Introduction to quantum information science

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Research Groups

- High Energy Theory
- Condensed Matter
- Cosmology
- Particle Physics
- Quantum Information Science

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17 Postdocs, 3 Ph.D. Students, 5 Visitors, and 11 Part-time Researchers

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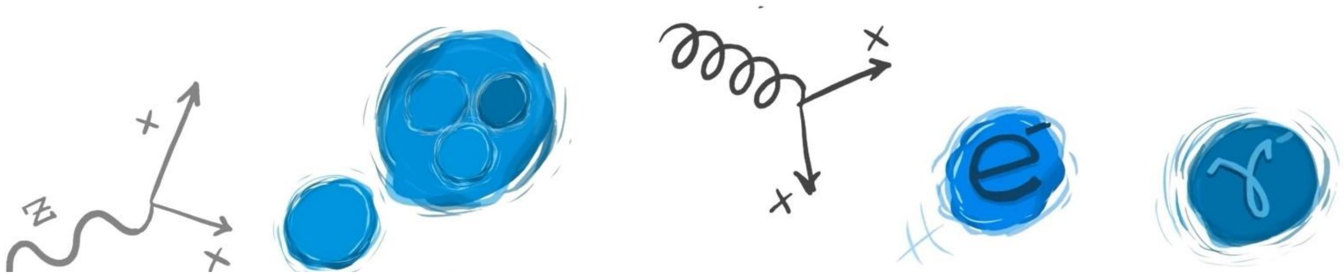
School and Workshop on Quantum Information and Quantum Gravity
Shahrivar 4-8, 1402

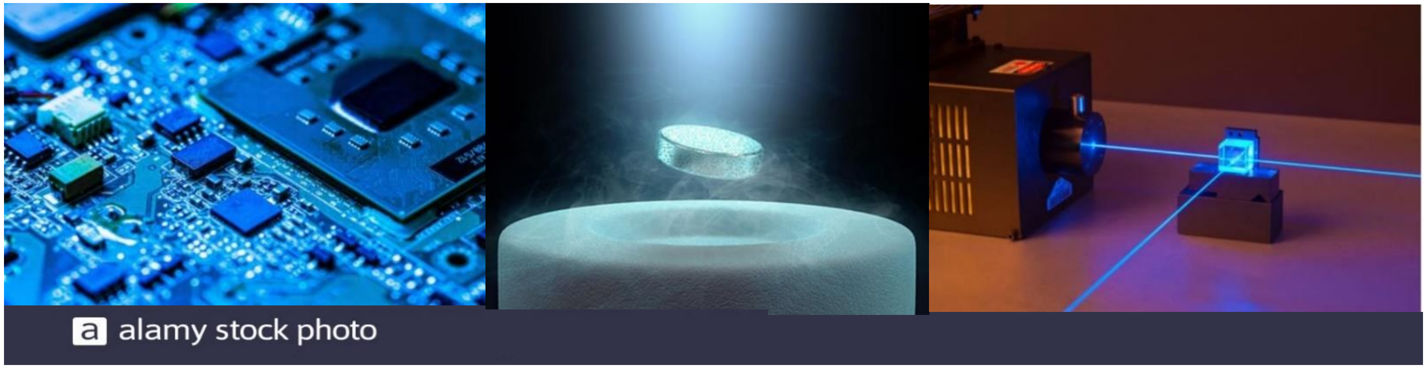
Quantum mechanics

A fundamental theory for describing nature.

Particle physics, condensed matter, quantum optics, …



Applications: semiconductors, superconducting materials, laser, …



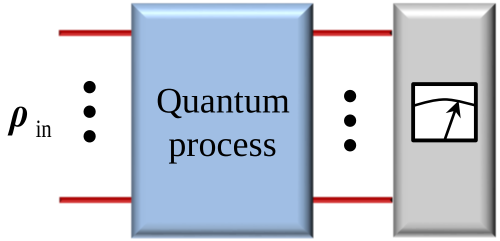
Quantum vs. Classical

W.H. Zurek, arXiv:quant-ph/0306072 (2003).

