A Performance Model for Estimating the Cost of Scaling to Practical Quantum Advantage

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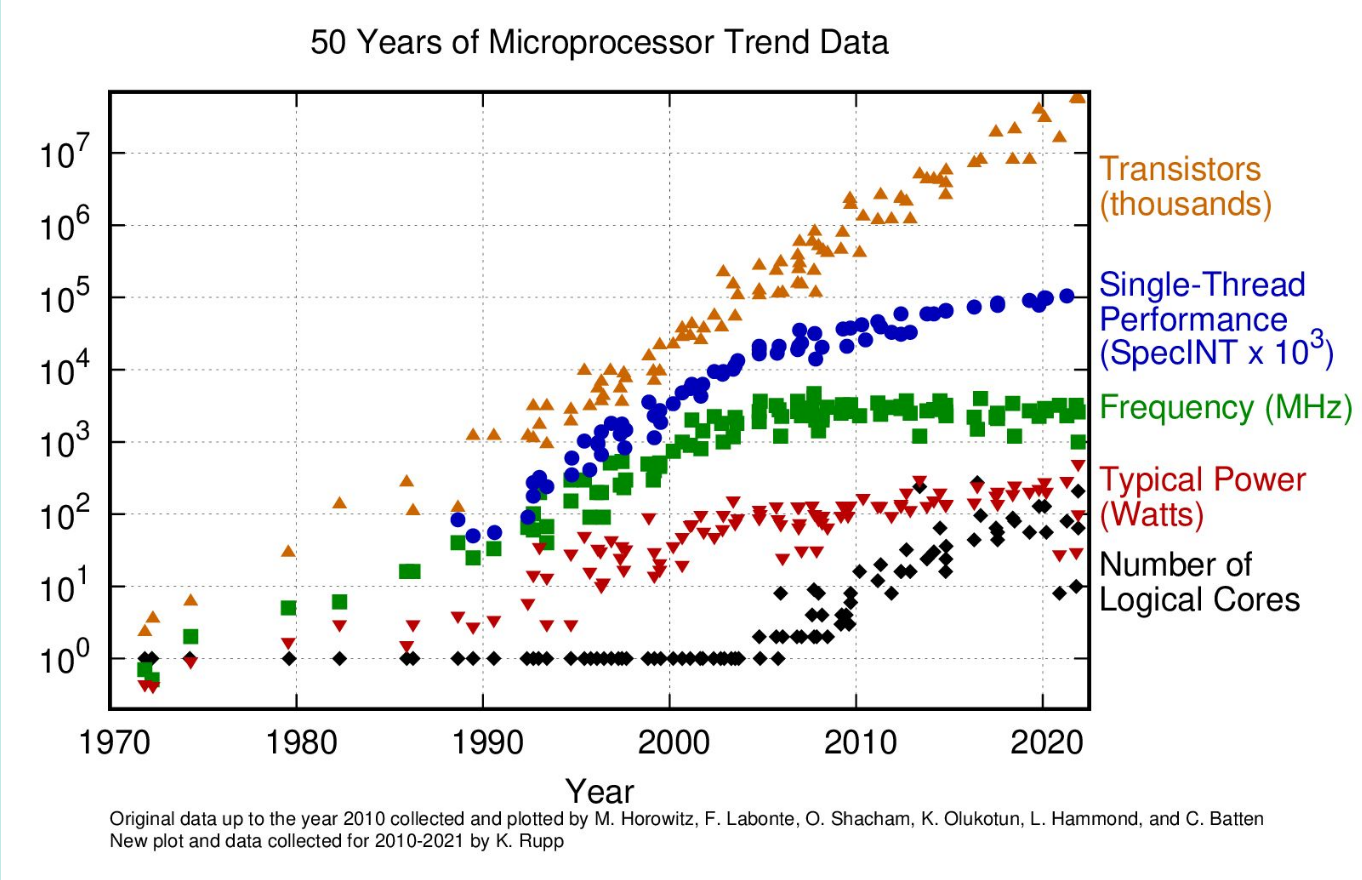
Economical and physical limits to Moore's scaling

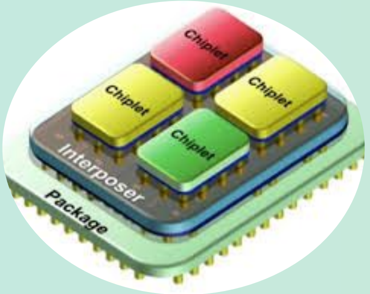


Signs of slowdown in Moore's scaling:

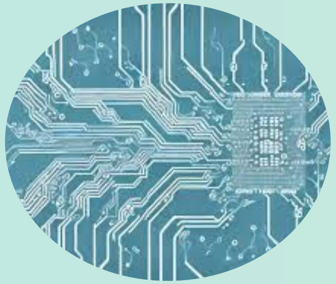
- cost per transistor flattening off?
- cost per fab going up?
- diminishing returns in process size improvements?
- …

