2024 Energy-Efficient Computing for Science Workshop

Office of Advanced Scientific Computing Research (ASCR)

Basic Research Needs and the Costs of Quantum Computing

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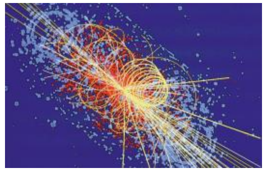
Why *quantum* computing?

- Proofs of quantum advantage in runtime
  (e.g., to find prime factors, solve linear systems of equations)

Quantum Algorithm Zoo
https://quantumalgorithmzoo.org



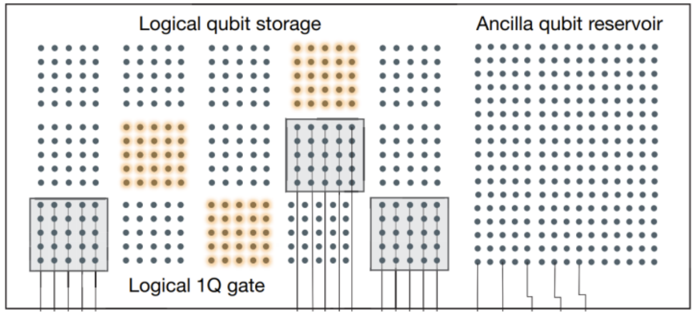
Quantum Simulation for High-Energy Physics

Christian W. Bauer *et al.*
PRX Quantum **4**, 027001 – Published 3 May 2023

- No alternative efficient classical methods to solve some problems
  (e.g., chemical reactions, high energy physics)

Logical quantum processor based on reconfigurable atom arrays

Nature **626**, 58–65 (2024)



- Experimental progress!
  (e.g., towards error correction)

REPORT FOR THE ASCR WORKSHOP ON

Basic Research Needs in Quantum Computing and Networking

JULY 11–13, 2023

- Pavel Lougovski (co-chair), Amazon Web Services
- Ojas Parekh (co-chair), Sandia National Laboratories

Five **Priority Research Directions** across a series of themes

Quantum computing stack:

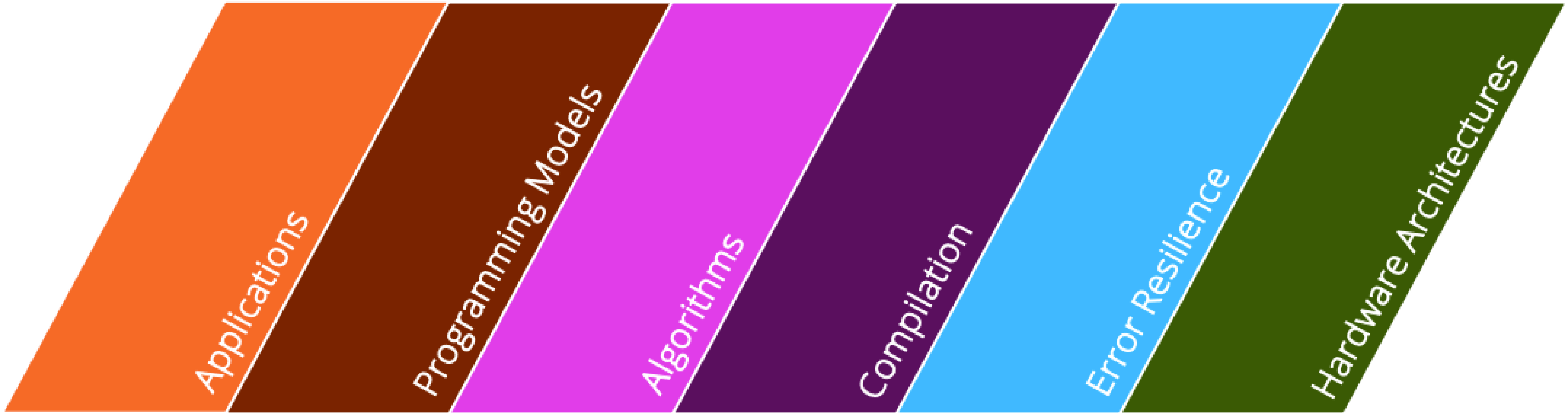


Figure 1: A stack depicting critical components of a quantum computing or networking system capable of end-to-end application impact.

Priority Research Directions

Grand Challenge: Demonstrate a rigorously quantifiable, end-to-end quantum advantage relative to state-of-the-art classical counterparts, particularly for problems with practical or scientific significance for which asymptotic exponential quantum advantages have been established.

Priority Research Direction 1

PRD 1. End-to-end software toolchains to program and control quantum systems and networks at scale

Driving questions How can we design expressive programming models and languages to attract broad user bases and facilitate quantum algorithm design and implementation? How can we incorporate these into end-to-end toolchains to produce resource-efficient quantum programs?

