Panel: How will we design Quantum Computers?

Chair: Robert Wille, TU Munich

Panelists:
Luca Amaru’, Synopsys
Edoardo Charbon, EPFL,
Thomas Haener, Amazon
Mathias Soeken, Microsoft
Andrei Vladimirescu, U.C. Berkeley

Summary: Quantum computers are a reality. And with them completely new design tasks emerged. Due to the radically different computational paradigm and physical setting, we have to re-think the design corresponding applications and devices: How much of the established design flow for classical circuits and systems can be used for these purposes? How much has to be developed from scratch? And do we all have to become quantum physicists now? At the same time, we should be realistic about the perspective of quantum computing: Within a 10-year horizon, can we count on quantum computing to solve practically relevant problems? Do we have metrics that show the superiority over classic server farms on relevant problems? This and more will be discussed in this panel.

Panel: "How will QC be designed?“

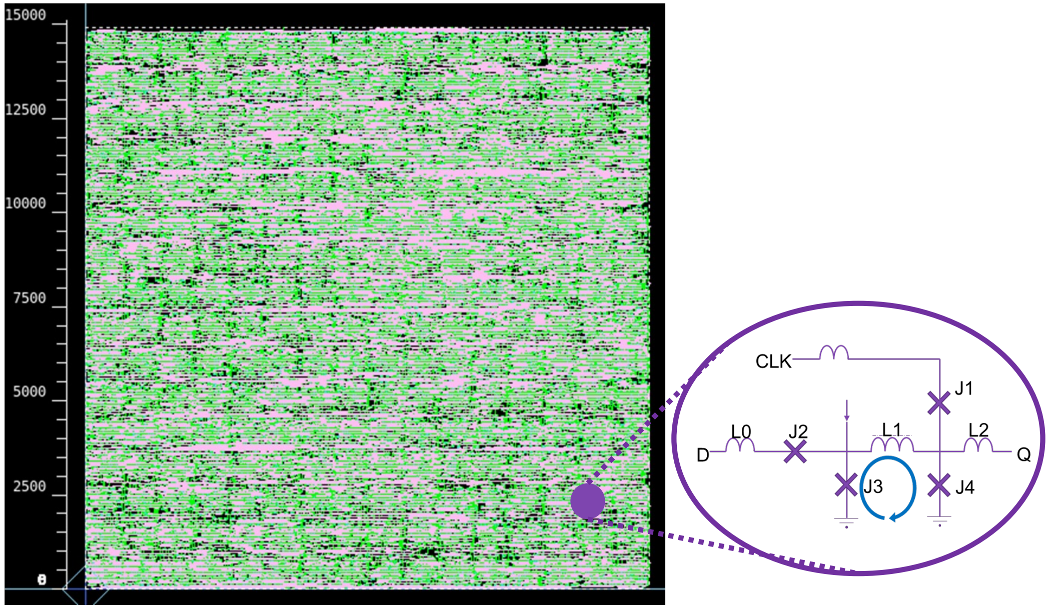
Luca Amaru

Agenda

- Intro
- Position statement: Synthesis
- Position statement: Verification
- Position statement: Summary
- Topics/questions to jointly discuss

Intro

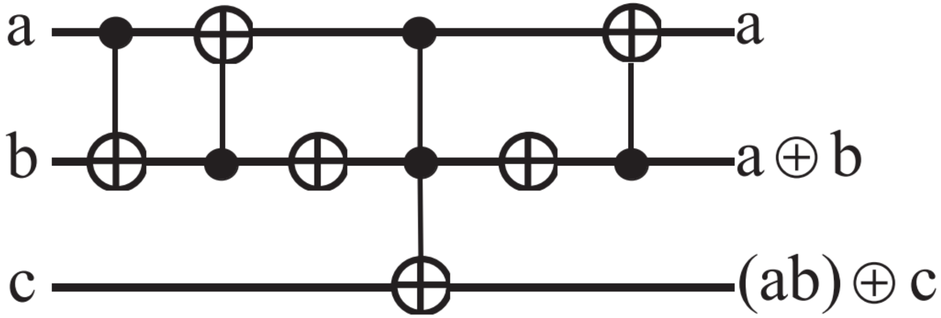
- My name is Luca Amaru, I am Principal R&D Engineer in EDA Group at Synopsys
- I lead the logic synthesis team for Fusion Compiler
- While our focus is CMOS, we have been also involved with SuperTools program
- With SuperTools, we worked on the differences & similarities to design circuits in superconducting electronics (SCE) families, like RSFQ and AQFP
  - SCE holds promise for: Peripheral circuitry in QC & SCE is one of modalities for QC


Routed AM2901

- We live in exciting times: QCs are making progress and can find their way into practical applications
- In order to scale into even more useful size, QC needs to address physics/realization challenges but will also benefit from strong EDA support.
- Synthesis and verification are key tasks to support QC advance. Synopsys leads synthesis and verification for CMOS. There are a lot of technologies we can re-use from classical synthesis & verification but also lots of enhancements needed.

Position statement: Synthesis

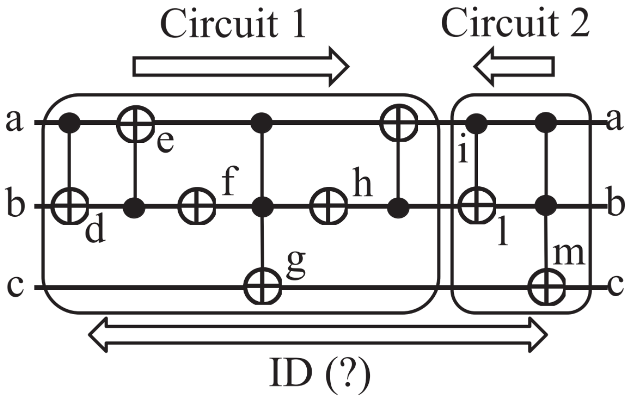
- Reversible (information-lossless) logic circuits are at the core of QC



