Recent progress in photonic quantum computation

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Quantum and Linear-Optical Computation group

International Iberian Nanotechnology Laboratory (INL)
- Inter-governmental Lab in Braga, Portugal
- Member states: Spain, Portugal
- RTO – Research and Technology Organization
- About 450 staff/associates
- Food and environment monitoring, renewable energy, health, ICT, quantum materials, q. computation
Quantum and Linear-Optical Computation group

- Established at INL in July, 2019. Research lines:
  - Principles enabling photonic quantum computation
  - Information processing with integrated photonic chips
  - Resources in different models of quantum computation

+5 recently admitted PhD students

Alexandra da Costa Alves (Master’s)
Ana Filipa Carvalho (Master’s)
Mafalda da Costa Alves (Master’s)
José Guimarães (Master’s)
António Pereira (Master’s)

Ernesto Galvão (Group leader)
Rui Soares Barbosa (Staff Researcher)
Carlos Fernandes (PhD student)
Michael Oliveira (PhD student)
Filipa Peres (PhD student)

Secured funding for 3 postdocs

Anita Camillini
Raman Chaudhary
Angelos Bampounis
Rafael Wagner
Antonio Molero
Outline

- Quantum computer platforms: current state-of-play
- Quantum advantage: towards useful QC
- Photonic quantum computation
  - Boson sampling devices
  - Q. advantage from Gaussian Boson Sampling
- Photonic route towards scalable QC
Quantum computation: current status

**Ion Traps**

Few ions trapped in EM fields, addressed individually by lasers

- Electronic levels = qubits
- Motional degrees of freedom = qubit-qubit interactions
- Long history: atomic clocks. Extremely good gates, up to 32 qubits

Key companies: IonQ (USA), Honeywell (USA), Alpine Q. Technologies (Austria)

Montage: ion trap, trapped ions (IonQ) – set to become first “pure” QC company floating in the stock market, valuation > US$ 2 billion

This field gave Dave Wineland his 2012 Physics Nobel Prize
Quantum computation: current status

Anyons
Exotic statistics of excitations in 2D electron gases in solids
• 2020 witnessed experimental signatures of anyons
• Naturally robust against decoherence = destruction of superpositions due to external interference

Key companies: Microsoft

H. Bartolomei et al., Science 368 (6487), 173 (2020)

Electrons in solid state
Electron spin of phosphorus atoms in silicon
• Two-qubit gates demonstrated
• Could leverage existing Si industry processes for scaling up

Key companies: Silicon Quantum Computing (Australia)

Y. He et al., Nature 571, 371 (2019)
Quantum computation: current status

Superconducting chips
Superconductor dynamics is governed by QM. Transmon qubits (2007) can be coupled and read out, and are the basic units in QCs based on superconductors

• Up to 72 qubits, although noise so far prevents deep circuits
• Recent demonstration of quantum computational advantage by the Google Quantum AI team (2019)
• For hands-on experience on quantum computers: [https://qiskit.org/](https://qiskit.org/) (IBM’s SDK)

Key companies: IBM Q Experience, Google Quantum AI, Rigetti Computing, IQM

Google CEO Sundar Pichai with QC cryostat

Image: Arute et al., Nature [574], 505 (2019)
Quantum computation: current status

Theory:

- Scalable, error-corrected QCs will provide computational break-throughs in data security, optimization, materials science, q. chemistry, etc.
- Open problem: can we obtain practical advantage with near-term Noisy, Intermediate-Scale Quantum (NISQ) devices?

Experiment:

- Small-scale QC prototypes using various physical platforms
- Demonstrations of computational advantage for contrived, useless tasks
- Still no practical advantage over classical computers
- Still a long way towards error-correction & large scale QC
Google Quantum AI experiment (2019)

Images from: Arute et al., Nature 574, 505 (2019)

- 53 superconducting qubits, connected to nearest neighbors in square lattice
- Up to 20 cycles of randomly chosen one- and two-qubit gates (random = hard instance). 2-qubit gates tile sequentially, 1-qubit gates randomly picked from 3-gate set \{\sqrt{X}, \sqrt{Y}, \sqrt{(X+Y)/\sqrt{2}}\}
- \(f_{\text{Sim}}\) gates chosen as they are harder than CZs to simulate using a Feynman path integral approach – circuits half as deep for the same simulation cost

\[f_{\text{Sim}}(\theta, \phi) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(\theta) & -i \sin(\theta) & 0 \\ 0 & -i \sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 0 & e^{-i\phi} \end{bmatrix}\]

- 2-qubit gates: \(f_{\text{Sim}}\)
- 2 \(f_{\text{Sim}}\) gates (+ single qubit gates) give a CZ
Google Quantum AI experiment (2019)

Images from: Arute et al., Nature 574, 505 (2019)

