Classical Computers Very Likely Can Not Efficiently Simulate Multimode Linear Optical Interferometers with Arbitrary Inputs

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Buy This Book or the Cat Will (and Will Not) Die!

Schrödinger’s Killer App
Race to Build the World’s First Quantum Computer

7 ★★★★★★ REVIEWS!

“I found myself LAUGHING OUT LOUD quite frequently.”

“The book itself is fine and well-written … I can thoroughly recommend it.”
Classical Computers Can Very Likely Not Efficiently Simulate Multimode Linear Optical Interferometers with Arbitrary Inputs


• Why Linear Optics Should Suck at Quantum Computing
• Multiphoton Quantum Random Walks
• Chasing Phases — Schrödinger Picture
• It Gets Better — Heisenberg Picture
• What? The Fock!
• Slater Determinant vs. Slater Permanent
• Experiments and More Theory

Andrew White!
Quantum computers and intractable (\(NP\)-complete) computing problems

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(Received 16 June 1992)

In this paper we discuss physical aspects of intractable (\(NP\)-complete) computing problems. We show, using a specific model, that a quantum-mechanical computer can in principle solve an \(NP\)-complete problem in polynomial time; however, it would use an exponentially large energy for that computation. We conjecture that our model reflects a complementarity principle concerning the time and the energy needed to perform an \(NP\)-complete computation.

FIG. 2. A trajectory corresponding to a TSP route.
Factoring integers with Young’s N-slit interferometer

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(Received 19 May 1995; revised manuscript received 28 September 1995)

We show that a Young’s N-slit interferometer can be used to factor the integer N. The device could factor four- or five-digit numbers in a practical fashion. This work shows how number theory may arise in physical problems, and may provide some insight as to how quantum computers can carry out factoring problems by interferometric means. [S1050-2947(96)01806-9]
Blow Up In Space!

Why Linear Optics Should Suck at Quantum Computing

Optical simulation of quantum logic

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(Received 23 September 1997)

A constructive method for simulating small-scale quantum circuits by use of linear optical devices is presented. It relies on the representation of several quantum bits by a single photon, and on the implementation of universal quantum gates using simple optical components (beam splitters, phase shifters, etc.). This suggests that the optical realization of small quantum networks with present-day quantum optics technology is a reasonable goal. This technique could be useful for demonstrating basic concepts of simple quantum algorithms or error-correction schemes. The optical analog of a nontrivial three-bit quantum circuit is presented as an illustration. [S1050-2947(98)50403-9]
Linear Optics Alone Can NOT Increase Entanglement—Even with Squeezed-State Inputs!
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Multi-Fock-Input Photonic Quantum Pachinko

Detectors are Photon-Number Resolving
Generalized Hong-Ou-Mandel

\[ |\psi\rangle_{\text{out}} = \sqrt{\frac{3}{8}} |4\rangle_A |0\rangle_B - \frac{1}{2} |2\rangle_A |2\rangle_B + \sqrt{\frac{3}{8}} |0\rangle_A |4\rangle_B \]

No odds! (But we’ll get even.)

NOON Components Dominate! (Bat State.)
Noninteracting Bosons & Linear Interferometer? My Assets!

A Revolution in Nonlinear Optics at the Few Photon Level: No Longer Limited by the Nonlinearities We Find in Nature!

\[ Q = \frac{\pi \hbar}{2} (5 \hat{n} - \hat{n}^2) \]

KLM CSIGN: Self Kerr

\[ Q = \frac{\pi \hbar}{2} (3 + a_b^\dagger (1 - \hat{n}_b) + (1 - \hat{n}_b) a_b) \hat{n}_a \]

Franson CNOT: Cross Kerr

\[ H_C \]
Computational Input

\[ H_A \]
Ancilla Input

\[ H_C \]
Computational Output

Measurement on \( H_A \)

NON-Unitary Gates ® Effective Nonlinear Gates
Noninteracting Bosons & Linear Interferometer?


Bosons on a Beamsplitter

\[ |\uparrow\rangle_{A_{\text{in}}} |\uparrow\rangle_{B_{\text{in}}} \]

\[ |\uparrow\uparrow\rangle_{A_{\text{out}}} |0\rangle_{B_{\text{out}}} + |0\rangle_{A_{\text{out}}} |\uparrow\uparrow\rangle_{B_{\text{out}}} \]

Hong-Ou-Mandel: Superposition Principle Does NOT Hold In the Usual Sense!