- Reversible logic synthesis can re-use many of the existing & successful classical logic synthesis engines (SAT/BDD/LUT/AIG/SOP/ESOP/etc.)
- However, reversible logic synthesis brings up also unique challenges:
  - Irreversible to reversible function mapping: minimize its cost
  - Best tradeoff between #qubits & #gates & #levels: Solution space grows
  - Opportunities for reversible sequential synthesis? Opportunities for HLO into QC synthesis?
  - Physical data & early physical optimization into QC synthesis?
- There exist already a lot of excellent research work in reversible synthesis for QC. Industrial synthesis can walk several clear paths & opportunities for innovation

Position statement: Verification

- Verifying the correct functionality of reversible circuits is also key EDA task
- Formal verification of reversible circuits could be done with classical engines too: mitering reference and implementation and using standard techniques
- However, opportunities for better verification of QC exist:
  - Use identity miter instead of classical miter: Then use XOR-CNF, DDs, or other dedicated tech. to solve the miter



  - Verify other properties of relevance to QC
  - Are hard to solve instances of QC verification problems same/similar to classical verification problems?
- There exist already a lot of excellent research work in formal verification for QC. Industrial formal verification can walk several clear paths & opportunities for innovation

Position statement: Summary

- Synthesis and Verification tool in industrial EDA can help QC design scale up

- Lots of synergies with classical CMOS design can be exploited…
  - … lots of enhancements are needed…
  - … in physical design too!

- Often research on new areas (such as QC) can bring innovation/help to classical areas (CMOS) too!

- Exciting times for innovation in such core areas of EDA!

Topics/questions to jointly discuss

- Are QC synthesis/verification problems harder than classical ones?

- What about QC library design? Should it be tied closely to QC synthesis?

- Still open discussion on which technology(ies) will lead next gen QC.
  - How much tech independent QC design do we need?
  - What is the role of EDA here?

- Market for QC-centric EDA

Building quantum computers: Why and how?

Thomas Haener
Sr. Research Scientist (QC / HPC)
Amazon Web Services (AWS)

Why quantum computers?

Chemistry and materials

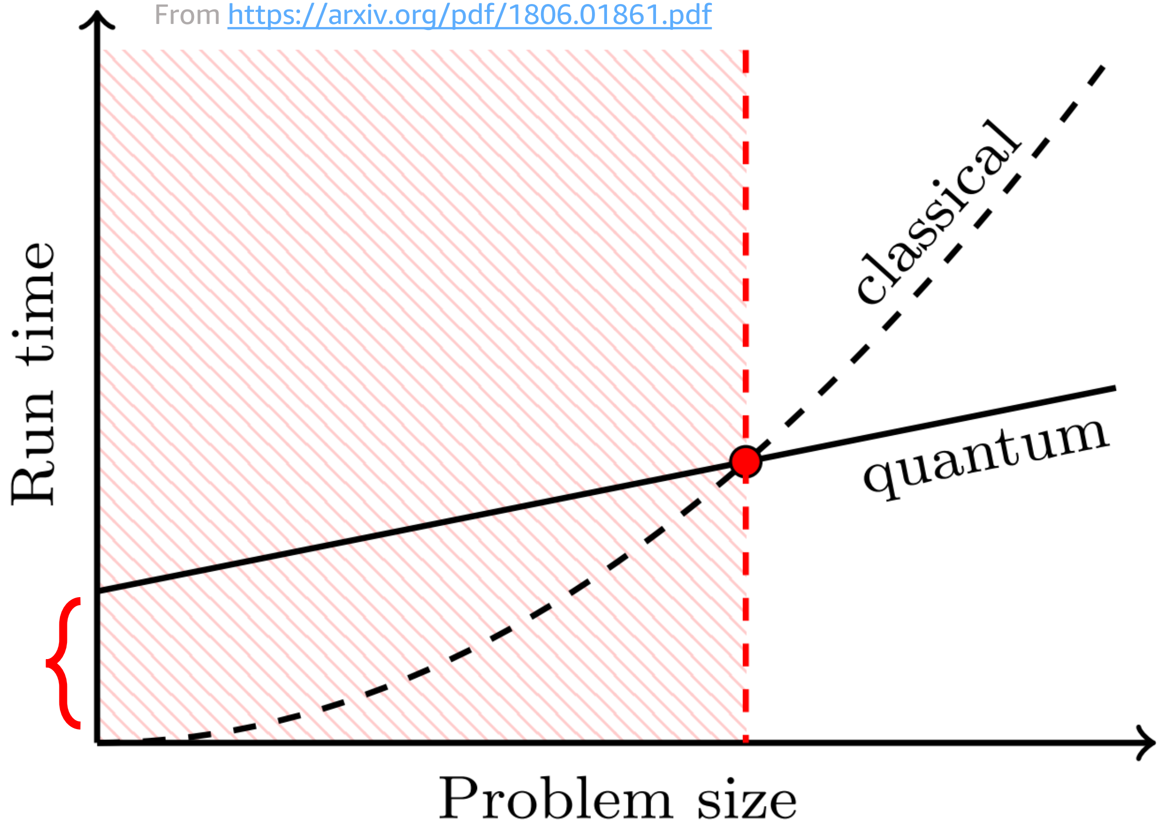
Options pricing, risk estimation

Optimization

Machine learning (quantum data)

Why quantum computers: Applications

From https://arxiv.org/pdf/1806.01861.pdf



Overhead
(reversibility, QEC, clock speed, …)

Identifying good applications

1. Quantum algorithm offers asymptotic speedup
2. Ensure correctness
3. Understand algorithmic overheads in detail
4. Analyze resource requirements (gates and qubits)
5. Determine low-level overheads (e.g., mapping, error correction)

Identifying good applications

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→ Software for quantum computing

How to build quantum computers?