Opportunities for new approaches to computing

FPGA

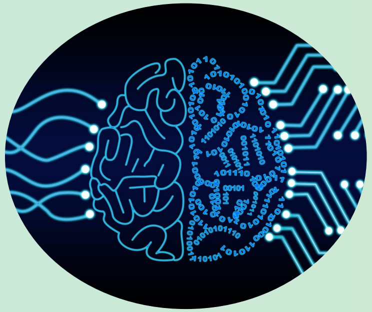


Chiplet

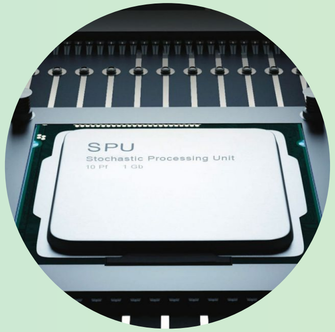


ASIC

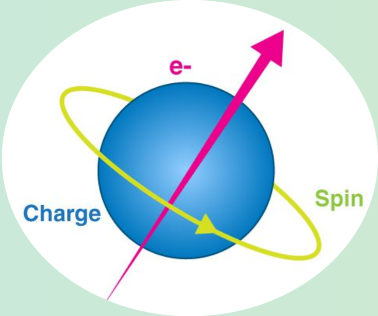
Improved energy efficiency through hardware specialization



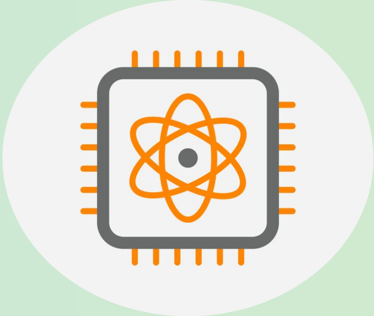
Neuromorphic



Stochastic



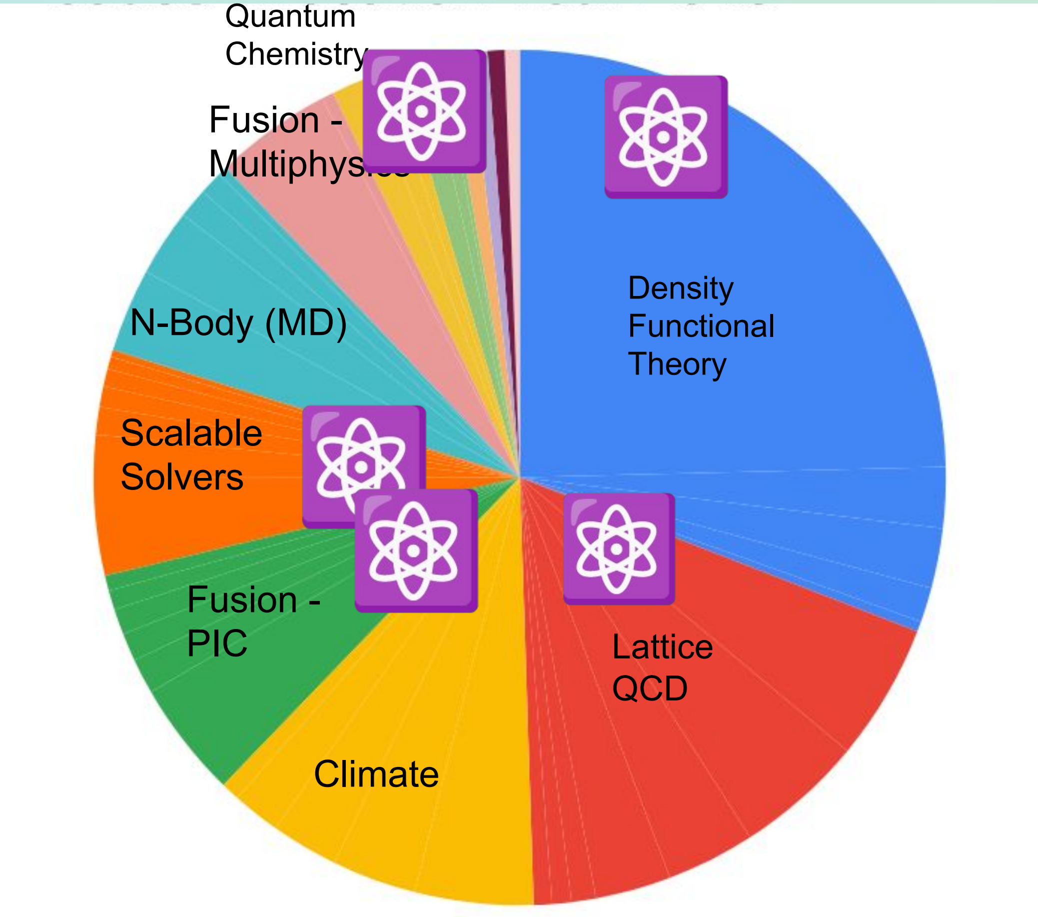
Spintronics



Quantum

New paradigms for computing

Why quantum computing for HPC?



