Musings on the Future of Quantum Software

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Quantum Symposium

University of Amsterdam

Centrum Wiskunde & Informatica
Amsterdam

QuSoft
Research Center for Quantum Software

Quantum.Amsterdam

NWO

Quantum Software Consortium

Quantum Software

- Quantum Software is fundamentally different from classical software:
  - Uses Superposition, interference, and entanglement
  - Not always possible to speed up computation
  - Much more effort needed to uncover the power of quantum devices
- 2015: Launch research center for quantum software

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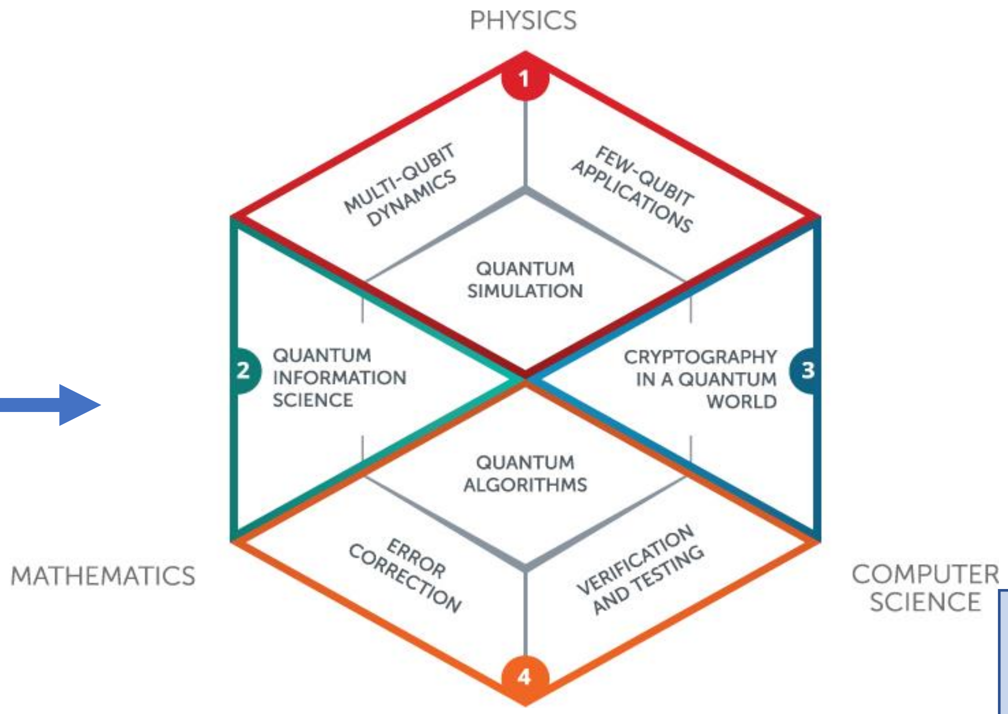
- 2017: Gravitation grant: Quantum Software Consortium

- Amsterdam-Delft-Leiden, 18.8 M€

Quantum Software Consortium

Research Center for Quantum Software

“Enabling the power of quantum computers”



- 25 permanent faculty
- CWI-UvA
- 50 PhD/Postdocs
- CS, Physics, Math
- Coordinate Dutch QSC
- Write NL/EU research agenda
- Engage with industry

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New theme: Quantum for Society & Business

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Which computational problems have quantum speed-up?

- Difficult and deep question!
  - No easy criterion exists or is expected to exist.

WARNING:
Requires hypotheses like SETH or $\mathrm{P} \neq \mathrm{NP}$

Roughly three categories of problems:

1. Exponential speedup
   - Factoring, quantum chemistry simulations, etc.
2. Polynomial speedup
   - Backtrack, search, satisfiability solvers, etc.
3. No speedup
   - Really hard problems: counting # satisfiable assignments to a formula
   - Really easy problems: edit distance, sorting, binary search