- **Software**: Simulators (for testing), programming languages, circuit synthesis/optimization, layout/routing, cloud access to devices, …
- **Applications**: Explore new applications, optimize existing algorithms, resource estimation for concrete use cases, …
- **Hardware**: Explore new architectures, optimize existing technologies, hardware-specific error mitigation/correction, learn from small(er) devices, …

Quantum Computing at AWS

Amazon Braket

Democratize quantum computing

Fully managed service that makes it easy to explore and experiment

Amazon Quantum Solutions Lab

Provide expert guidance

Practical and cross-discipline support and collaboration

AWS Center for Quantum Technologies

Push the boundaries

Research quantum algorithms, hardware, and networking

Thank you!

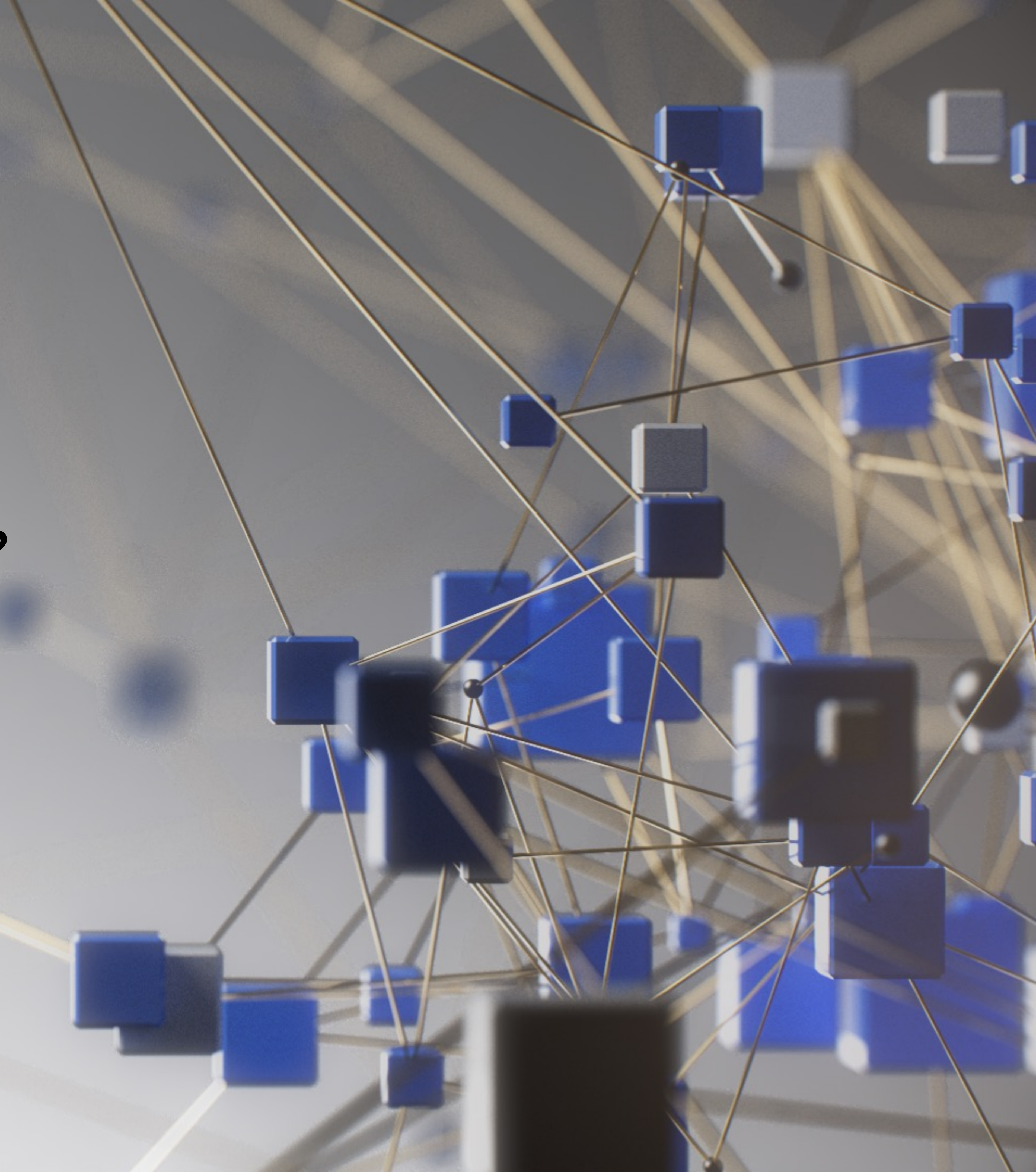
Thomas Haener
Sr. Research Scientist
thaener@amazon.com

How many qubits do you need, really?