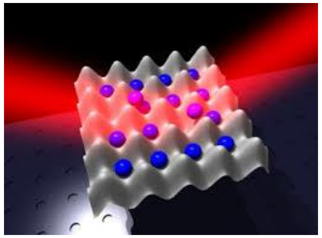
Quantum information science

What are the scientific and technological implications if we can manipulate and control complex quantum systems to behave the way that we want instead of what they do naturally?

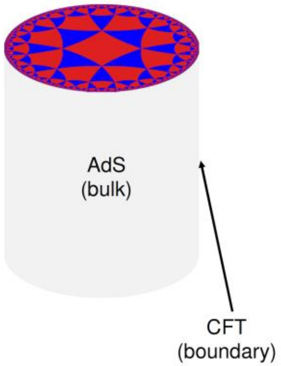
- Entanglement Theory, Quantum Control Theory, Quantum Estimation, Open Quantum Systems, Quantum Information Theory, …



- Quantum Computation, Quantum Simulation, Quantum Communication, Quantum Sensing, …



- Applications in condensed matter, high-energy physics, quantum gravity, …

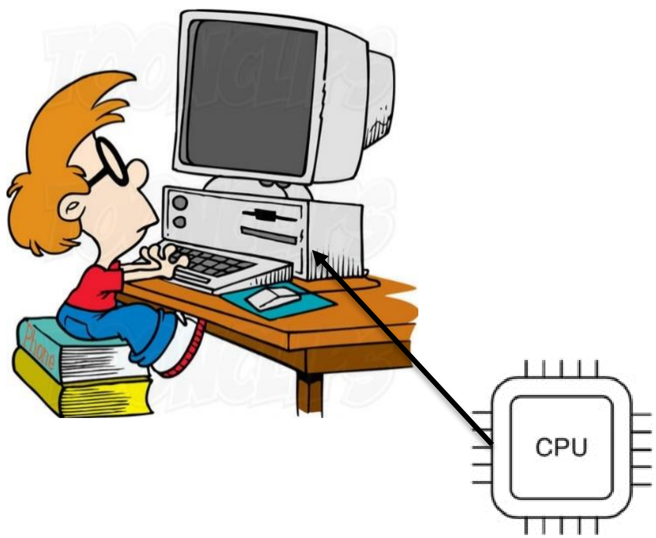


Quantum computational supremacy

Based on computational complexity arguments, it is strongly believed that quantum computers can perform <u>certain computational tasks</u> faster than classical computers.

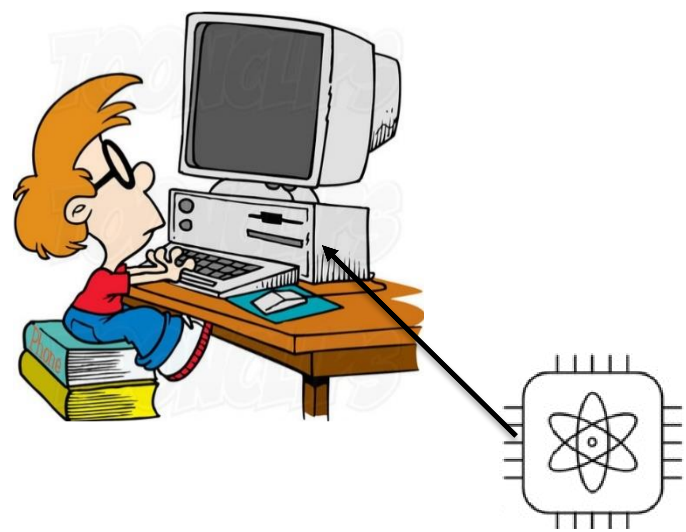
Factoring problem: Find prime factors, $N = p \times q$

Classical computer



500 digits in 10^{12} CPU years (2.2 GHz)