Noninteracting Bosons

\[ |\uparrow\rangle_{A_{\text{in}}} |\uparrow\rangle_{B_{\text{in}}} \]

\[ |\uparrow\downarrow\rangle_{A_{\text{out}}} |0\rangle_{B_{\text{out}}} \]

\[ |0\rangle_{A_{\text{out}}} |\uparrow\rangle_{B_{\text{out}}} \]

\[ |0\rangle_{A_{\text{out}}} |\uparrow\rangle_{B_{\text{out}}} \]
Schrödinger Picture: Feynman Paths

“One photon only ever interferes with itself.”
— P.A.M Dirac
Schrödinger Picture: Feynman Paths

HOM effect in two-photon coincidences

Two photons interfere with each other! (Take that — Dirac!)
Schrödinger Picture: Feynman Paths

Exploded Rubik’s Cube of Three-Photon Coincidences

Three photons interfere with each other!
(Take that and that — Dirac!)
How Many Paths? Let Us Count the Ways.

This requires 8 Feynman paths to compute.
Calculations go to Helena Handbasket!
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How Many Paths? Let Us Count the Ways.

$L$ is total number of levels.

$N+M$ is the total number of photons.
How Many Paths? Let Us Count the Ways.

Total Number of Paths

\[ P[L, N, M] = 2^{L(N+M)} \]

Choosing photon numbers \( N = M = 9 \) and level depth \( L = 16 \), we have \( 2^{288} = 5 \times 10^{86} \) total possible paths, which is about four orders of magnitude larger than the number of atoms in the observable universe.

So Much For the Schrödinger Picture!
Theorem 1  The exact BosonSampling problem is not efficiently solvable by a classical computer, unless $\mathsf{P}^\# \subseteq \mathsf{BPP}^{\mathsf{NP}}$ and the polynomial hierarchy collapses to the third level.

More generally, let $\mathcal{O}$ be any oracle that “simulates boson computers,” in the sense that $\mathcal{O}$ takes as input a random string $r$ (which $\mathcal{O}$ uses as its only source of randomness) and a description of a boson computer $A$, and returns a sample $\mathcal{O}_A(r)$ from the probability distribution $D_A$ over possible outputs of $A$. Then $\mathsf{P}^\# \subseteq \mathsf{BPP}^{\mathsf{NP}^\mathcal{O}}$. 

From the Quantum Blogosphere: http://quantumpundit.blogspot.com

“… you have to talk about the complexity-theoretic difference between the n*n permanent and the n*n determinant.” — Scott “Shtetl-Optimized” Aaronson

“What will happen to me if I don’t!?" — Jonathan “Quantum-Pundit” Dowling
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What? The Fock! — Heisenberg Picture

\[ M = 0 \]

\[ |N\rangle_1^0 |0\rangle_2^0 = (\hat{a}_1^{0\dagger})^N |0\rangle_1^0 |0\rangle_2^0 / \sqrt{N!} \]

**BS XFMRS**

\[ \hat{a}_1^{\dagger 0} = ir\hat{a}_1^{\dagger 1} - t\hat{a}_2^{\dagger 1} \]
\[ \hat{a}_2^{\dagger 0} = t\hat{a}_1^{\dagger 1} - ir\hat{a}_2^{\dagger 1} \]

\[ \prod_{\ell=1}^{6} |\psi\rangle_\ell^3 = \frac{1}{\sqrt{N!}} \left( -irt^2 \hat{a}_1^{\dagger 3} + r^2 t\hat{a}_2^{\dagger 3} + ir(t^2 - r^2)\hat{a}_3^{\dagger 3} - 2r^2 t\hat{a}_4^{\dagger 3} - irt^2 \hat{a}_5^{\dagger 3} - t^3 \hat{a}_6^{\dagger 3} \right)^N \prod_{\ell=1}^{6} |0\rangle_\ell^3 \]

Example: \( L=3 \). Powers of Operators in Expansion Generate Complete Orthonormal Set Of Basis Vectors for Hilbert Space.
What? The Fock! — Heisenberg Picture

The General Case:
Multinomial Expansion!