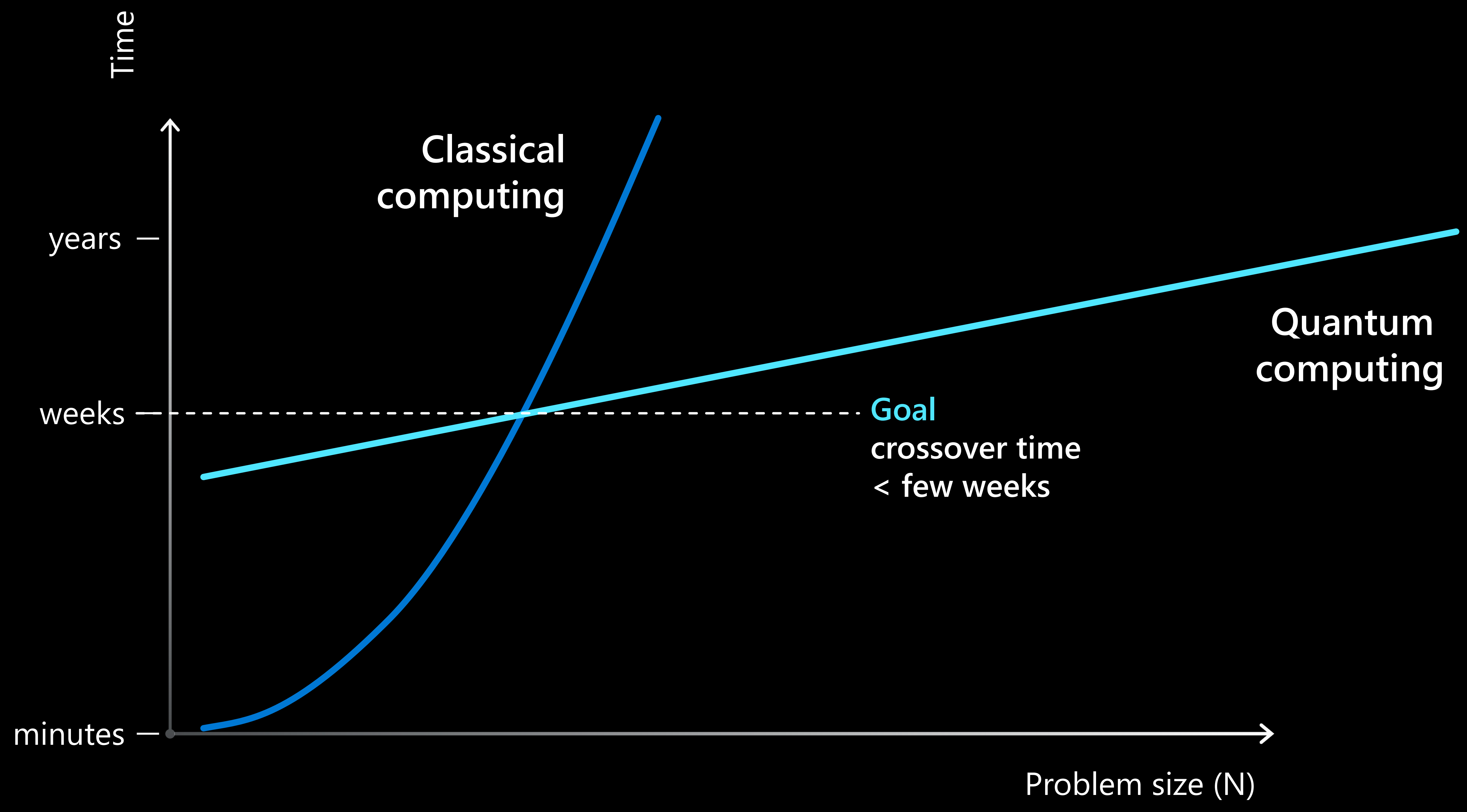
Mathias Soeken

Try it out: ***aka.ms/AQ/RE***

Read about it: ***arXiv:2211.07629***

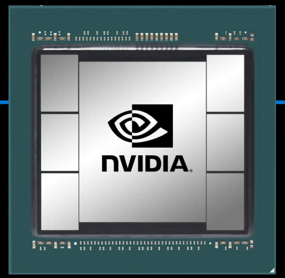


Achieving practical quantum advantage



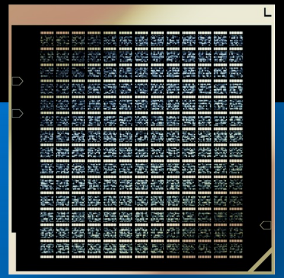
Practical quantum advantage requires fewer operations

Each operation is orders of magnitude slower



Classical chip

Nvidia A100 GPU
54 billion transistors
0.7 ns cycle time



Quantum chip

All-to-all connectivity
10,000 logical qubits
10 μs logical cycle time

5 Pops/s (GPU)	Logic operations	**2 Mops/s**
310 Tops/s (GPU)	16-bit floating point operations	**7 Kops/s**
10,000 Gbit/s	Read rate	**1 Gbit/s**

arXiv:2211.07629

Practical quantum advantage requires fault tolerance

Error protection takes more timesteps and physical qubits

Classical computing stack	Quantum computing stack
High-level	High-level quantum
IR	Quantum IR
ISA	Quantum ISA (logical)
Microcode	Microcode (QEC)
Microarchitecture	Microarchitecture (phys.)
Transistor control	Device control

Resource estimation

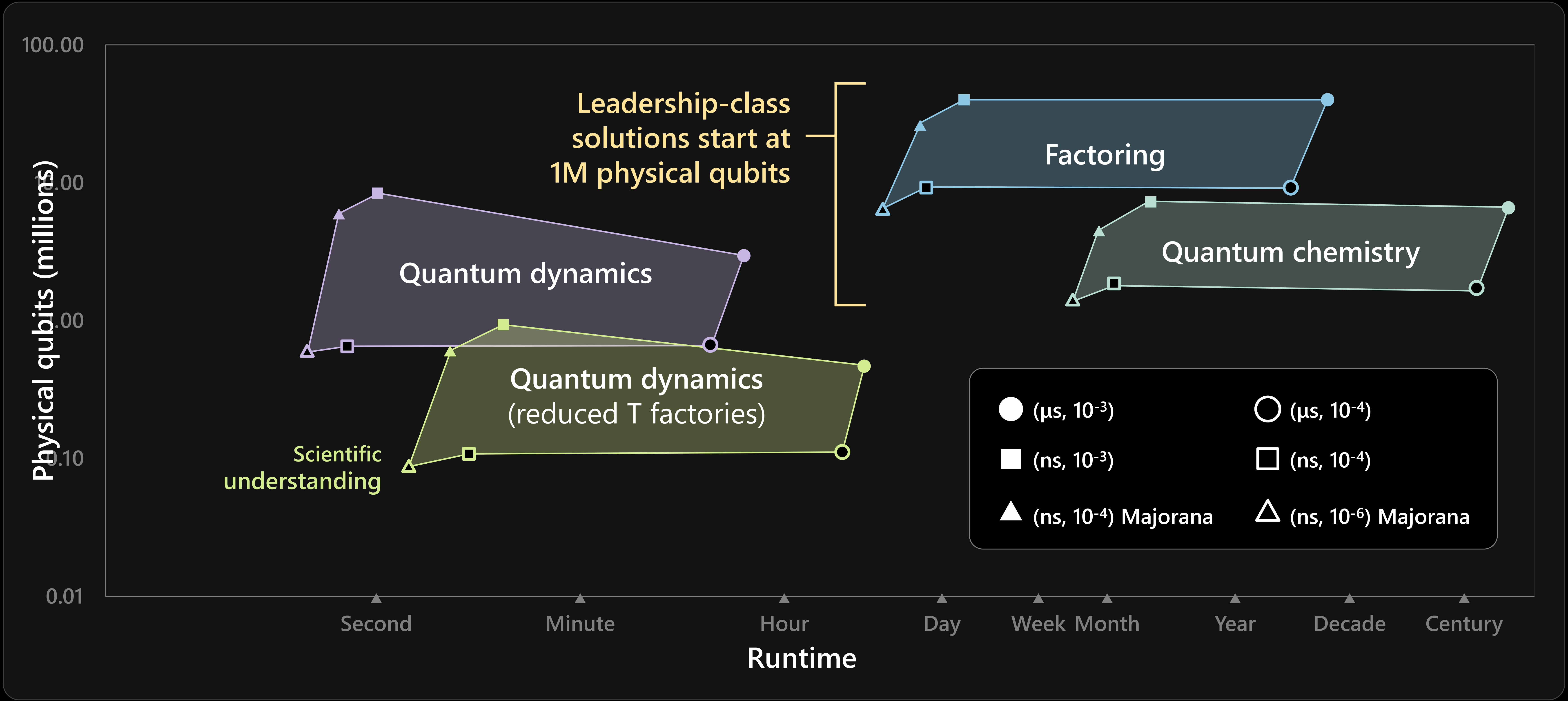
Quantum program representations
Estimated instruction counts
of ISA program