Priority Research Direction 3

PRD 3. Benchmarking, verification, and simulation methods to assess quantum advantages

Driving questions How can we fairly assess quantum advantage relative to classical capabilities, especially as underlying technologies evolve and scale from the noisy intermediate-scale quantum (NISQ) to fault-tolerant paradigms? How can we measure progress of quantum systems toward demonstrating quantum advantage, across the computing and networking stacks? Which representative scientific use cases serve as insightful and scalable benchmarks for quantum computing and networking applications? How can we verify demonstrations of quantum advantage? How can we leverage numerical simulation of quantum systems to validate large-scale quantum applications?

Priority Research Direction 5

PRD 5. Hardware and protocols for next-generation quantum networks

Driving questions Can quantum repeater hardware be built to achieve entanglement distribution rates higher than those of "repeat-until-success" direct transmission experiments? What software and hardware, besides the repeaters, are needed to build scalable quantum networks? What applications and advantages will those networks enable? What kinds of distributed quantum computing models will result in novel quantum applications and advantages?

Priority Research Direction 2

PRD 2. Efficient algorithms delivering quantum advantages

Driving questions What classes of existing and understudied scientific applications admit substantial quantum advantages over conventional classical computing paradigms? How can we design novel algorithms and supporting mathematical models to realize such advantages? Are there any provable or empirical barriers to quantum advantages? What are the physical resource requirements of practical implementations of such algorithms, including numbers of physical qubits and quantum circuit depth?

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quantum advantages have primarily focused on improving execution time. Advantages concerning other critical resources, such as quality/accuracy of solution, energy consumption[a], space/memory, or communication, are understudied, especially in the context of quantum networking.

[a]The energy consumption of quantum computing is an often-overlooked but critical parameter in developing sustainable computing ecosystems.

Priority Research Direction 4

PRD 4. Resilience through error detection, prevention, protection, mitigation, and correction

Driving questions How can we enhance the resilience of quantum systems to noise and errors to relieve scalability and quantum advantage bottlenecks? What kinds of quantum algorithm codesign techniques can aid in yielding resilient quantum systems?

Error Correction Zoo
https://errorcorrectionzoo.org

Noise resilience (PR4) versus runtime (PR2):

Resilience-Runtime Tradeoff Relations for Quantum Algorithms

Luis Pedro García-Pintos, Tom O'Leary, Tanmoy Biswas, Jacob Bringewatt, Lukasz Cincio, Lucas T Brady, Yi-Kai Liu

On the costs of quantum computing

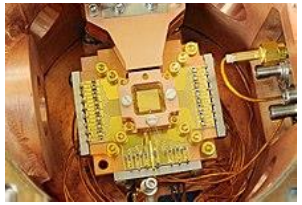
[a]The energy consumption of quantum computing is an often-overlooked but critical parameter in developing sustainable computing ecosystems.

On the costs of quantum computing

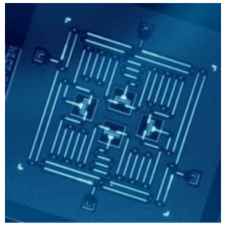
- End-to-end energetic estimates

Estimate costs of each layer of a Q computer (fridges, lasers, ancillary qubits, ...)

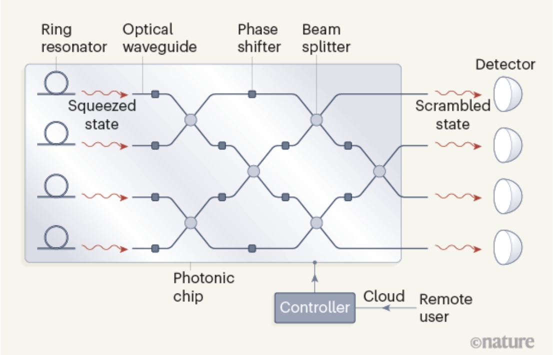
trapped ions $\neq$ superconducting qubits $\neq$ photonic



NIST

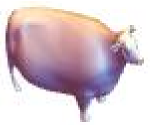


npj Quantum Information (2017)



Nature 591, 40-41 (2021)