Quantum mechanical problem
Quantum algorithms proposed

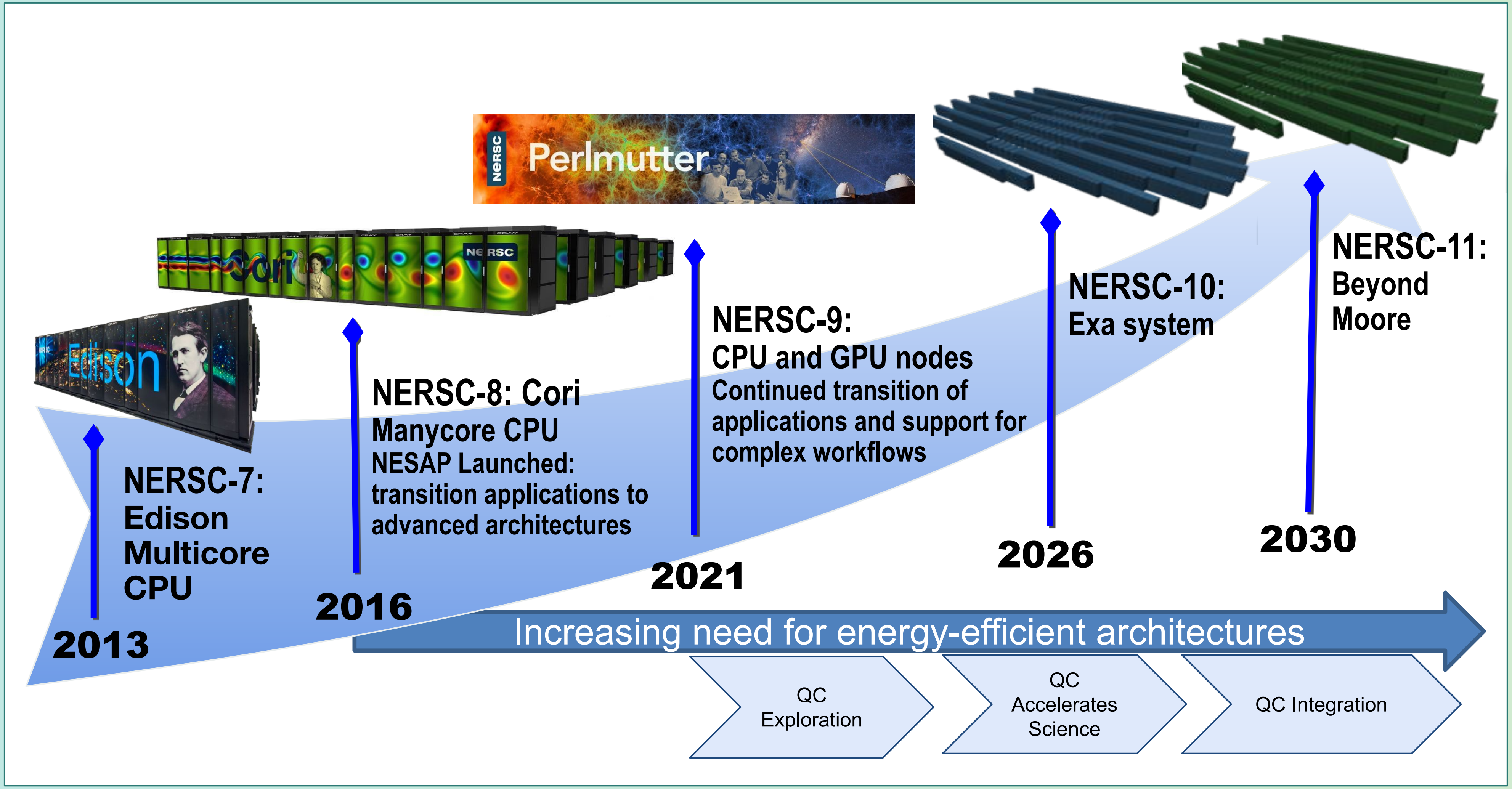
>50% of compute cycles

non-Quantum mechanical problem
Quantum algorithms proposed

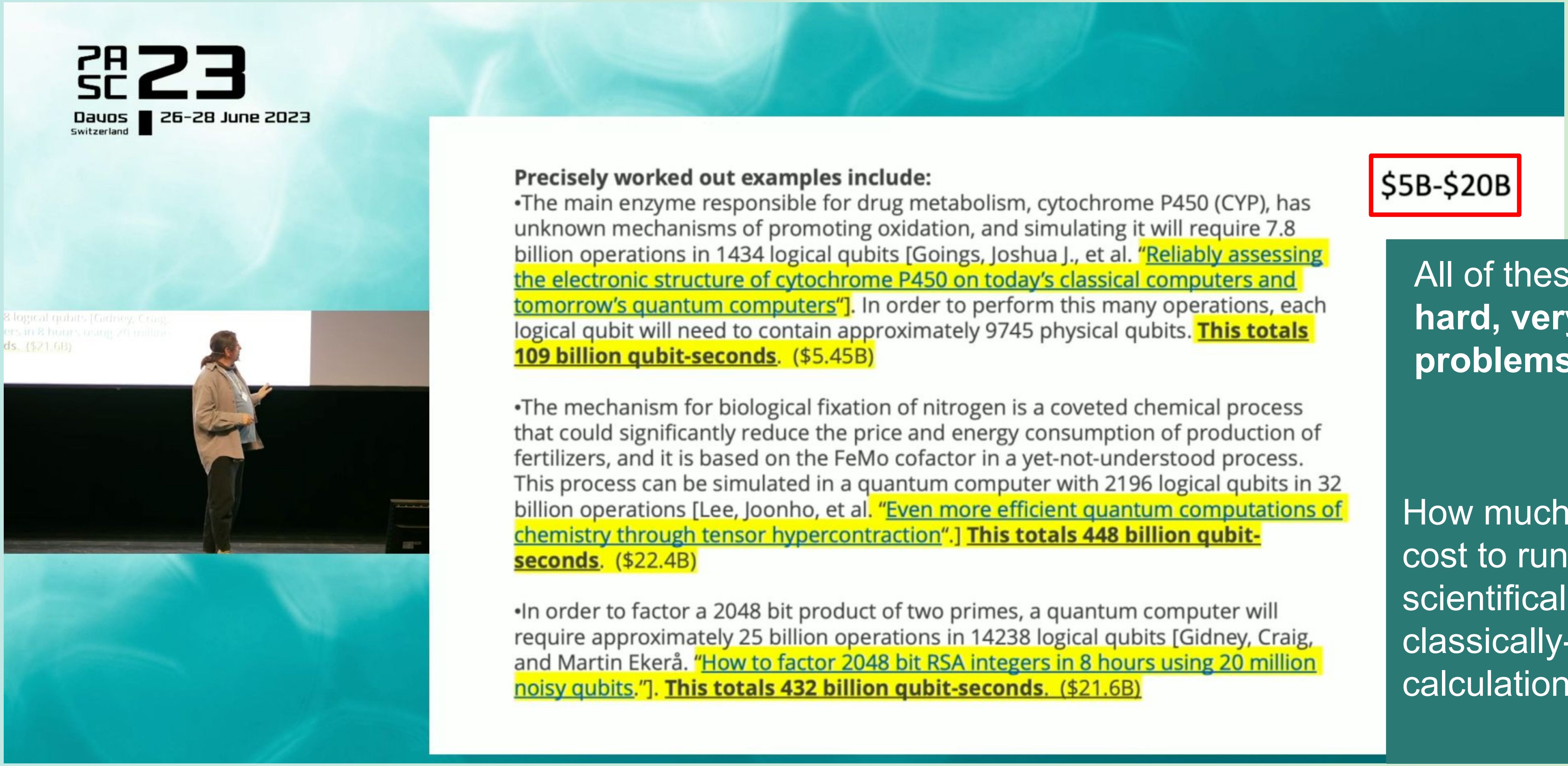
20% of cycles

What is **not** on the pie chart? Enabling the previously inconceivable with quantum technologies?