← Quantum ISA

Estimate physical resources
to supply ISA instruction
Quantum machine models

Practical quantum advantage begins with millions of qubits

The challenge is all about scaling



Azure Quantum Resource Estimator

Application Input

Q#

Qiskit

Libraries

BRING YOUR OWN

Application Program

Compilation Tools

Q# and Qiskit Compilers

BRING YOUR OWN

Compilation and Optimization Tools

QIR

Quantum Intermediate Representation

BRING YOUR OWN

QIR Code

QEC Models

Built-in QEC Schemes

BRING YOUR OWN

QEC Models

Qubit Models

Built-in Qubit Parameter Settings

BRING YOUR OWN

Qubit Parameters

Analysis

Analysis and Visualization Tools

BRING YOUR OWN

Analysis and Visualization Tools

Quantum Computing
Panel

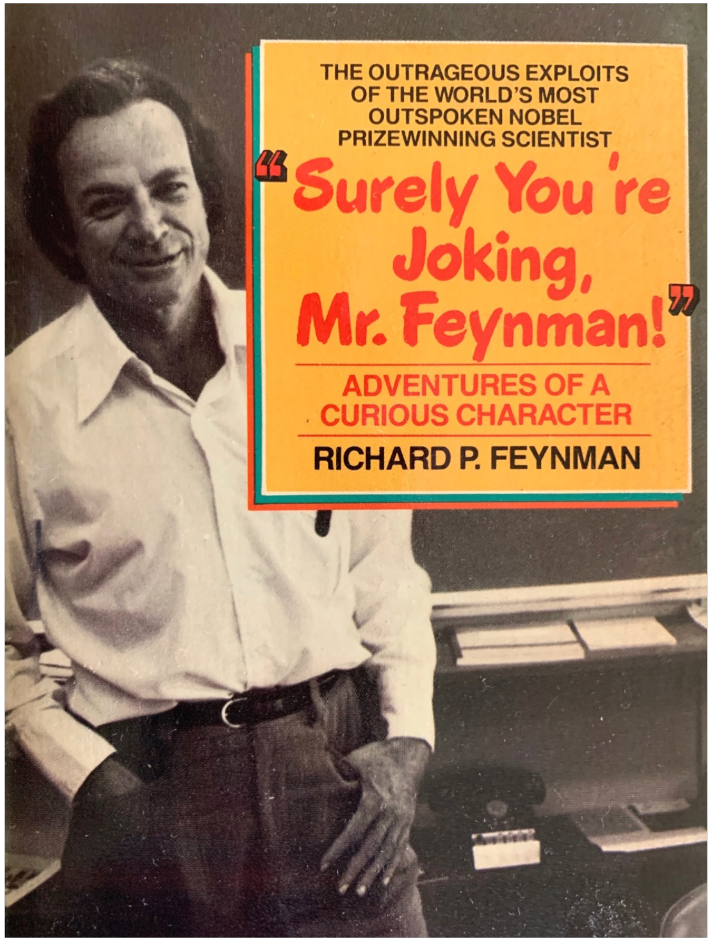
Emerging Applications and Technologies
Montreux - April 2023

Andrei Vladimirescu[1,2]

[1] Delft University of Technology, Delft, The Netherlands, [2] University of California, Berkeley, CA,

Are Quantum Computers only for Physicists?

- An outrageous idea that came from a physicist
    - Richard Feynman
- Proposal to use **entanglement** and **superposition** of quantum entities for computation
- Theories always come from Physicists
    - But it is **Engineers who make them work**!
- QC Programmers do not need knowledge of QP
    - But should know that a Qubit can be both 0 and 1 at the same time