Quantum computer

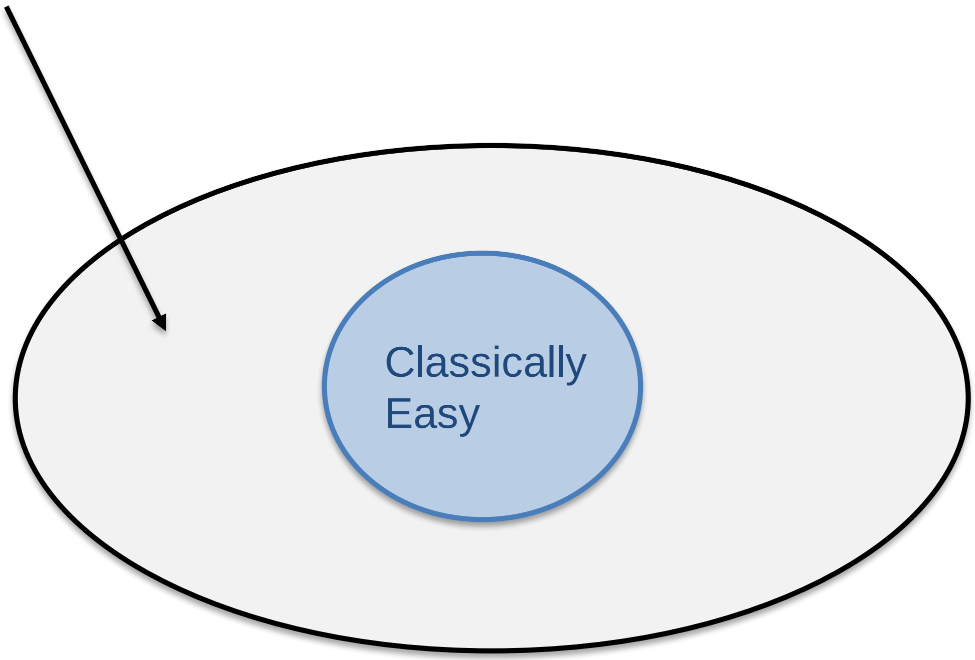


500 digits in 2 seconds

Computational complexity

Easy = Solvable in a time that is a polynomial function of the size of the problem

Hard = not easy (not efficiently solvable)



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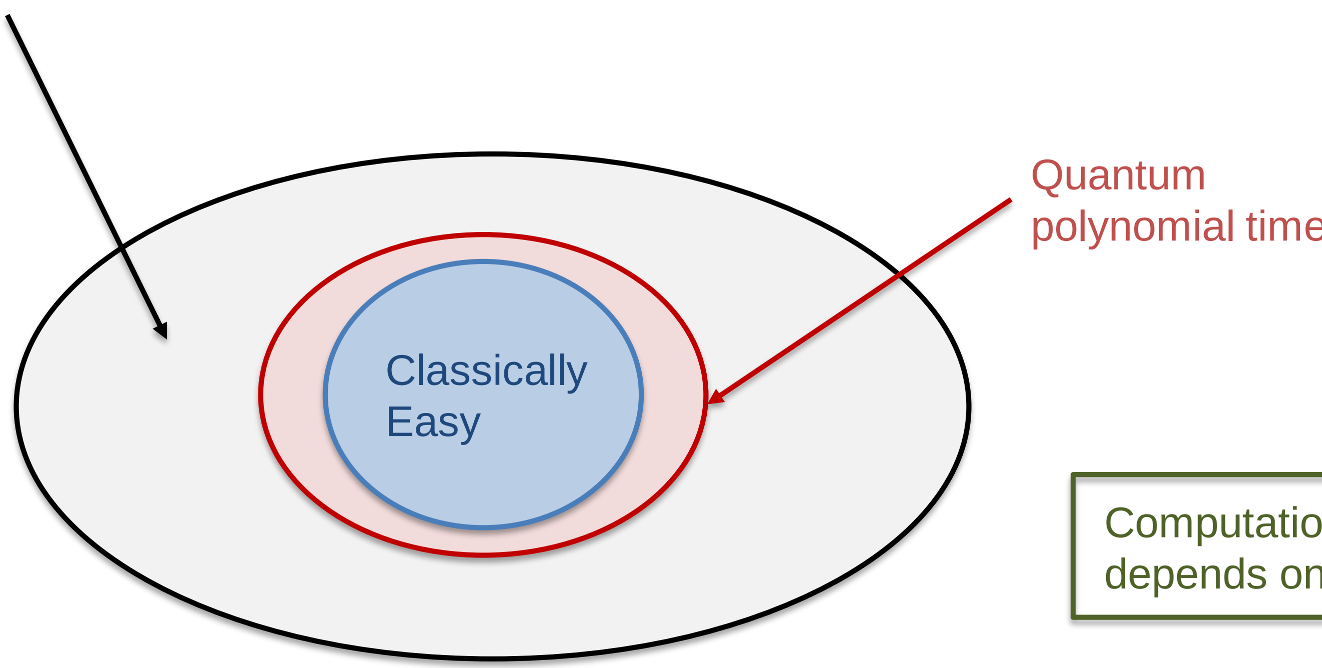

Computational complexity depends on physical law!

