution of the optimization problem
  - No indication of “quantum” exponential speed-up

- Our own benchmarks* on small 2-SAT problems show that the D-Wave machine indeed solves one class of these problems as described by quantum annealing but for another class it solves the problems in some other, yet to be identified, manner

*K. Michielsen et al., in preparation

Conclusion

- Now may be the right time to test if QC technologies can live up to their promises when confronted with real-life applications

- Universal gate-based QC approach
  - Current physics experiments (IBM, Google) are tantalizing
  - Need to demonstrate that there are real-life applications beyond diagonalizing 2x2 or 4x4 matrices
  - Until demonstrated beyond doubt, quantum speed-up is a pipedream
    - Feature of the mathematical description only

- D-Wave: has potential to solve optimization problems that are "unsolvable" (in real time) by digital computers*
  - If upscaling continues ➔ very fast, low e-power, large parallel machine
  - Looks very promising, research efforts focus on applications

*Traffic flow optimization using a quantum annealer, F. Neukart et al., arXiv:1708.01625

World accessible to our senses

Mathematical world

Laboratory experiments

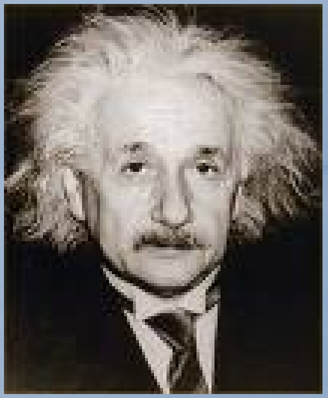
Digital computers

Mathematical (classical) (probabilistic) (quantum) models

THANK YOU

THANK YOU

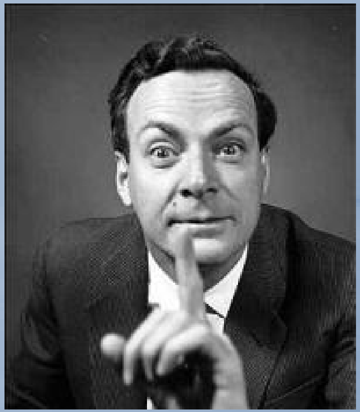
The attempt to conceive the quantum mechanical description as the complete description of individual systems leads to unnatural theoretical interpretations, which become immediately unnecessary if one accepts the interpretation that the description refers to ensembles of systems and not to individual systems



Albert Einstein

Albert Einstein: Philosopher-Scientist, ed. P.A. Schilpp (Harper & Row, New York 1949)

We have always had a great deal of difficulty understanding the world view that quantum mechanics represents…
I cannot define the real problem, therefore I suspect there's no real problem, but I'm not sure there's no real problem.



Richard Feynman

Richard Feynman, *Simulating Physics with Computers,* International Journal of Theoretical Physics 21, 467 (1982)