For many problems we don't (yet) know in which category they fall

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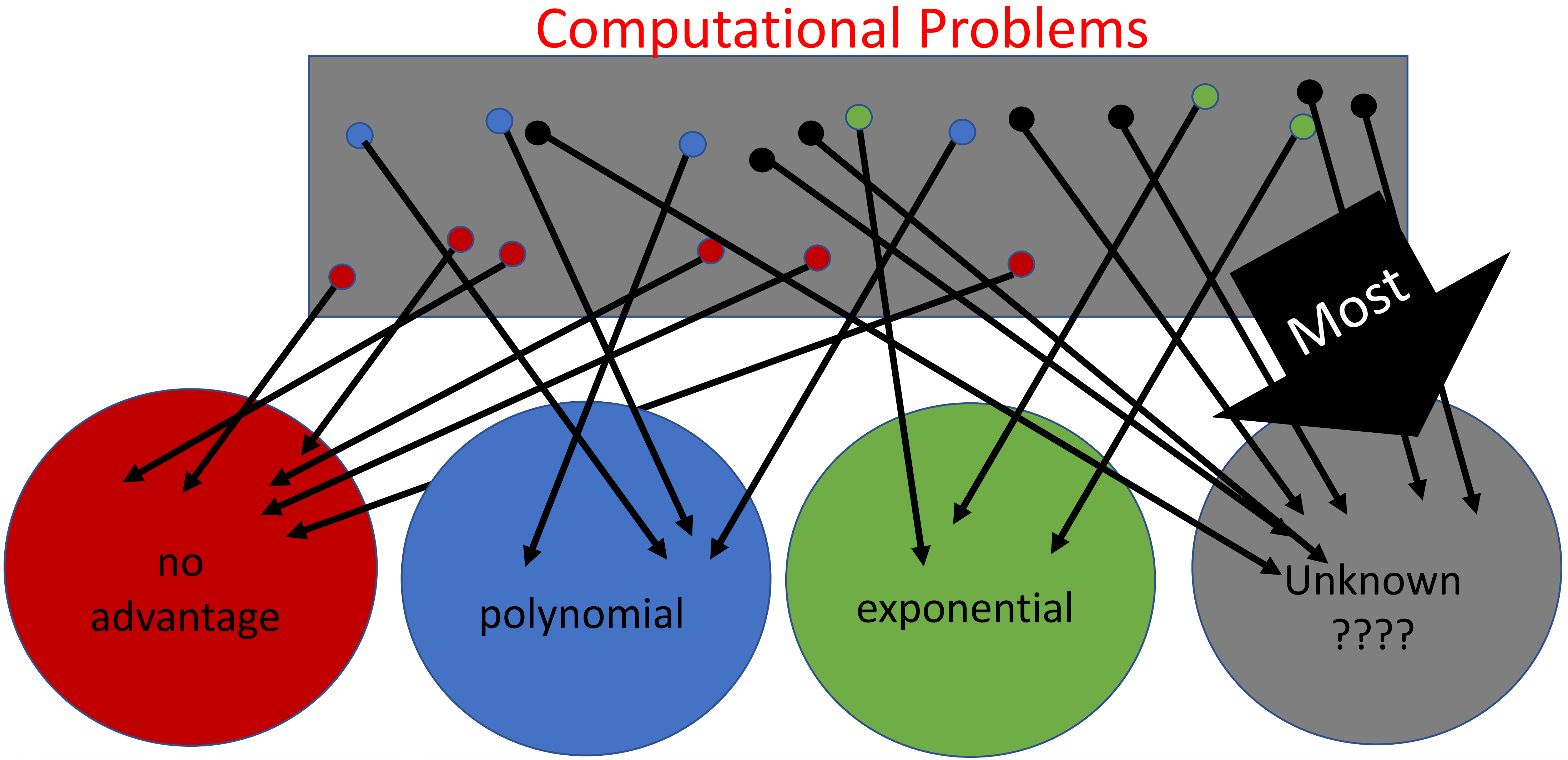
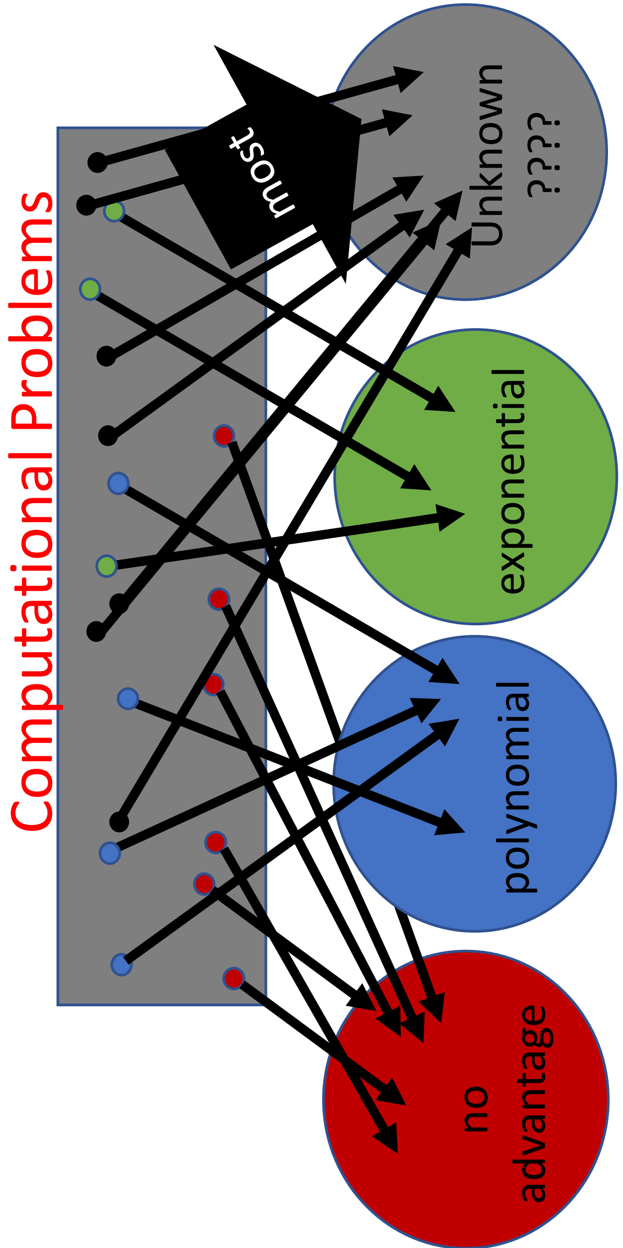
Quantum Advantage Classicification