Computational complexity

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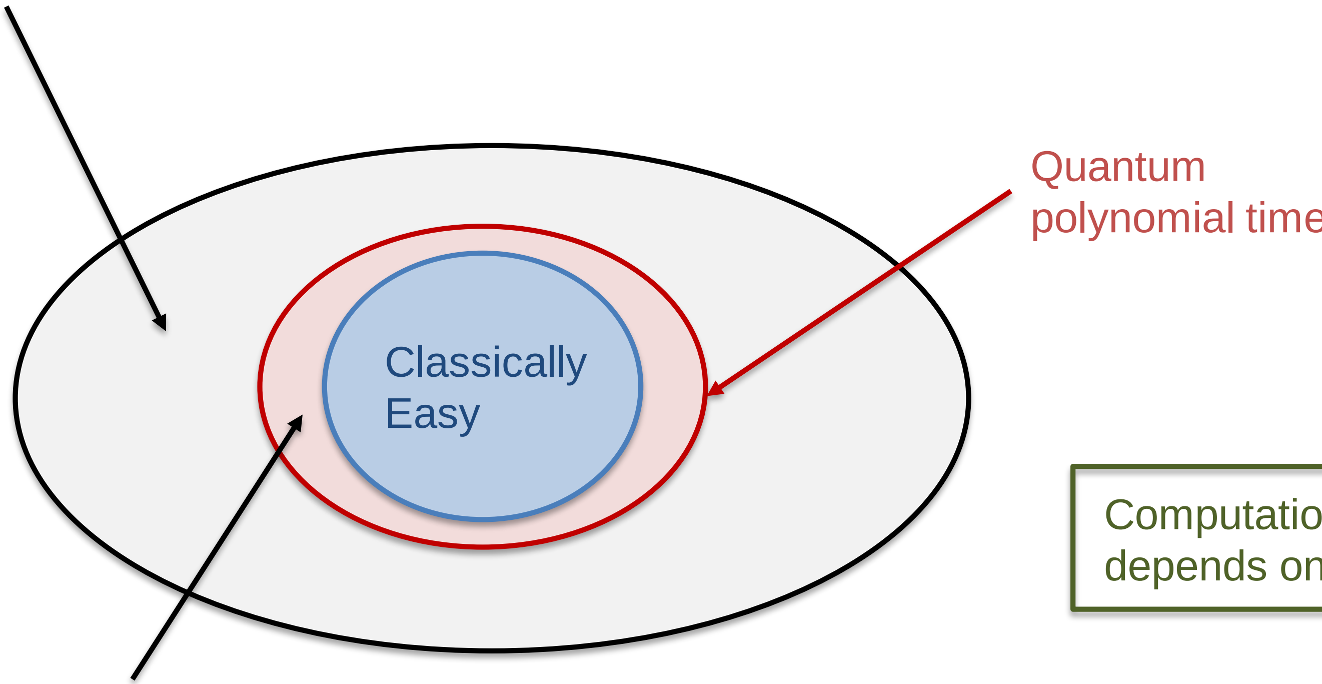
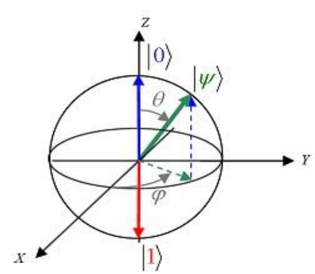


Computational complexity depends on physical law!