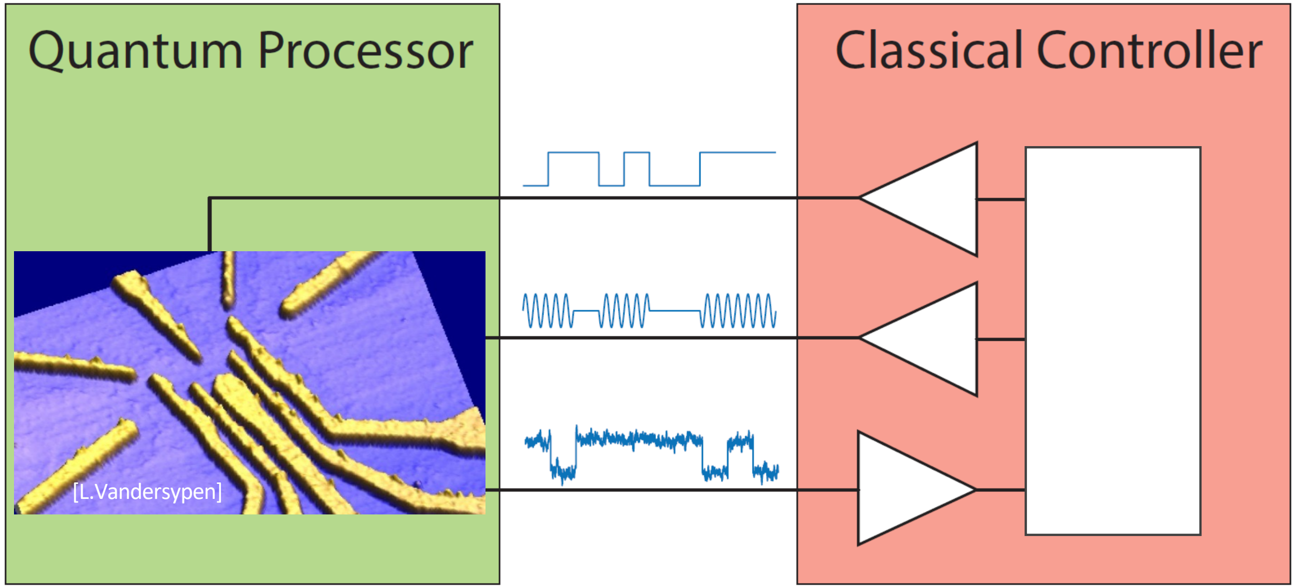

THE OUTRAGEOUS EXPLOITS OF THE WORLD'S MOST OUTSPOKEN NOBEL PRIZEWINNING SCIENTIST

"Surely You're Joking, Mr. Feynman!"

ADVENTURES OF A CURIOUS CHARACTER

RICHARD P. FEYNMAN

Quantum Computer or Quantum Processor?



Quantum Processor:

- E.g. spin qubit, transmons
- Cooled down to T << 1 K

Classical electronic controller:

- Qubit manipulation
- Qubit read-out
- Implementation?

QC State-of-the-Art and Metrics to Compare?

- Order of magnitude: 100 Qubits
  - 127 for IBM Eagle (Transmons)
- The Quantum World tries to find Metrics for QC's Today
  - Number of Physical/Logic Qubits;
  - Algorithmic Qubits (IonQ);
  - Scale (# Qubits) + Quality (Q Volume) + Speed (CLOPS) – IBM
- Comparing QC to a Server Farm
  - It's apples and oranges!
    - QC for dedicated algorithms, SF for traditional tasks

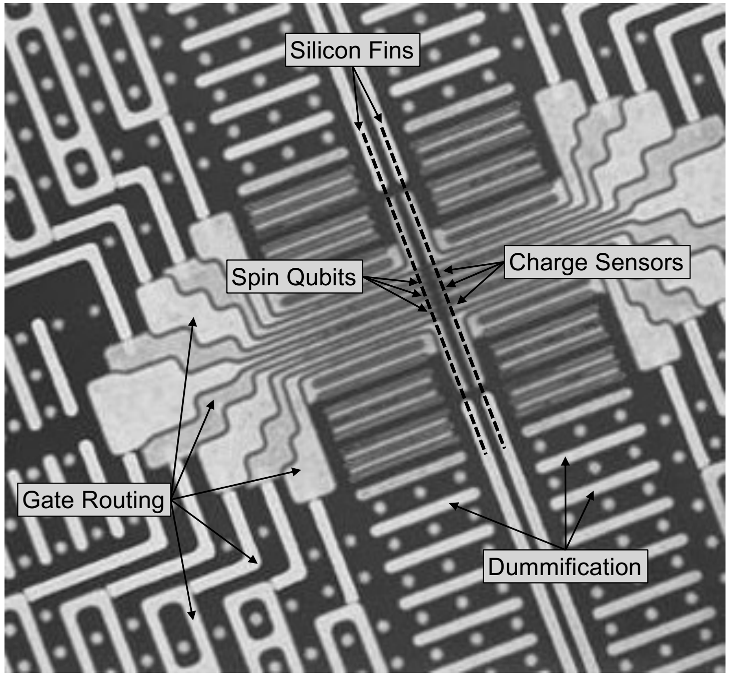
QC Technology Environment Today

- Major QC implementation trends
  - Electron spin in Semiconductor
  - Superconducting resonators (Transmons, Jossephson Junctions)
  - Trapped Ions
- How many Qubits do we need for relevant computation?
  - 100,000+
- Control Electronics – standard instrumentation at Room Temperature
  - Ok for 10-100 Qbits
  - CryoCMOS Controller – Better Solution
- Silicon processing has advanced to the nm feature size
  - Technology nodes 14nm, 10nm, 7nm, …
  - SET – control the spin of an electron in a Qdot (MOS equivalent)
- Silicon Technology is scalable!