- Costs to performing operations



Cost to run, e.g., a gate or an annealing schedule

- Minimum theoretical costs of a computation

Processing information incurs a cost

Andre314 @ mathematica.stackexchange

On the minimum costs of quantum computing

The Thermodynamics of Computation—a Review

Charles H. Bennett

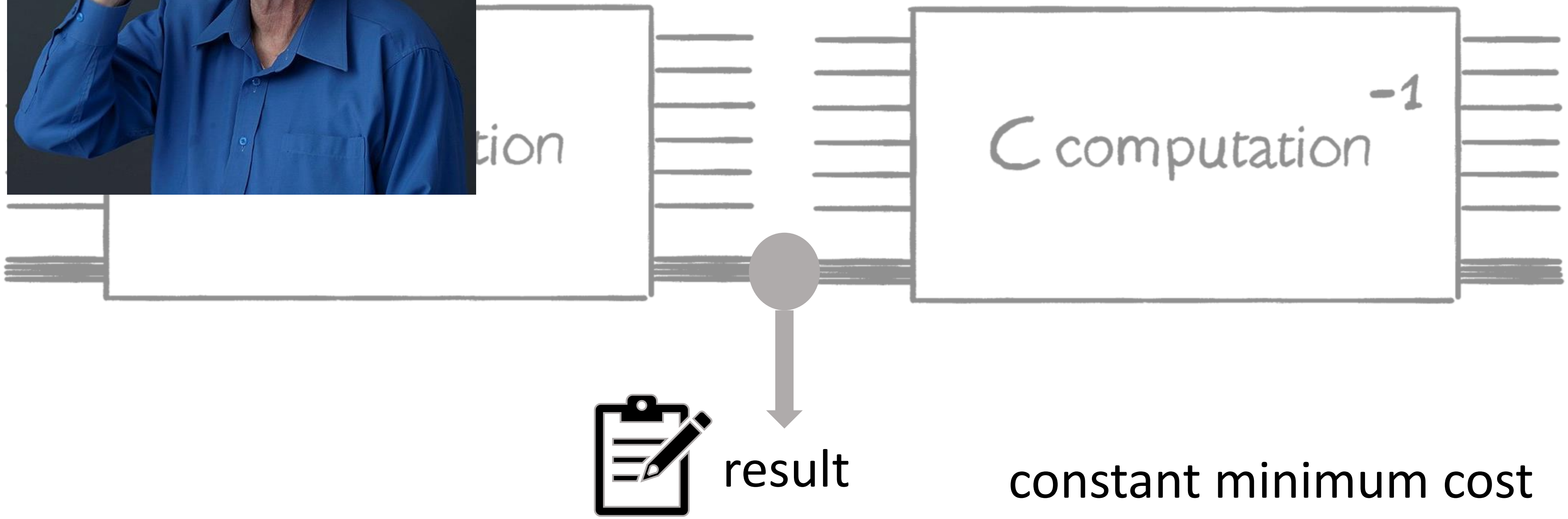
Computers may be thought of as engines for transforming free energy into waste heat and mathematical work. Existing electronic computers dissipate energy

Logically reversible operations can be done without thermodynamic cost, but **erasing information costs**!

$$\text{Landauer: } W \geq K_B T \log 2$$

Zero minimum cost

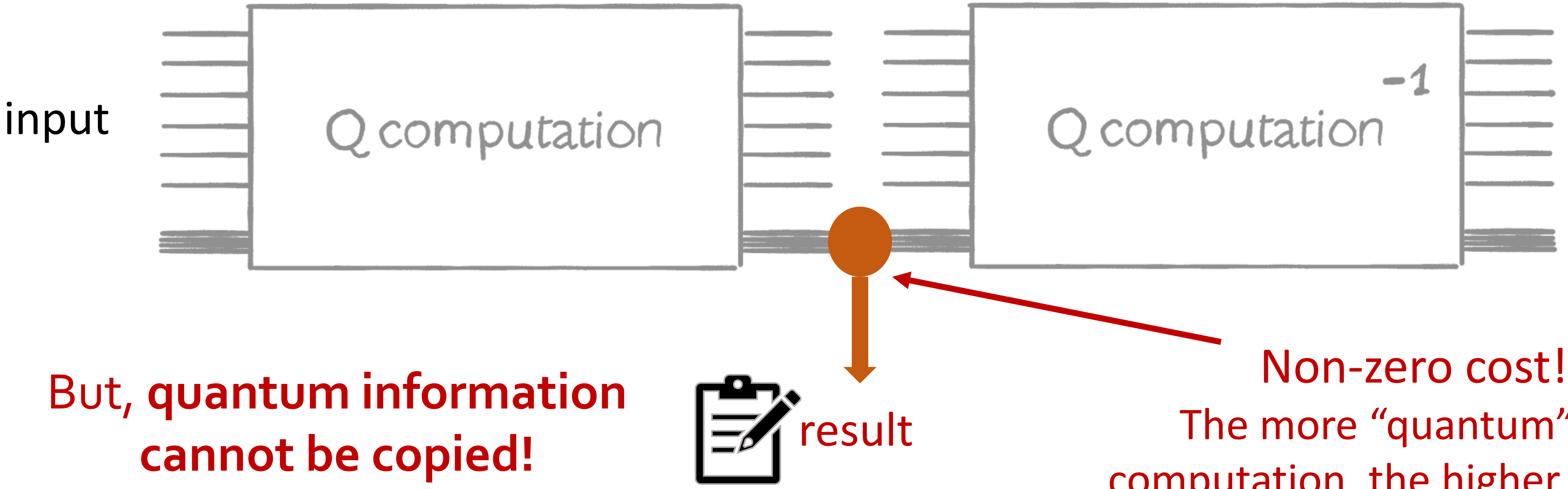
input



input

constant minimum cost

On the minimum costs of quantum computing



But, **quantum information cannot be copied!**

Non-zero cost!
The more "quantum" the computation, the higher the cost

Ongoing work: one can decrease the minimum cost at the expense of time or space

(with S. Slezak, T. Biswas, others)

(longer computations or more qubits)

- Proofs of quantum advantage

- Experimental progress

- Priority Research Direction 2: $\underbrace{\text{efficiency of quantum computing?}}$

#QEI
the quantum energy initiative

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Thank you!

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