Factoring problem that is important for public-key cryptography!
But it requires around **20 million physical qubits**!

$$|\psi\rangle = a|0\rangle + b|1\rangle$$



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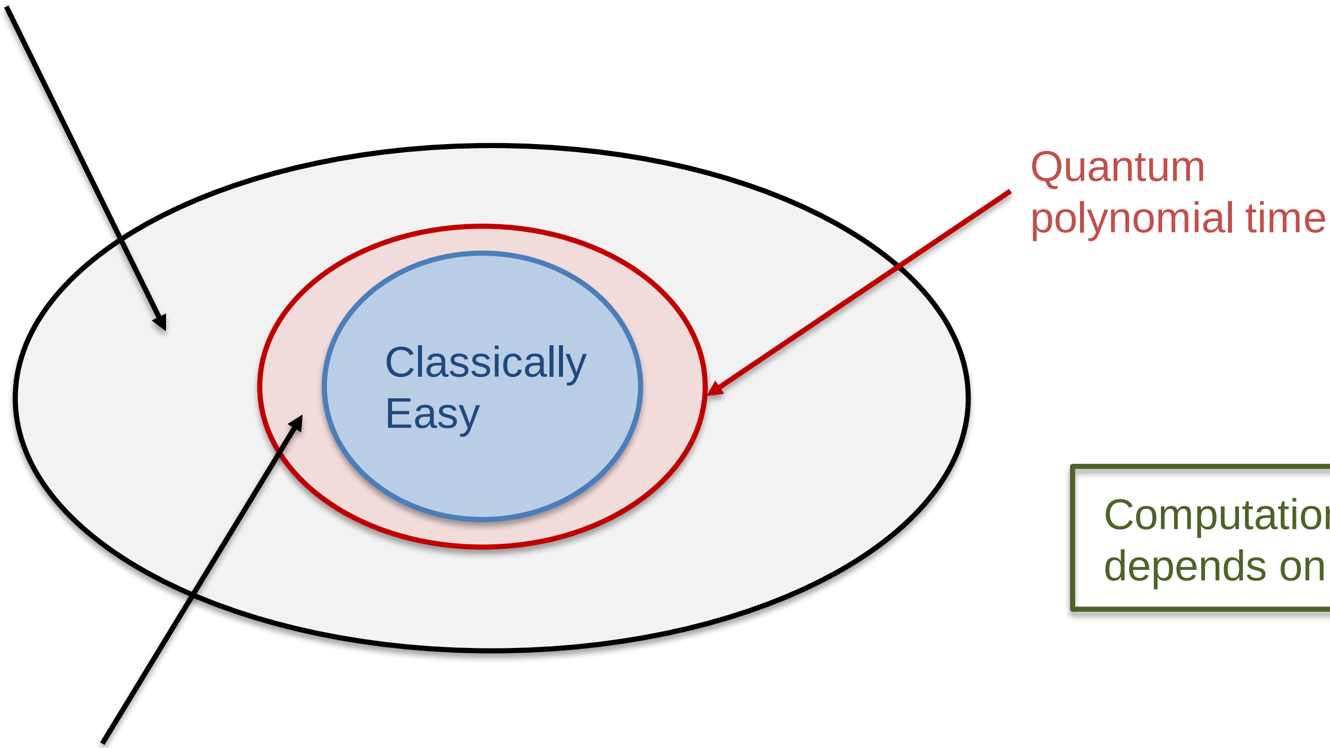
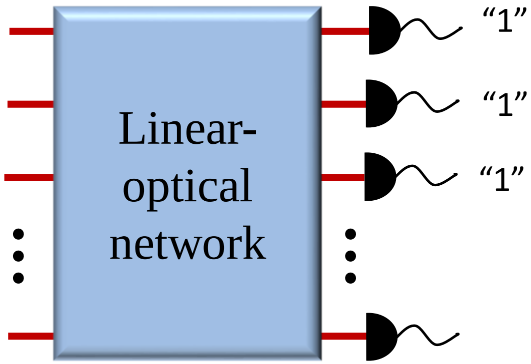


Computational complexity depends on physical law!

Simulation of many physical systems!