When quantum computing for HPC?



How much will quantum computation cost?

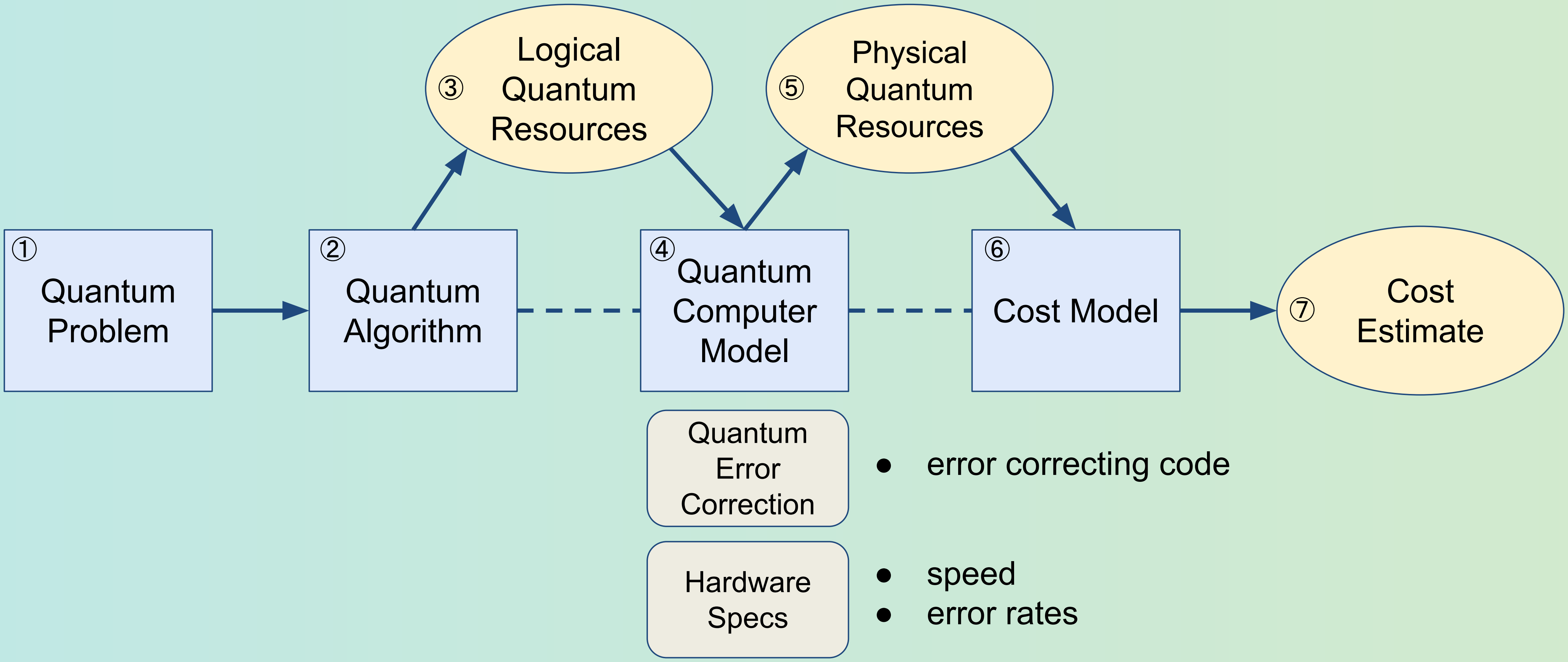


All of these are **very hard, very large problems!**

How much would it cost to run the **first** scientifically relevant, classically-intractable calculation?