\[
|\psi\rangle^L = \frac{1}{\sqrt{N!}} \sum_{N=\sum_{\ell=1}^{2L} n_\ell}^N \left( \begin{array}{c} N \\ n_1, n_2, \ldots n_{2L} \end{array} \right) \prod_{1\leq k \leq 2L} (\alpha_k^L \hat{a}_k^L)^{n_k} |0\rangle^L
\]

\[
\text{dim} [H(N, L)] = \binom{N + 2L - 1}{N}
\]

Dimension of Hilbert State Space for \(N\) Photons At Level \(L\).
$N = 2L - 1$ Computationally Complex Regime

$$\text{dim}[H(N)] \sim \frac{2^{2N}}{\sqrt{\pi N}} \ll 2^{N^2/2} \sim P[N]$$

$L = 69$ and fix $N = 2L - 1 = 137$

$$\text{dim}[H(137)] \sim 10^{81} \ll 4 \times 10^{2845} \sim P[N]$$

The Heisenberg and Schrödinger Pictures are NOT Computationally Equivalent.

(This Result is Implicit in the Gottesman-Knill Theorem.)

This Blow Up Does NOT Occur for Coherent or Squeezed Input States.
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What? The Fock! — Heisenberg Picture

Coherent-State No-Blow Theorem!

\[ \hat{D}_1^0 (\beta) = \exp \left( \beta \hat{a}_1^+ - \beta^* \hat{a}_1 \right) \]

\[ \hat{D}_1^0 (\beta) |0\rangle_1 |0\rangle_2 \]

\[ |\beta|^2 = \bar{n} = N = 2L + 1 \]

\[ |\psi\rangle^L = \exp \left( \beta \sum_{\ell=1}^{2L} \alpha_\ell \hat{a}_\ell^+ - \text{H.c.} \right) |0\rangle^L = \prod_{\ell=1}^{2L} \exp (\beta \alpha_\ell \hat{a}_\ell^+ - \text{H.c.}) |0\rangle^L = \prod_{\ell=1}^{2L} \hat{D}_\ell^L (\beta \alpha_\ell) |0\rangle^L = \prod_{\ell=1}^{2L} |\beta \alpha_\ell\rangle^L \]

Displacement Operator

Input State

Computationally Complex?

Output is Product of Coherent States: Efficiently Computable
What ? The Fock ! — Heisenberg Picture

Squeezed-State No-Blow Theorem!

\[ \hat{S}_1^0 (\xi) = \exp \left[ \left( \xi^* (\hat{a}_1^0)^2 - \xi (\hat{a}_1^{+0})^2 \right) / 2 \right] \]

Input State

\[ |\xi\rangle_1^0 |0\rangle_2^0 = \hat{S}_1^0 (\xi) |0\rangle_1^0 |0\rangle_2^0 \]

\[ \bar{n} = N = 2L + 1 \]

Squeezed Vacuum Operator

Computationally Complex?

Output Can Be Efficiently Transformed into \(2L\) Single Mode Squeezers: Classically Computable.
News From the Quantum Complexity Front!? 

Ref. A: “… classical computers cannot efficiently simulate linear optics interferometer … unless the polynomial hierarchy collapses… I cannot recommend publication of this work.”

Response to Ref A: “… very few physicists know what the polynomial hierarchy is … Physical Review is … not a computer science journal.

Ref: B: “… a much more physical and accessible approach to the result. If the authors … bolster their evidence … the manuscript might be suitable for publication in Physical Review A.
Hilbert Space Dimension Not the Whole Story: Multi-Particle Wave Functions Must be Symmetrized!

Bosons (Total WF Symmetric)

\[ |\uparrow\rangle_{A_{in}} |\uparrow\rangle_{B_{in}} + |0\rangle_{A_{out}} |\uparrow\rangle_{B_{out}} + |\uparrow\rangle_{A_{out}} |\uparrow\rangle_{B_{out}} \]

Spatial WF Symmetric (Bosonic)

\[ |\uparrow\rangle_{A_{in}} |\downarrow\rangle_{B_{in}} - |\downarrow\rangle_{A_{in}} |\uparrow\rangle_{B_{in}} \]

Spatial WF AntiSymmetric (Bosonic)

Fermions (Total WF AntiSymmetric)

\[ |\uparrow\rangle_{A_{in}} |\uparrow\rangle_{B_{in}} + |\downarrow\rangle_{A_{in}} |\downarrow\rangle_{B_{in}} \]

Spatial WF AntiSymmetric (Fermionic)

\[ |\uparrow\rangle_{A_{out}} |\downarrow\rangle_{B_{out}} - |\downarrow\rangle_{A_{out}} |\uparrow\rangle_{B_{out}} + |\uparrow\rangle_{A_{out}} |\downarrow\rangle_{B_{out}} \]

Spatial WF Symmetric (Bosonic)

Effect Explains Bound State Of Neutral Hydrogen Molecule!
Fermion Fock Dimension Blows Up Too!?

\[
\text{dim}[H(N,L)] = \left(\frac{2L}{N}\right)^L \sim 2^{2N}/\sqrt{\pi N}
\]

Choosing Computationally Complex Regime: \( N = L \).