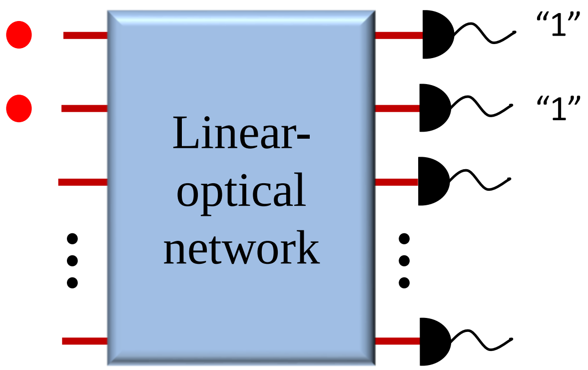
Boson sampling



$$U = \begin{pmatrix} U_{11} & U_{12} & U_{13} & . & . & U_{1M} \\ U_{21} & U_{22} & U_{23} & . & . & . \\ U_{31} & U_{32} & U_{33} & . & . & . \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ U_{M1} & . & . & . & . & U_{MM} \end{pmatrix}$$

The transfer matrix

Boson sampling



$$P(1,1) = |U_{11}\,U_{22} + U_{12}U_{21}|^2$$

$$U = \begin{pmatrix} U_{11} & U_{12} & U_{13} & . & . & U_{1M} \\ U_{21} & U_{22} & U_{23} & . & . & . \\ U_{31} & U_{32} & U_{33} & . & . & . \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ U_{M1} & . & . & . & . & U_{MM} \end{pmatrix}$$

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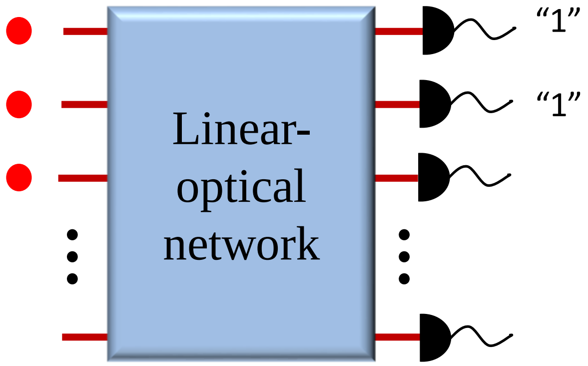
Boson sampling



$$p = \left| U_{11}U_{22}U_{33} + U_{11}U_{23}U_{32} + U_{12}U_{21}U_{33} + U_{12}U_{23}U_{31} + U_{13}U_{22}U_{31} + U_{13}U_{21}U_{32} \right|^2 = \left| \sum_{\sigma \in S_3} \prod_{i=1}^{3} A_{i,\sigma(i)} \right|^2 = \left| \mathrm{Per}\left([U]_{3\times 3} \right) \right|^2$$

$$U = \begin{pmatrix} U_{11} & U_{12} & U_{13} & . & . & U_{1M} \\ U_{21} & U_{22} & U_{23} & . & . & . \\ U_{31} & U_{32} & U_{33} & . & . & . \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ U_{M1} & . & . & . & . & U_{MM} \end{pmatrix}$$

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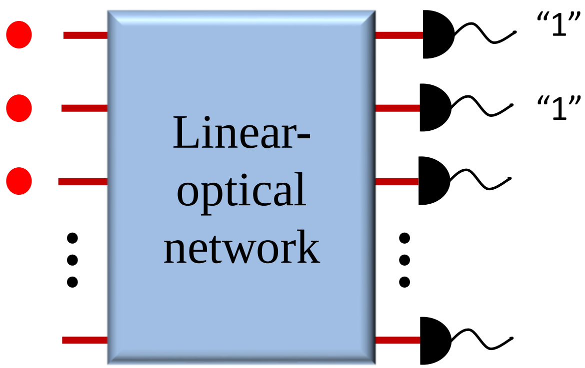
Boson sampling



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$$= \left| \sum_{\sigma \in S_3} \prod_{i=1}^{3} A_{i,\sigma(i)} \right|^2 = \left| \mathrm{Per}\left([U]_{3\times 3} \right) \right|^2$$

