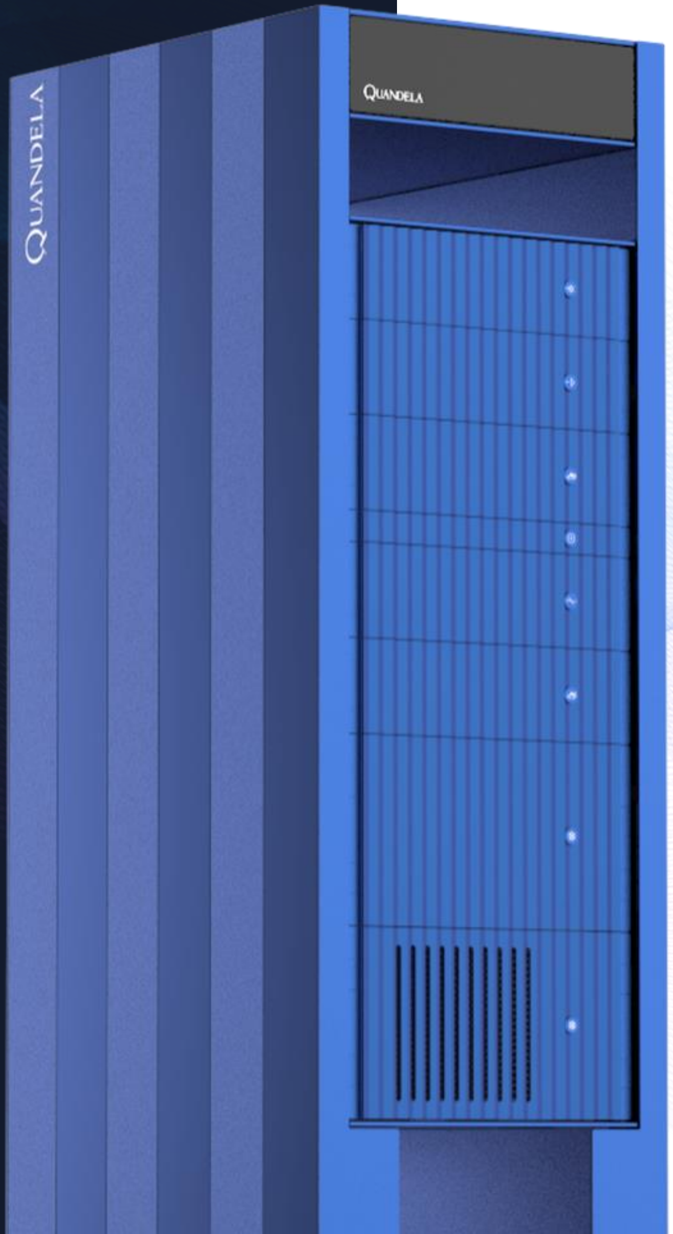
QUANDELA

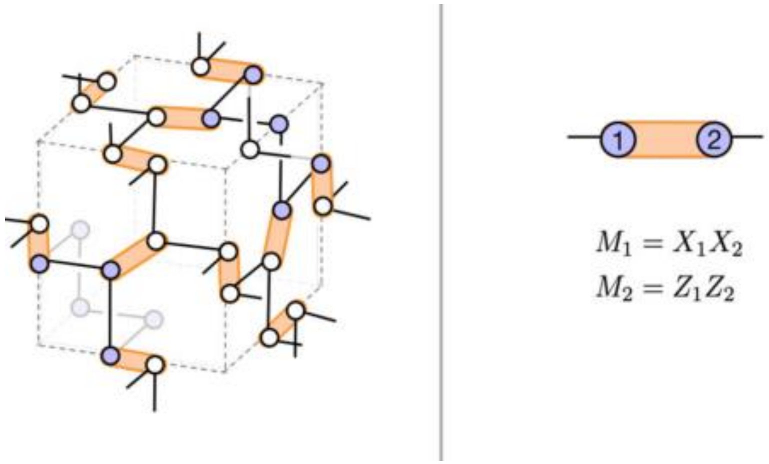
Benchmarking Photonic Quantum Computers

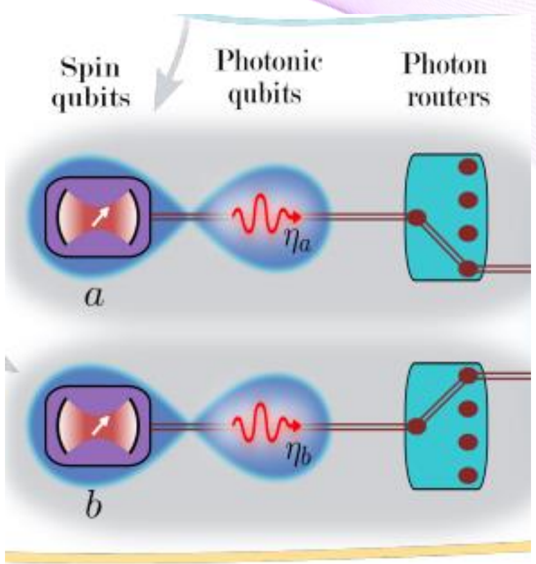
Rawad Mezher



Motivation

- Some very promising proposals to achieve fault-tolerance, particularly in measurement-based quantum computation using photons Kieling et al. 07', Bartolucci et al. 21'; Raussendorf and Briegel 01', De Gliniasty et al. 23'