Hilbert Space Dimension Blow Up Necessary but NOT Sufficient for Computational Complexity — Gottesman & Knill Theorem
A Shortcut Through Hilbert Space? Treat as Input-Output with Matrix Transfer!

$$|\psi\rangle^\text{f/b}_{\text{in}}$$

$$|\psi\rangle^\text{f/b}_{\text{out}} = M_1 M_2 M_3 |\psi\rangle^\text{f/b}_{\text{in}}$$

Efficient!!! $O(L^3)$
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Must Properly Symmetrize Input State!

\[ |\psi\rangle_{in}^{f} = \text{Totally Anti-Symmetric} \rightarrow \text{Slater Determinant of Matrix} \]

\[ |\psi\rangle_{in}^{b} = \text{Totally Symmetric} \rightarrow \text{'Slater' Permanent of Matrix} \]

\[ |\psi\rangle_{out}^{f} = \text{Totally Anti-Symmetric} \]

\[ |\psi\rangle_{out}^{b} = \text{Totally Symmetric} \]

BS XFRMs Insure Proper Symmetry All the Way Down

Take coherence length $>> L$
Laplace Decomposition

Determinant: $(2L)! \text{ Steps}$

Permanent: $(2L)! \text{ Steps}$
Slater Determinant vs. ‘Slater’ Permanent

Fermions:
- Dim(H) exponential
- Anti-Symmetric Wavefunction
- Slater Determinant: $O(L^2)$
- Gaussian Elimination Does Compute!

Bosons:
- Dim(H) exponential
- Symmetric Wavefunction
- Slater Permanent: $O(2^L L^2)$
- Ryser’s Algorithm (1963) Does NOT Compute!

Hilbert Space Dimension Blow Up Necessary but NOT Sufficient!
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Publication Sampling 2013–2014

Inefficiency of classically simulating linear optical quantum computing with Fock-state inputs; Gard BT, …, Dowling JP; PRA 89 022328; 2014.

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Boson sampling on a chip; Ralph, T. C.; NATURE PHOTONICS 7; Page: 514; 2013.

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Integrated multimode interferometers with arbitrary designs for photonic boson sampling
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Quantum random walks with multiphoton interference and high-order correlation functions; Gard BT, …, Dowling JP; JOSA B 30; 1538; 2013.

The rise of the boson-sampling computer; PHOTONICS SPECTRA 47; 33; 2013.

Photonic Boson Sampling in a Tunable Circuit; Broome MA, …, White AG; SCIENCE 339; 6121; 794 2013.

3-Photon Sampling Schmämpling!

Only ONE Photon Fock State Input is Heralded & No Guarantee it is a Single Photon!

Aaronson’s Three-Photon Boson Sampling Requires Three Heralded Single-Photon Fock Inputs. Input Here is a Unknown-Number-Photon-Added Two-Mode Squeezed Vacuum.
3-Photon Sampling Schmämpling!

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To Implement Aaronson’s Protocol All Single Photons Must Be Heralded by PNRDs
Cat state sampling in the Fock limit

Keith R. Motes,¹ Paul Knott,² Jonathan P. Dowling,³,⁴ William J. Munro,² and Peter P. Rohde¹

arXiv:1310.0297

FIG. 1: The boson-sampling model. A series of single photon and vacuum states are evolved through a linear optics network, $U$, and the output distribution is sampled via number-resolved coincidence photodetection.

FIG. 2: Model for generalised boson-sampling using superpositions of coherent states.