Integration of Qubits and Control Electronics

- Semiconductor Spin-Qubits
  - Industrial Process on 300 mm Wafers
- Integration with CMOS Control Electronics
  - Possible in standard IC Processes
  - MOSFETs operate down to mK
- Quantum – Electronics Interface Design
  - Mixed-Mode SPICE-QSolver -> SPINE (TUD)
  - Need MOSFET Cryogenic Model Params

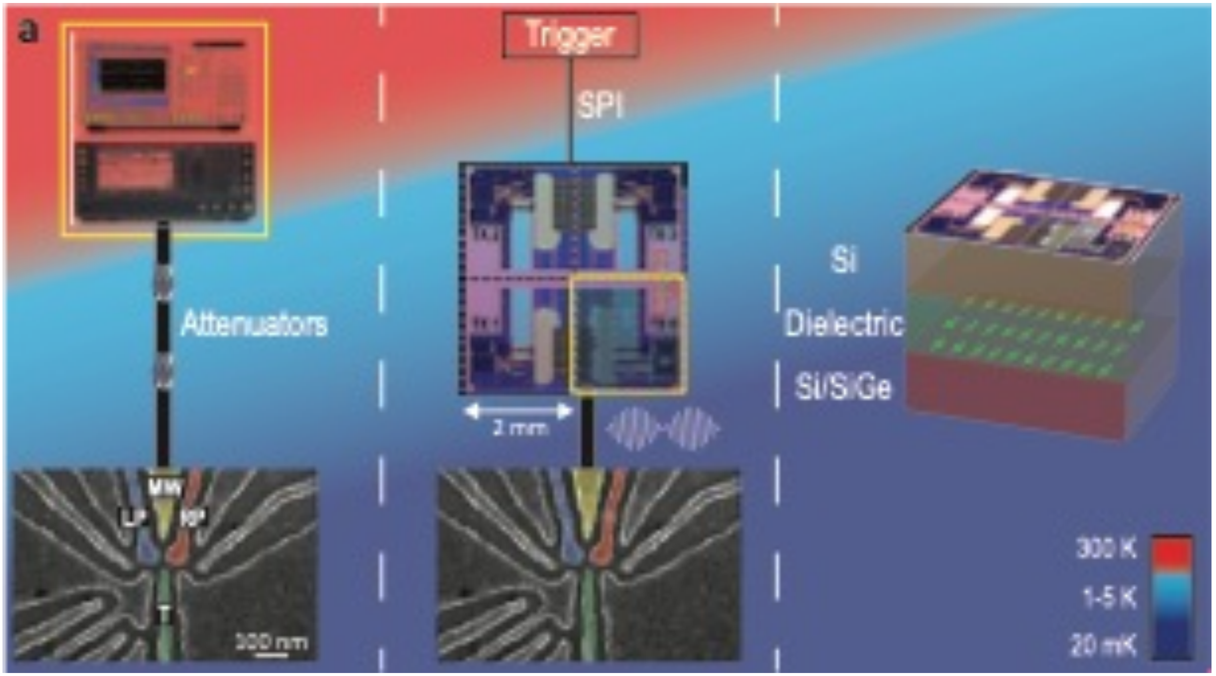
✓Available EDA Tools can be used!



A.M. Zwerver et al, Nature Electronics 2022

Vision

Spin-Qubit QC with Integrated Controller



X. Xue, B. Patra, J. van Dijk, et al., Nature 2021

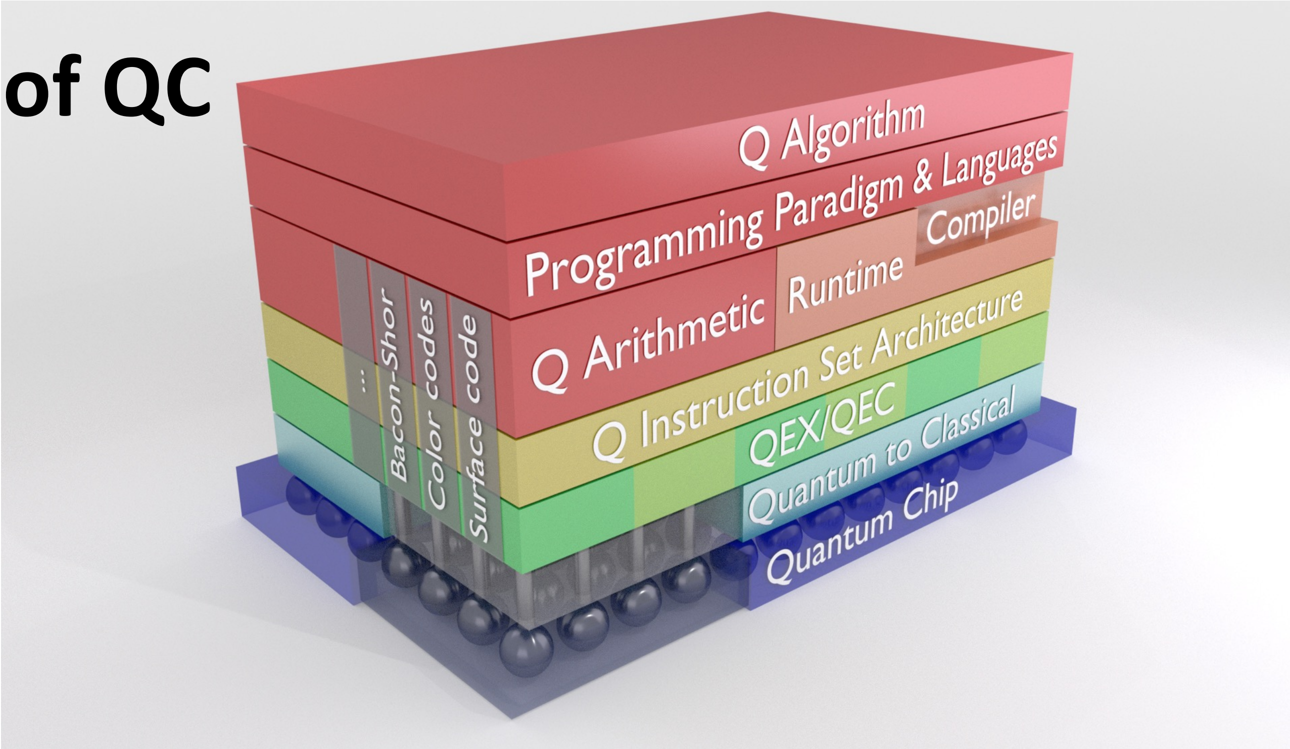
How will QC be designed?