Device verification: use of cross-entropy fidelity

- $P(x_i)$ are calculated probabilities of experimental outcomes
- $F$ correlated with how often we sample high-probability outcomes
- $F=1$ for ideal distribution, $F=0$ for uniform distribution

Test circuits can be simulated classically:

- Patch circuit: 2-qubit gates between two halves of computer not implemented.
- Elided circuit: only a few early 2-qubit gates are removed.
Google Quantum AI experiment (2019)

Images from: Arute et al., Nature 574, 505 (2019)

- Estimated simulation run-time of largest circuits on supercomputer: 10000 years
- Estimated energy cost: 1 petawatt hour
- IBM controversy: simulation possible in a few days?
Google Quantum AI experiment (2019)

Images from: Arute et al., Nature 574, 505 (2019)

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Follow-up: Zuchongzhi chips (2020)

- Superconducting chips at University of Science and Technology of China (Shanghai), led by Jian-Wei Pan

- Same connectivity, similar random circuits

- Zuchongzhi 1.0 – 56 qubits, 20 cycles
  - Simulation estimated to take 8 years on supercomputer

- Zuchongzhi 2.1 – 66 qubits, 24 cycles
  - Simulation estimated to take $4.8 \times 10^4$ years


Zuchongzhi 2.1 chip, from arXiv:2109.03494
Follow-up: computational chemistry on Sycamore (2020)

Rubin et al., Science 369, 1084–1089 (2020)

- Application: ground-state energy estimation using variational methods – variational quantum eigensolver (VQE) using Hartree-Fock technique
- Demonstration on Sycamore: [Rubin et al., Science 369, 1084–1089 (2020)]

- Quantum simulation of H chain (up to 12 atoms), and diazine (C₄H₄N₂) isomerization
- Right: Hartree-Fock orbitals of H12 mapped onto qubits. Variational circuit optimized to minimize energy, mean-field approximation
- In some cases, chemical accuracy achieved
- Still simulable, but demonstration of error mitigation and calibration techniques. Step towards larger-scale simulators
Path encodings

**Dual-rail:** single photon in two propagation modes, labelled 0/1
- arbitrary single-photon gates easy – beam splitters (BS) and phase shifters:

\[
R(\varphi) = \begin{pmatrix} 1 & 0 \\ 0 & e^{i\varphi} \end{pmatrix} \quad U(\theta) = \begin{pmatrix} \cos(\theta) & i\sin(\theta) \\ i\sin(\theta) & \cos(\theta) \end{pmatrix}
\]

- Arbitrary single-qubit unitaries implementable with a BS and phase shifters
- The problem is two-qubit unitaries – how to make the two photons interact?
  - One way: medium with large cross-Kerr non-linearity (hard to do)
  - Measurement-induced non-linearities: key idea of **Knill-Laflamme-Milburn (KLM)** proposal

**What kind of QC can we build with linear optical elements only?**
Non-interacting photons in linear interferometers

- Input to output creation operators mapped by unitary:

\[ a_k^+ \rightarrow \sum_j U_{j,k} a_j^+ \]

- Any \( m \)-mode linear interferometer can be decomposed into:
  - 2-mode beam splitters;
  - single-mode phase shifters.

- Output probabilities given by permanents of matrices associated with \( U \):
  - Example: the probability of an output of one photon per mode, with an input of one photon per mode, is:

\[ p = |\text{per}(U)|^2 \]

- The permanent is similar to the determinant, but with no negative signs. The calculation is intractable (\( \#P \)-hard).
Example: Hong-Ou-Mandel effect

• Two identical photons simultaneously arrive at a beam splitter

• If the beam splitter is unbalanced, we have
  • $T =$ transmissivity
  • $R =$ reflectivity

• Probability that the two photons exit in different modes is

$$p = \left| \text{per}(U) \right|^2 = \left| T^2 - R^2 \right|^2$$

Hong-Ou-Mandel effect: for balanced beam-splitter $T = R$, and $p = 0$

Photons always leave the BS in the same mode:

or
Photonic Boson Sampling

• Given $m$-mode interferometer description $U$, sample from the output distribution of:

  1. Input of $n$ indistinguishable photons;
  2. Multi-photon interference in interferometer;
  3. Yes/no detection at output modes.

• Classical exact simulation would imply a highly unlikely computational complexity result ("collapse of the polynomial hierarchy")

• Even approximate simulation is hard, modulo a couple of reasonable conjectures.