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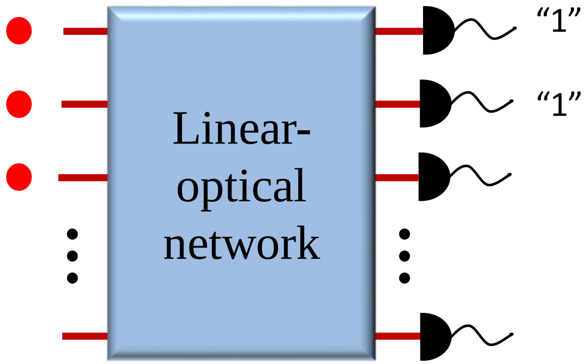
The transfer matrix

Ryser's algorithm evaluates permanents in $\mathcal{O}(2^{n-1}n^2)$ arithmetic operations.

Boson sampling



$$p = \left| U_{11}U_{22}U_{33} + U_{11}U_{23}U_{32} + U_{12}U_{21}U_{33} + U_{12}U_{23}U_{31} + U_{13}U_{22}U_{31} + U_{13}U_{21}U_{32} \right|^2$$

$$= \left| \sum_{\sigma \in S_3} \prod_{i=1}^{3} A_{i,\sigma(i)} \right|^2 = \left| \mathrm{Per}\left([U]_{3\times 3} \right) \right|^2$$

$$U = \begin{pmatrix} U_{11} & U_{12} & U_{13} & . & . & U_{1M} \\ U_{21} & U_{22} & U_{23} & . & . & . \\ U_{31} & U_{32} & U_{33} & . & . & . \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ U_{M1} & . & . & . & . & U_{MM} \end{pmatrix}$$

The transfer matrix

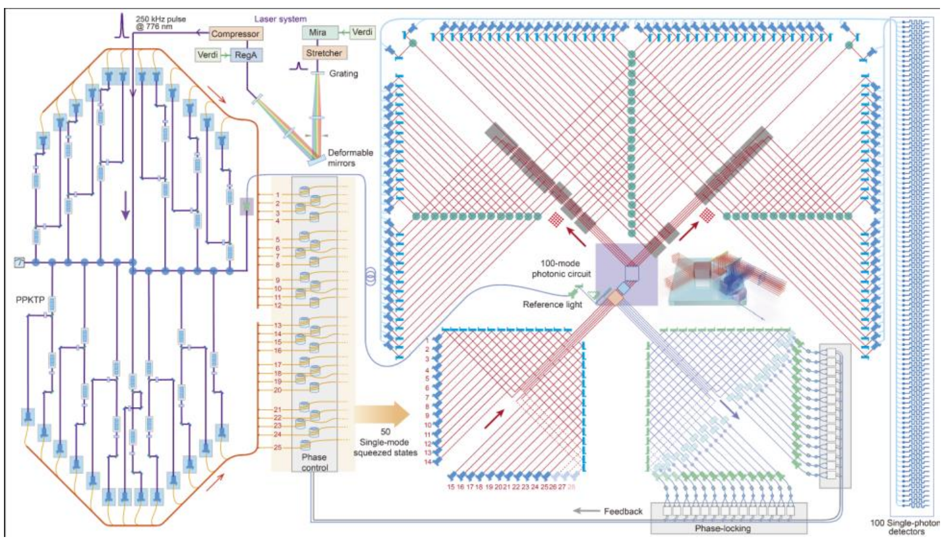
Ryser’s algorithm evaluates permanents in $\mathcal{O}(2^{n-1}n^2)$ arithmetic operations.

Sampling from the probability distribution of photon-counting events at the output of an *M*-mode linear-optical network for *N* input single photons ($N \ll M$) cannot be simulated efficiently classically [Aaronson & Arkhipov 2010].

Quantum computational advantage using photons

Cite as: H.-S. Zhong *et al.*, *Science* 10.1126/science.abe8770 (2020).

Quantum computers promises to perform certain tasks that are believed to be intractable to classical computers. Boson sampling is such a task and is considered as a strong candidate to demonstrate the quantum computational advantage. We perform Gaussian boson sampling by sending 50 indistinguishable single-mode squeezed states into a 100-mode ultralow-loss interferometer with full connectivity and random matrix—the whole optical setup is phase-locked—and sampling the output using 100 high-efficiency single-photon detectors. The obtained samples are validated against plausible hypotheses exploiting thermal states, distinguishable photons, and uniform distribution. The photonic quantum computer generates up to 76 output photon clicks, which yields an output state-space dimension of 10^{30} and a sampling rate that is ~10^{14} faster than using the state-of-the-art simulation strategy and supercomputers.