Edoardo Charbon

EPFL

April 20th, 2023

The main problems of QC today

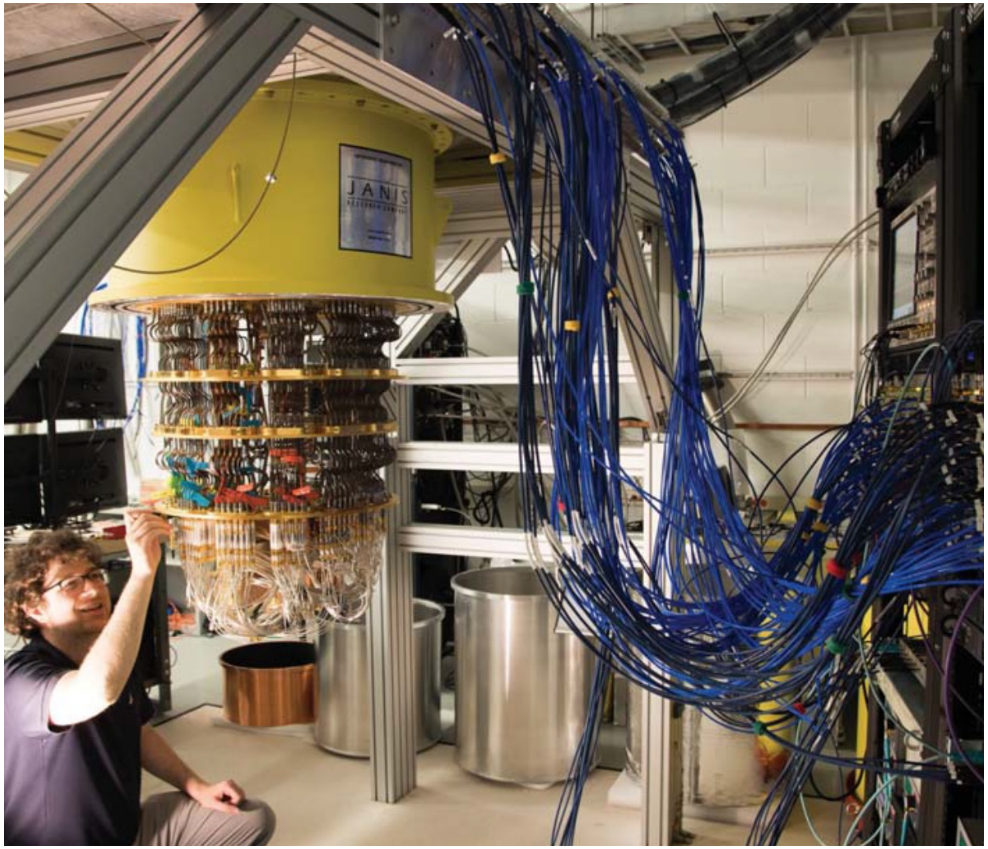


1. How to program it
   - How to compile a conventional algorithm to a quantum algorithm?
   - There is no way to do that systematically (Mathias, correct me if I am wrong)!

   →This is the main failure of parallel processing in the 1990s until people figured out multi-threads

   →EDA experience could help

The main problems of QC today



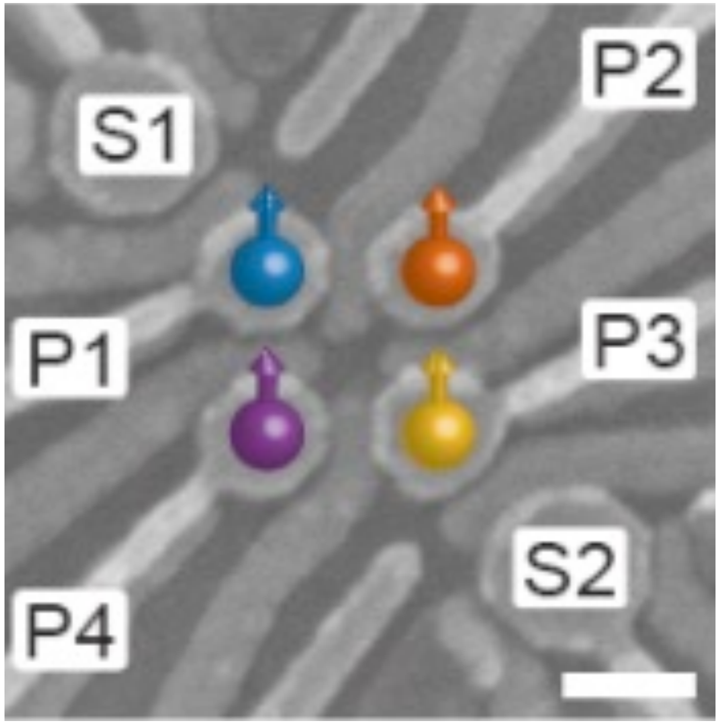
2. How to make it reliable

- We are clearly pre-1947,
- There is no equivalent of qubits to BJT or MOS

→This was the main failure of the first large-scale computers (e.g. ENIAC) in the 1940s

→We need to think of a solution that could be reproducible and reliable

The main problems of QC today



3. How to scale it
   - Though thousands of physical qubits have been demonstrated, there are only a few logical qubits one can actually program.
   - This is short of the millions of qubits needed by any serious algorithm!

   →We need to accelerate the process before QC becomes irrelevant

Questions

- Why is this field so compartimentalized? Why physicists are not interested in architectures? Why computer scientists are not interested in HW? Why engineers do not see the whole thing coming together?
- Quantum computers are a reality. And with them completely new design tasks emerged.
- Due to the radically different computational paradigm and physical setting, we have to re-think the design of corresponding applications and devices.
- How much of the established design flow for classical circuits and systems can be used for these purposes? How much has to be developed from scratch? And do we all have to become quantum physicists now?
- Moreover, what is the perspective of quantum computing? Within a 10-year horizon, can we count on quantum computing to solve practically relevant problems?
- Do we have metrics that show the superiority over classic server farms on relevant problems?