Quantum Advantage



Three Problems:

1. Quantum Hardware is not perfect
   - Have noisy NISQ devices
   - New quantum algorithms
2. Worst case quantum advantage
   - Interested in *true* advantage
   - Quantum Heuristics
3. Asymptotic analysis
   - Complexity theory of finite inputs
   - Important for quantum supremacy

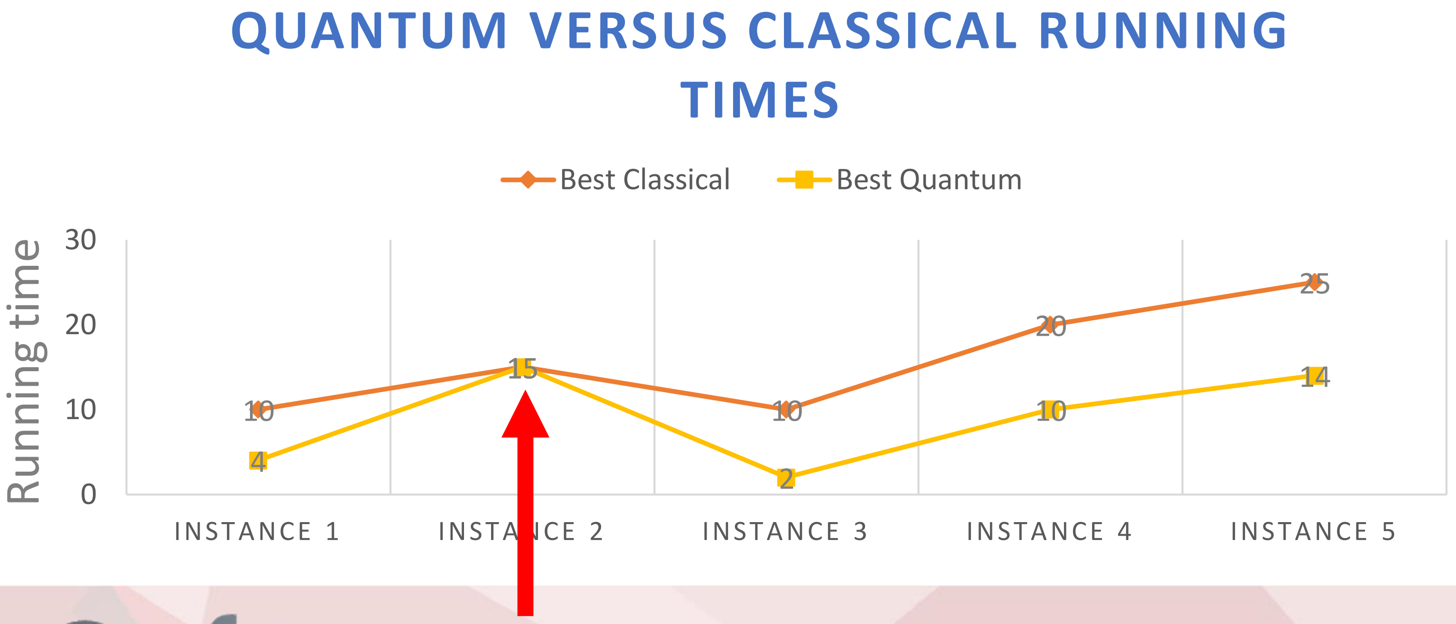
Quantum Software 2.0

Problem1: Noisy Qubits

- Qubits degrade over time (NISQ regime)
  - Limited number of steps possible ⇒ short time to run quantum computer
  - Readout is probabilistic ⇒ repeat computation and take average outcome
- Run quantum computer often for short periods use classical computation before, inbetween, and after. (Hybrid computation)
- Quantum Algorithms have to reflect this:
  - QAOA & VQE frameworks
  - Shallow quantum circuits: short quantum paralell time with quantum advantage
  - Note: Shor's algorithm can be computed by shallow-ish quantum circuits
  - Hamiltonian Programming: make optimal use of specific quantum hardware
- Not clear how well these really work in the NISQ setting!
- New ideas and techniques & fine tuning needed (both hardware & software)

Problem 2: Worst Case vs Real Case

- Traditionally design algorithms with respect to worst case behaviour
- Best algorithm has good running time guarantee on all instances
- Quantum Advantage/Complexity is also measured in the worst case