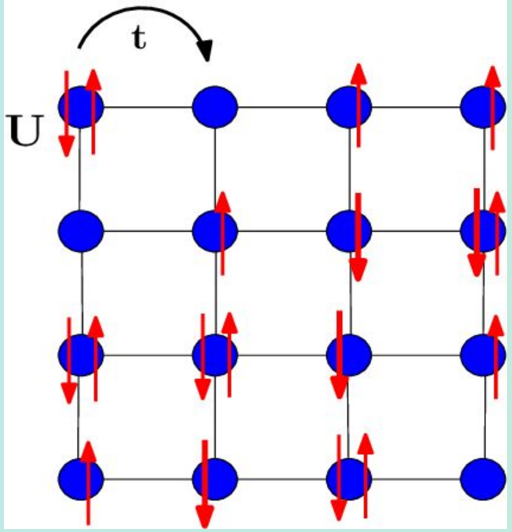
R. Stevens: *A View of Post-Exascale Computational Science and the Emerging Mix of HPC, AI, and Quantum*

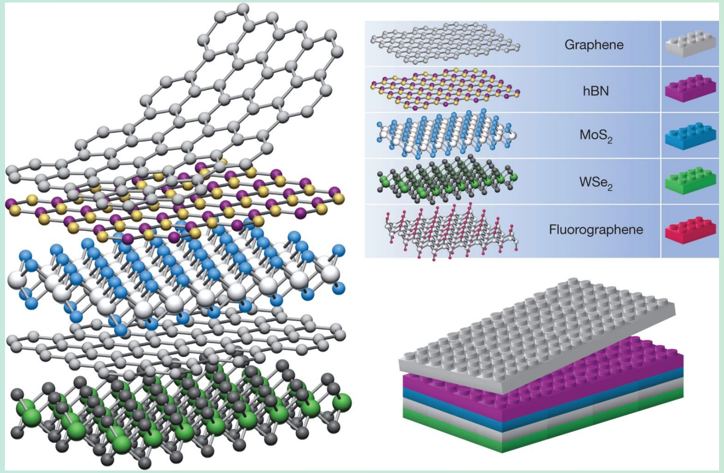
Flowchart for quantum computing cost estimation



Two-dimensional Hubbard model

- Quantum physics model of interacting **electrons on a square lattice with L^2 sites**
- Complex phenomena such as **metal-insulator transitions** and **superconductivity**
- Applications in 2D materials
- Good approximate classical algorithms exist based on tensor networks and quantum monte carlo
  - They break down in certain difficult regimes that are of most interest
- General solution is classically hard and scales exponentially





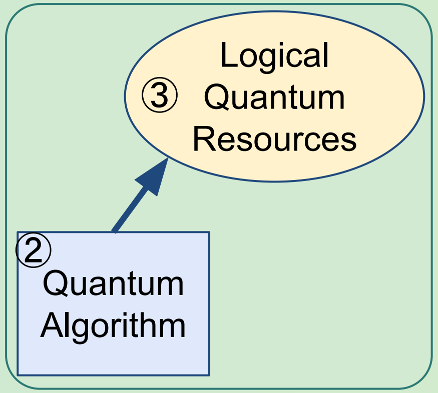
Source: Geim, *Nature (499) 419–425*

Classical complexity:

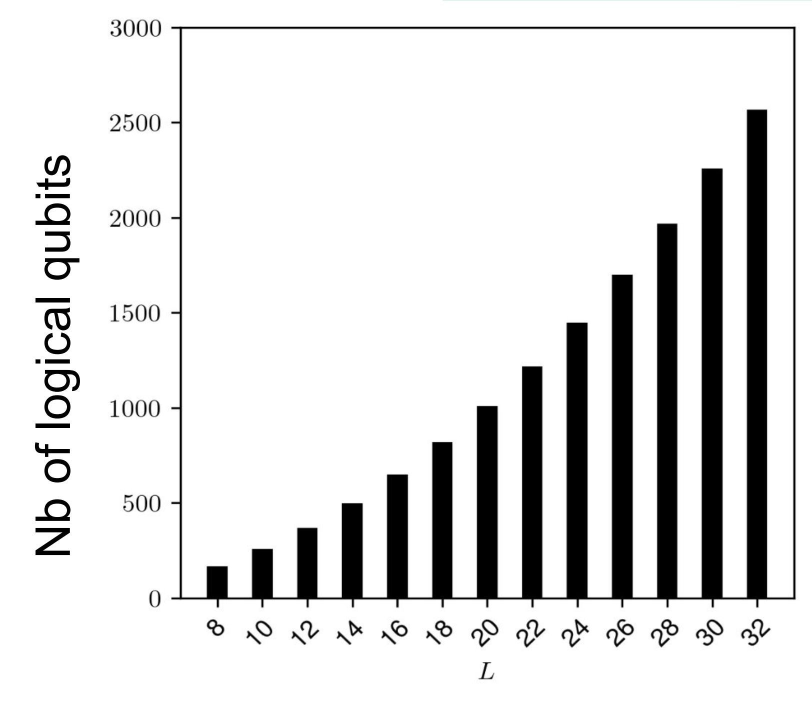
- exact diagonalization - memory: $\mathcal{O}(4^{L^2})$
- Quantum Monte Carlo: 13h on 3,456 CPUs (Fugaku) in "easy regime" for 8 x 8 lattice