WHY DID YOU SAMPLE MY DATA?
Boson-sampling with photon-added coherent states

Kaushik P. Seshadreesan,1 Jonathan P. Olson,1 Keith R. Motes,2 Peter P. Rohde,2,∗ and Jonathan P. Dowling1,3

arXiv:1402.0531

FIG. 1: Preparation of a photon added coherent state (PACS). A coherent state and a single photon state are mixed on a beamsplitter and heralded upon detecting no photon at one of the outputs. This heralds the preparation of the PACS in the other output.

\[ \hat{U} \left( \prod_{i=1}^{n} \frac{\hat{a}_i^\dagger}{\sqrt{1 + |\alpha^{(i)}|^2}} \right) \hat{U}^\dagger \hat{U} |\alpha^{(1)}\rangle_1 \otimes |\alpha^{(2)}\rangle_2 \otimes \ldots |\alpha^{(m)}\rangle_m \]

AA's exact boson-sampling

another multimode coherent state

FIG. 2: (Color online) Wigner function of (top) a single-photon-added coherent state, (bottom) a coherent state, with amplitude $|\alpha|^2 = 0.25$. The former is seen to take negative values close to the phase space origin, while that of the latter is positive everywhere. $W(0)$ is at the center of the plane. Sampling $W(0)$ distinguishes between coherent states and photon-added coherent state.
Scalable boson-sampling with time-bin encoding using a loop-based architecture

Keith R. Motes,1 Alexei Gilchrist,1 Jonathan P. Dowling,2,3 and Peter P. Rohde1,*

arXiv:1403.4007

FIG. 2: (a) A fiber loop fed by a pulse train of single photons, each separated in time by τ (or length τ in units of c = 1). The box represents a dynamically controlled, variable reflectivity beamsplitter, given by the beamsplitter matrix $U_{BS}(t)$ at time $t$. The switching time of the beamsplitter must be less than τ to allow each time-bin to be individually addressed. (b) Expansion of the fiber loop architecture into its equivalent beamsplitter network, obtained by ‘unravelling’ the loop and mapping time-bins to spatial modes.

FIG. 3: (Color online) The equivalent beamsplitter representation for the fiber loop architecture. Closed circles represent beamsplitter operations, open circles are fully reflective operations, and the numbers represent the time-bin associated with a path. (a) A single loop is represented for $n$ photons in the pulse train. The first photon is deterministically coupled into the loop and interferes with the second photon. At this point some of the amplitude leaves the loop which represents the first time-bin. This process is repeated until the $n$th photon transverses the loop, whereby any remaining amplitude is deterministically coupled out. (b) The equivalent beamsplitter network of three consecutive loops with three input modes (horizontal lines, top-left). The lengths of the black lines represent time in units of $\tau$. The three modes on the left represent the pulse train of photons at the input of the device at the first round-trip. The first photon reaches the first beamsplitter at $\tau = 1$, the second photon reaches it at $\tau = 2$, and so on. The photons travel through the fiber loop network interacting arbitrarily, which yields an arbitrary Reck et al.-style decomposition.
In computer science, the renowned "extended Church-Turing thesis" says a Turing machine can perform a computation as efficiently as any physical device. Proof the thesis is wrong would come from showing a quantum machine solves a problem significantly faster than a classical one—and would shake up the current way in which computer scientists classify the difficulty of a problem. In *Physical Review Letters*, Chao Shen at the University of Michigan, Ann Arbor, and colleagues propose a way to make such a quantum machine with ions.

Shen et al.'s theorized machine would perform a task, first proposed in 2011, called boson sampling. Roughly, the idea is to start with an "input" of $N$ identical bosons, allow them to make a random walk and then find the probability (the "output") that they are distributed over a certain set of positions. The time it takes to calculate this probability on a classical machine grows exponentially with $N$, while an appropriately designed quantum machine could find a solution much more efficiently.

Boson sampling experiments have already been carried out with photons, but these tests involved, at most, four particles; according to theory, ten or more are needed to see a quantum speedup. Shen et al.'s boson sampling machine instead consists of a line of trapped ions, spaced roughly 10 micrometers apart. The "input" bosons are the quantized vibrations (phonons) in the ion string, which could be initialized by a laser; the "output" is the phonons' final states, which shift the atoms' internal energy levels and could therefore be read out with another laser. The authors argue that, using existing ion trap technology, their machine could handle 20 to 30 bosons. – Jessica Thomas
Boson Sampling With BECs

Bosonic Atoms Initialized in Optical Lattice

Atoms Dropped into Blue-Detuned Optical Linear Interferometer

High-Efficiency Detection with CCD Array
"Quantum Physics is NOT a Branch of Computer Science!"
— D.F.V. P.D.Q. P.A.M. James
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