• **Advantages:** about 45 photons would be non-trivial to simulate. Step towards reconfigurable, universal photonic quantum computation

• **Disadvantages:** it doesn’t solve a “useful” problem; certification can be difficult.
**Experimental progress:** first small-scale experiments (2013)

- Interference of 3,4 photons in integrated photonic chips with 5,6 modes
- Verified that probabilities are given in terms of permanents of 3x3 matrices

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Spring et al., *Science* 339, 798 (2013) [Walmsley group]


Broome et al., *Science* 339, 794 (2013) [White group]

Crespi et al., *Nat. Photon.* 7, 545 (2013) [Sciarrino group]
Integrated multi-mode interferometers

- **Challenge**: stability of complex interferometers
- **Solution**: integrated interferometers with waveguides inscribed with lasers in glass:
  - Beam splitting by evanescent-field coupling between close waveguides
  - Phase shifts implemented by differences in path length
  - 3D design technology
Experimental progress: reconfigurability (2015-)

Fully reconfigurable 6-mode interferometer [Carolan et al., Science 349, 711 (2015)]

- Full reconfigurability in seconds by thermo-optic phase shifters
- 6-photon boson sampling (only 15 events)
- Automated experiments

Universal 12-mode reconfigurable chip [Taballione et al., Materials for Quantum Technology 1 (3), 035002 (2021)]
- Silicon nitrite
- 128 tunable thermo-optic phase shifters
Experimental progress: current state-of-the-art (2019)

- Boson Sampling experiment at University of Science and Technology of China (Chao-Yang Lu’s group) - H. Wang et al., Phys. Rev. Lett. 123, 250503 (2019)
  - quantum-dot micropillar, demultiplexed solid state source
  - Up to 14 photons detected
  - Still simulable on a conventional computer
Photonic quantum advantage: Gaussian boson sampling (2020-21)

- Gaussian Boson Sampling experiment @ Univ. of Science and Technology of China (Hefei) - H. Wang et al., Science 370 (6523), 1460 (Dec. 2020), preprint arXiv:2106.15534 [quant-ph]

- GBS is a variation of boson sampling using squeezed light as inputs (higher event rate)
- Up to 73 photons, 100 modes
- v2: up to 113 photons, 144 modes (June 2021)
- Simulation on supercomputer estimated to be $10^{24}$ times slower

- Open questions:
  - improved classical simulation, “faking” events using supercomputer
  - Future: higher complexity regime, encoding qubits into continuous variables for scalable computation (Gottesman-Kitaev-Preskill encoding) – approach of Canadian company Xanadu
Growing photonic cluster states for MBQC

• Using one-way model to advantage: building large resource states from probabilistic operations; at once or on the go


• Schemes for adapting imperfect clusters for MBQC

Universal QC with measurement-based quantum computation

- Measurement-based quantum computation (MBQC) relies only on
  - entangling gates;
  - adaptive single-qubit measurements.
- Teleportation-based gates – states are teleported (and transformed) step by step


- MBQC is uniquely suited to photonic quantum computation:
  - Photons fly away fast…
  - …so they are stored for short times, measured, and information teleported to fresh photons.
- Approach being pursued by US company PsiQuantum (> 3 billion US$ valuation)
**Universal QC with measurement-based quantum computation**

- MBQC using 3-photon GHZ-state sources on-chip: [Rudolph, arXiv:160708535]
  - (2+1)-dimensional architecture
  - probabilistic entangling gates sufficient, if above percolation threshold (essential use of error correction)
  - adaptive single-qubit measurements (delay lines)

- Key advantages: room-temperature chips (small cryo units for e.g. detectors), compatible with major chip foundry techniques, i.e. potentially scalable
INL in 2 EC-funded projects on photonic quantum computation

ERC Advanced Grant QU-BOSS (“Quantum advantage via non-linear Boson Sampling”) 2020-2025
• PI: Fabio Sciarrino (Univ. of Rome, La Sapienza)
• Partners: Istituto de Fotonica e Nanotecnologie (IFN-CNR – Milan), INL

H2020 FETOPEN PHOQUSING (“Photonic Quantum Sampling Machine”) 2020-2024
• PI: Fabio Sciarrino (Univ. of Rome, La Sapienza)
• Partners: CNR (IT), CNRS (FR), Sorbonne Univ. (FR), Veriqloud (FR), QuiX BV (NL), INL

• Development of complex linear and non-linear interferometers
  • Theoretical characterization of photonic indistinguishability, resources such as contextuality and coherence
  • Scalability of photonic QC, MBQC ideas
• Noisy, Intermediate-Scale Quantum (NISQ) computational applications: variational algorithms, randomness manipulation, cryptography, quantum chemistry
Conclusion

• Q. computers promise extreme computational speed-up for many problems

… and they’re already much faster than supercomputers at some contrived tasks

• Q. computational advantage has (arguably) been demonstrated using superconducting chips and photonic systems

• Next steps:

  • Practical applications in small-scale q. simulation, optimization, graph theory
  • Scientific, technological, and engineering challenges to scale up QCs and incorporate quantum error correction for general applicability

Thank you for your attention!