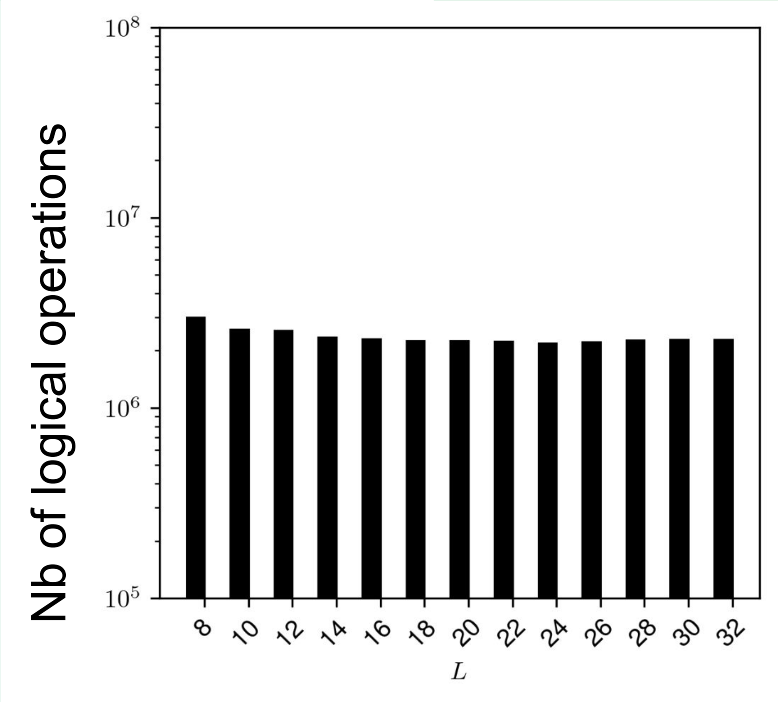
Charlebois, Imada, PRX (2020)

Logical Quantum Resources for L^2 Hubbard Model



- **Quantum phase estimation** for computing ground state energy in "hard regime"
- $O(L^2)$ scaling of quantum algorithm → **exponential advantage** over $\mathcal{O}(4^{L^2})$ classical scaling
- Fixed relative error per lattice site leads to constant logical operations
- Perfect weak scaling





Logical Resources
- Logical qubits
- Logical gates

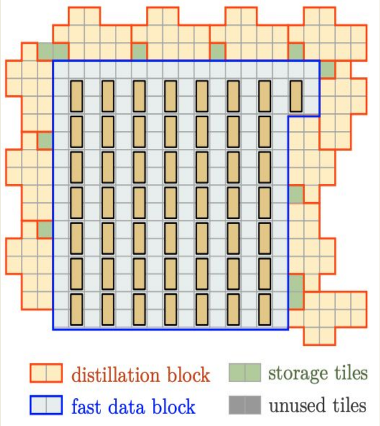
Data based on: Campbell, 2022 Quantum Sci. Technol. 7 015007

Convert Logical to Physical Quantum Resources

⑤ Physical Quantum Resources

④ Quantum Computer Model

Quantum Computer Model



Litinski, Quantum 3, 128 (2019)