Questions

- What are resources for quantum computational speedups?

[S. R-K, T. C. Ralph and C. M. Caves, *Physical Review X* **6**, 021039 (2016)]

- How to develope similar protocols based on other physical systems?

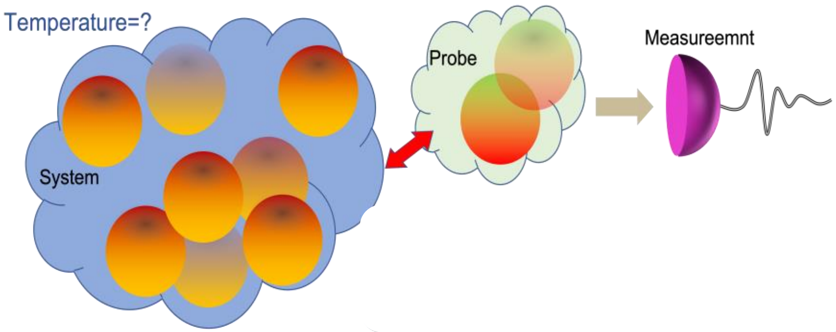
[A. P. Lund, A. Liang, S. R-K, T. Rudolph, J. L. O'Brien and T. C. Ralph, *Physical Review Letters* **113**, 100502 (2014)]

- How to characterize and verify quantum experiments?

[S. R-K, S. Baghbanzadeh, C. M. Caves, *Phys. Rev.* A **101**, 043809 (2020).]
[S. R-K, M. Mehboudi, D. De Santis, D. Cavalcanti, A. Acín, *Phys. Rev. A* **104**, 042212 (2021).]

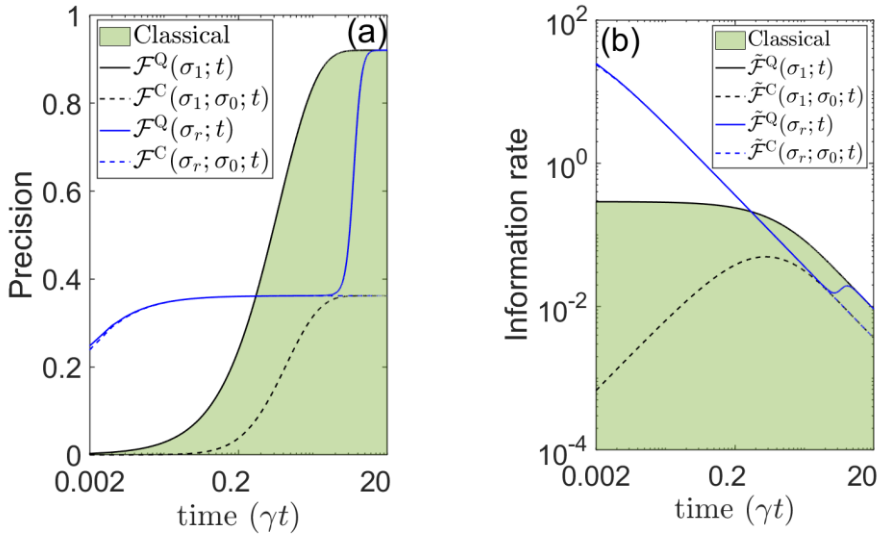
Nonequilibrium thermometry

Classical or quantum probe states?



The mean square error of the estimator function is given by the Cramér-Rao bound for $M = \tau/t$

$$\left\langle \left(\tilde{T}(\mathrm{x}) - T_0\right)^2 \right\rangle_{\mathrm{x}} \geq \frac{t}{\tau\, \mathcal{F}^C(\rho; \Pi; t)}$$



S. Mirkhalaf, M. Mehboudi, S. R-K, arxiv:2207.10742v1 (2022).

Summary

Quantum information science is a new way of thinking in physics with interesting and useful scientific and technological applications.

Thank you for your attention!