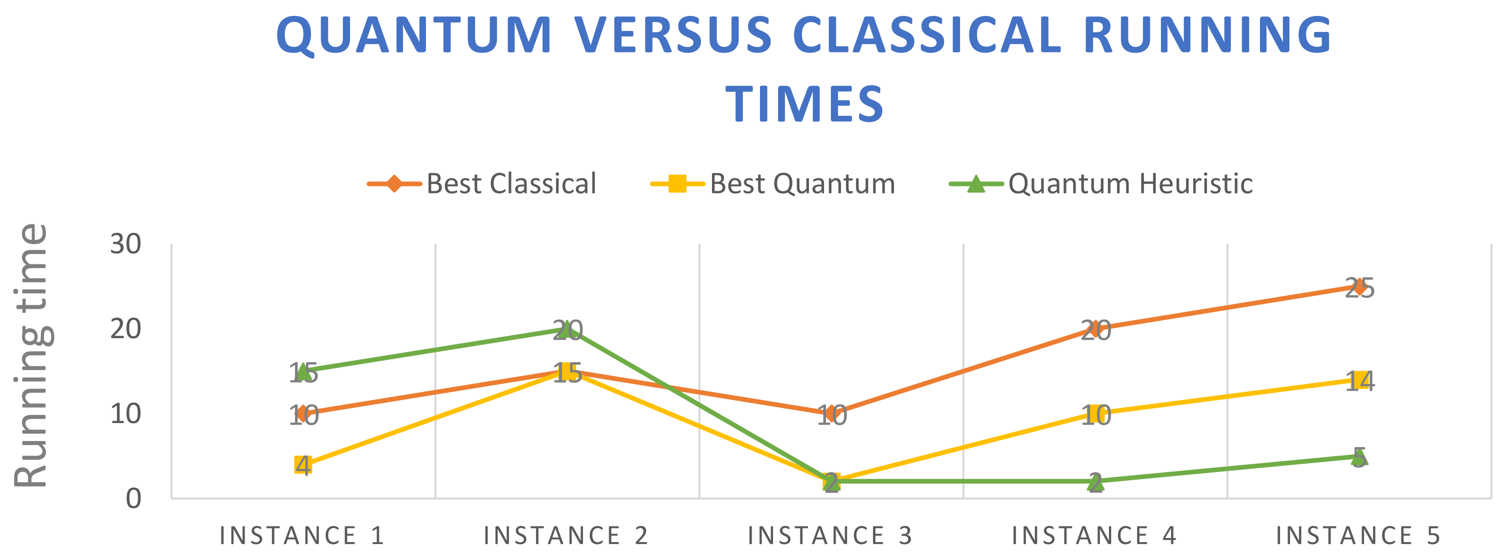


On instance 2

- Classical = Quantum
- Classifies as no advantage
- Instance 2 may never occur in practice!
- real case design & analysis needed.

Quantum Heuristic Algorithms

- Design quantum algorithms to optimize real case difference



Instance 4 & 5

- Real occurring instances
- Heuristic quantum algo
- Quantuml advantage!
- Average/real case analysis

Quantum Heuristics

- Hard to analyze quantum heuristic algorithms
  - We don't have a quantum computer to try them out!
  - Need to develop techniques to do this
- We need a theory to reason about (quantum) heuristics

Some examples:

- Quantum speed-ups of classical heuristic algorithms (like SAT solvers)
- Quantum advantage for pattern matching on average [Montanaro'15]

Quantum Software 2.0

- Quantum Algorithms Designed to deal with NISQ devices
  - Generalize & improve QAOA & VQE algorithms
  - Develop new hybrid algorithms with short quantum running times
  - Develop shallow quantum circuits and show advantage
- Quantum Heuristic Algorithms
  - Optimize for real world instances
  - What are real world instances?
  - Develop tools to analyze quantum heuristic algorithms due to lack of good quantum hardware
- Combination of the two

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Quantum Feedback loops

Feedback Loops

Hardware cycle

Hybrid Algorithms

Mathematicians
Computer Scientists
Theoretical physics
Engineers
Experimental Physics

Quantum algorithms, crypto & communication
Few-qubit versions
Quantum hardware

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QDNL
QUANTUM DELTA NEDERLAND

QA

Industry cycle

Mathematicians
Computer Scientists
Software Engineers
Industry Applications

Quantum algorithms, crypto & communication
Few-qubit versions
Industrial Use Cases

Quantum Heuristics

- Different speeds!
- Independent
- Interaction
- Similar to classical

Summary

- Quantum advantage 1.0 has three problems:
  - Analysis is on perfect quantum computers but we are in the NISQ regime
  - Analysis & algorithm design is for the worst-case but we care about real-case
  - Complexity theory: we rely on unproven hypotheses
- Quantum Software 2.0 (partially) addresses these problems
  - Develop hybrid algorithms that have short quantum running times
  - Develop quantum heuristics and investigate real-world instances/distribution
  - Complexity for finite inputs (not asymptotic)
- Feedback cycles
  - Close cooperation hardware & software (co-design)
  - Academia-Industry (real case instances & heuristics)

Warning

- The field is overhyped with unrealistic claims:
  - “It will very soon change the way we do computing”
  - “It is a disruptive technology that is pervasive to everything”
- Lots of money and venture capital is poured into the field

Truth:

- Quantum Computing is still in its very early stages. Perhaps comparable to the 40’s or 50’s for classical computing
- We will not have useful quantum computers in the next 5-10 years
- The field is still very much in exploring/academic mode
- QC is very interesting and has potential but lets be realistic!

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