Logical Resources

- Logical qubits
- Logical gates

Physical Resources

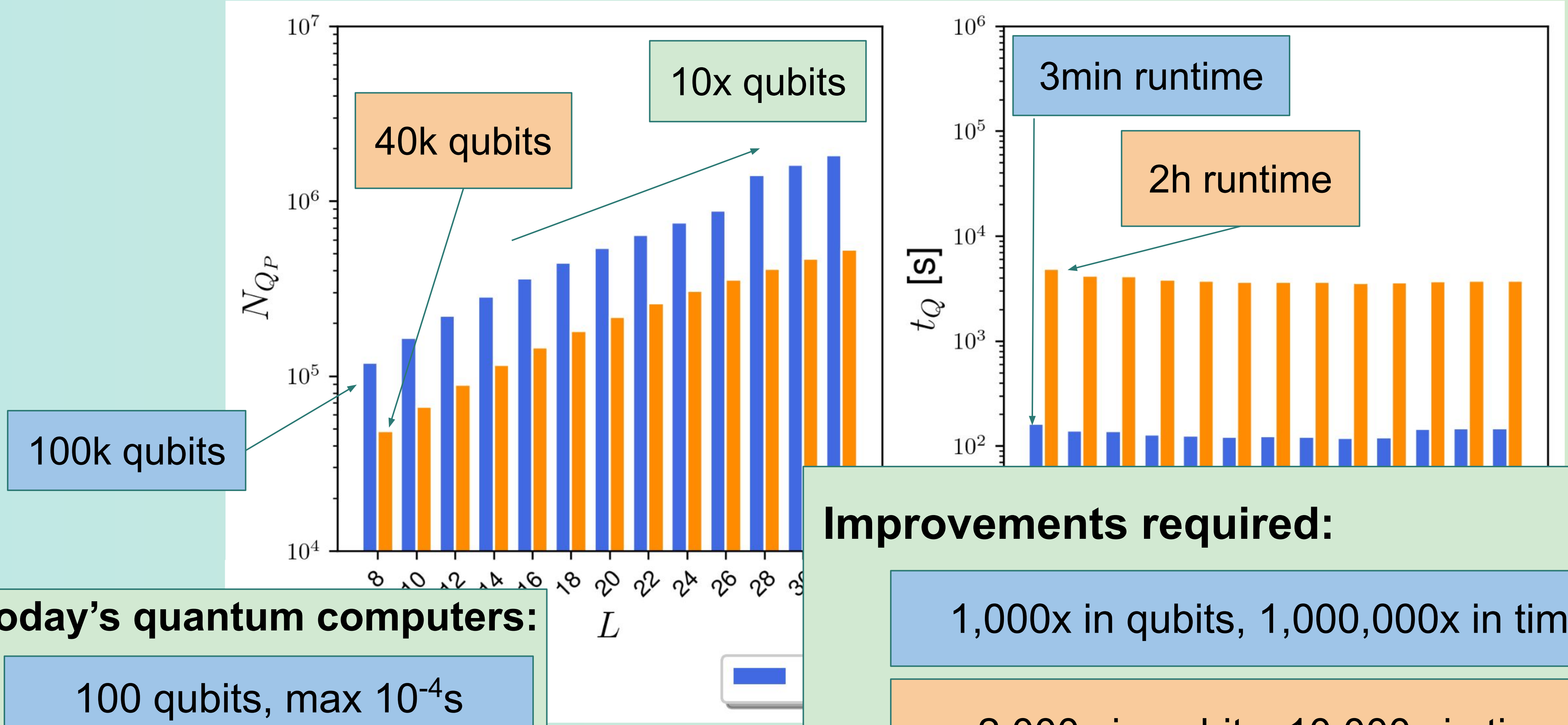
- Physical qubits
- Run time

technology	rel. speed	rel. error
superconducting QC	200x	10x
ion trap QC	1x	1x

Figure of merit: $N_{Q_P} \cdot t_Q$

units: *qubit-seconds*
(similar to *node hours*)

Physical Resources for the Hubbard Model



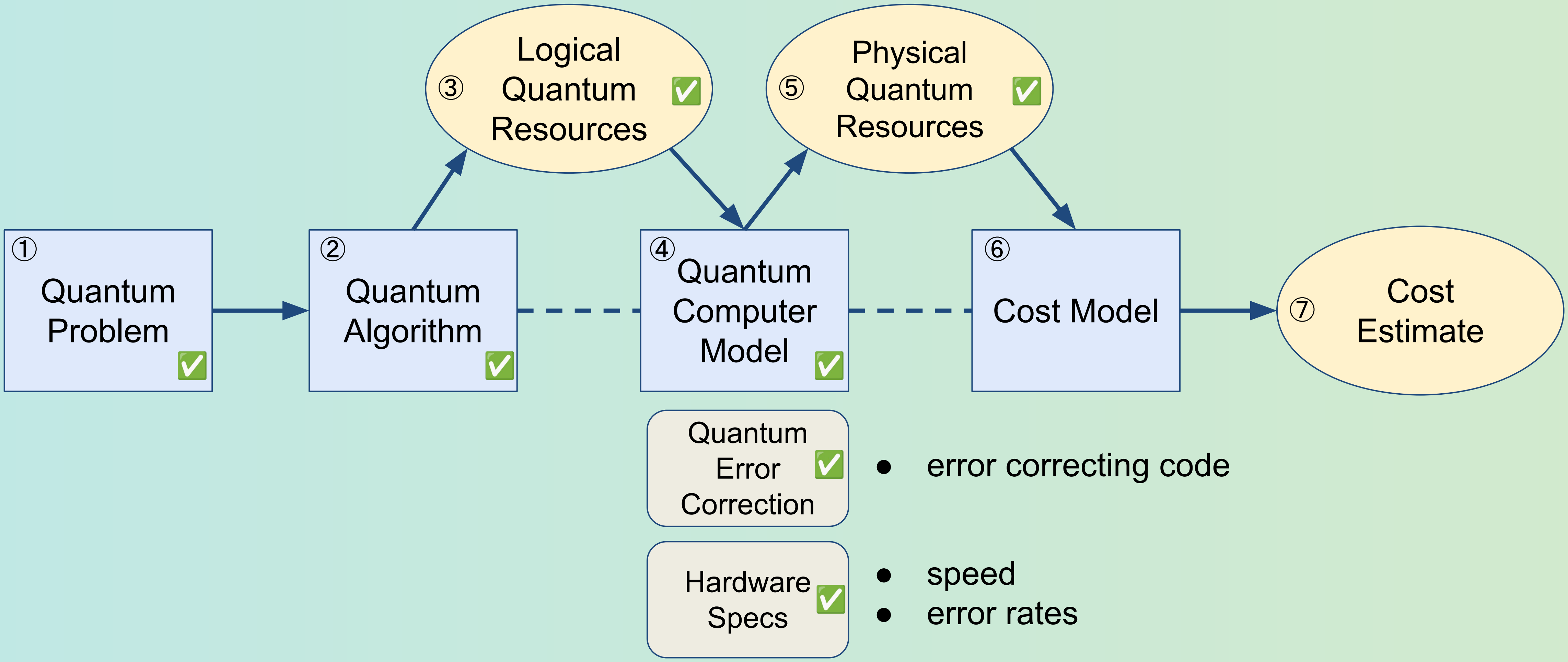
Today's quantum computers:

- 100 qubits, max 10^{-4}s
- 20 qubits, max 1s

Improvements required:

- 1,000x in qubits, 1,000,000x in time
- 2,000x in qubits, 10,000x in time

Flowchart for quantum computing cost estimation



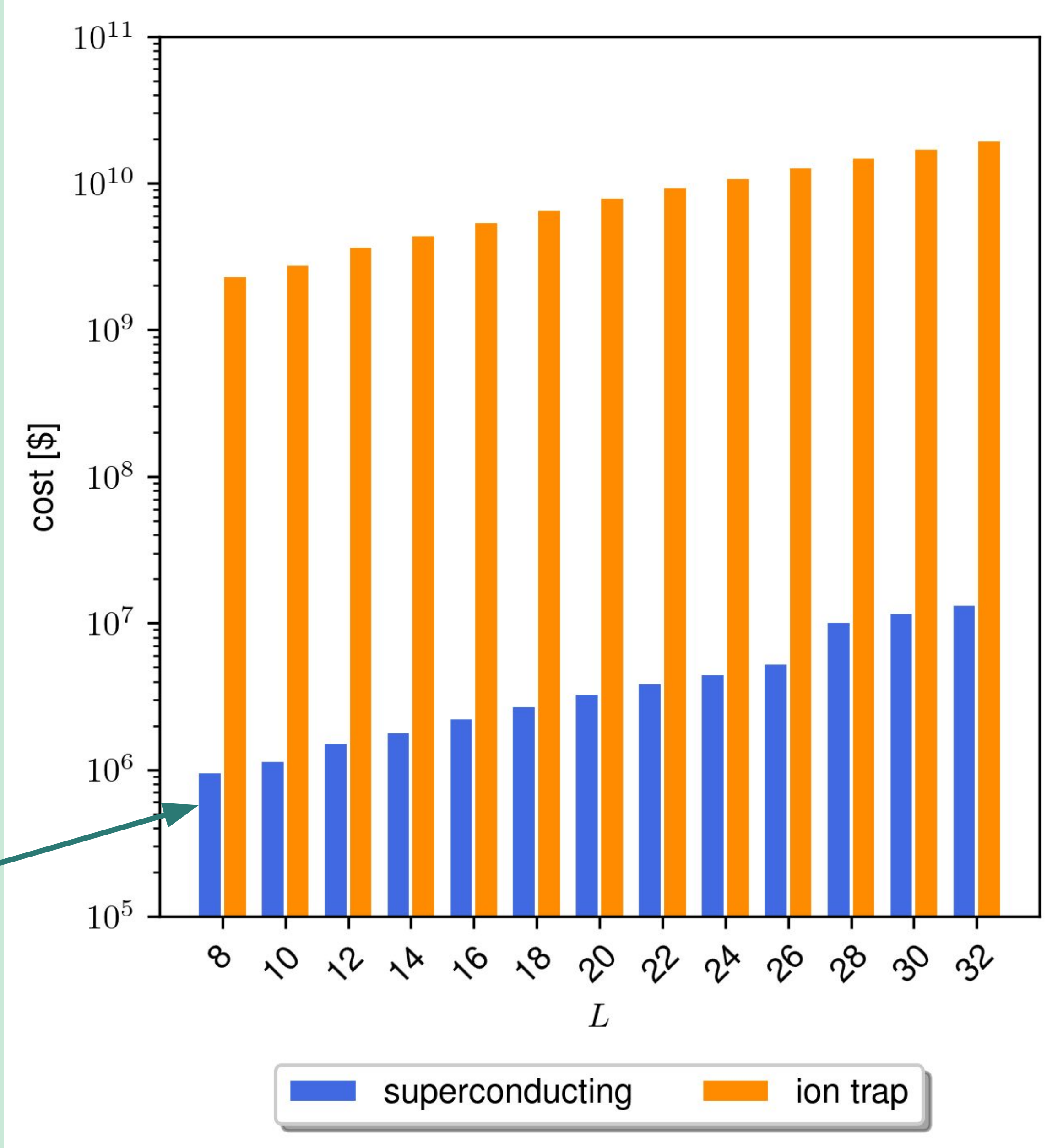
- error correcting code

- speed
- error rates

What does this cost?

Public Pricing data from Quantum Cloud Providers:

Technology	N_Q	Usage cost [$/qs]
Superconducting	8-80	0.05
Ion Traps	~20	10



Conclusions

- Developed new performance model to estimate cost of quantum computation
- Our resource and cost analysis projects that intractable quantum computation could be realized at $1M - not $1B!
- Many caveats and uncertainties remain:
  - does pricing model scale linearly?
  - will future QC architectures be modular?
  - improvements in QEC and algorithms?

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