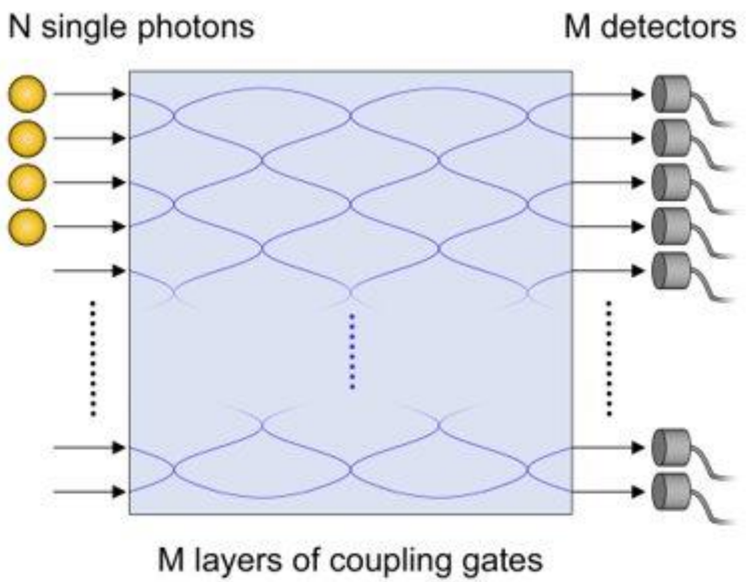


- But, we’re not there yet….

Photonic NISQ Computing

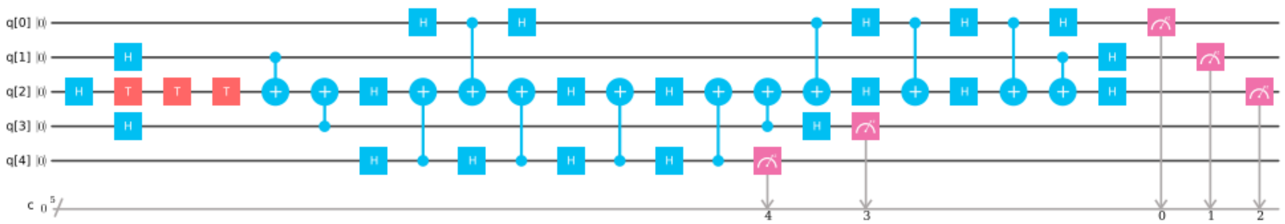
- Noisy intermediate scale quantum (NISQ) devices are the devices we have currently

Figs. from : Garcia-Patron et al. 19', Michielsen et al. 17'



KLM encoding

Boson sampling encoding Aaronson and Arkhipov 11'

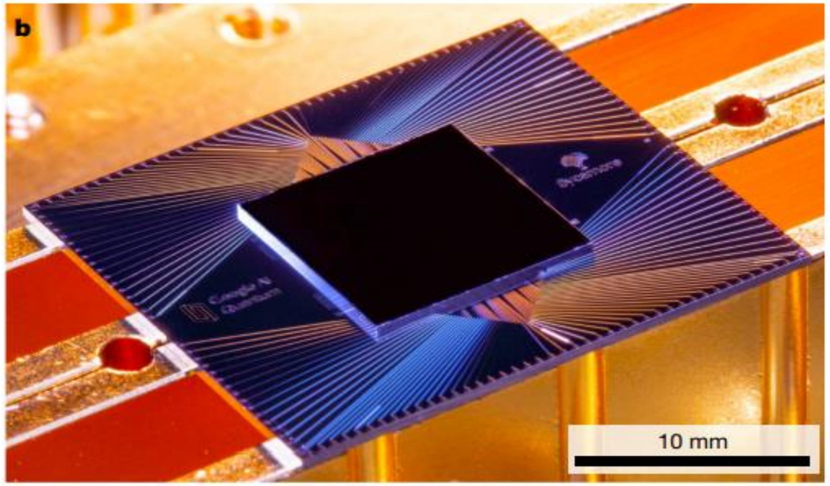


- **Photonic NISQ devices**
  Several photons affected by various noise sources (photon loss, distinguishability errors,…) Ex: The ***Ascella*** processor

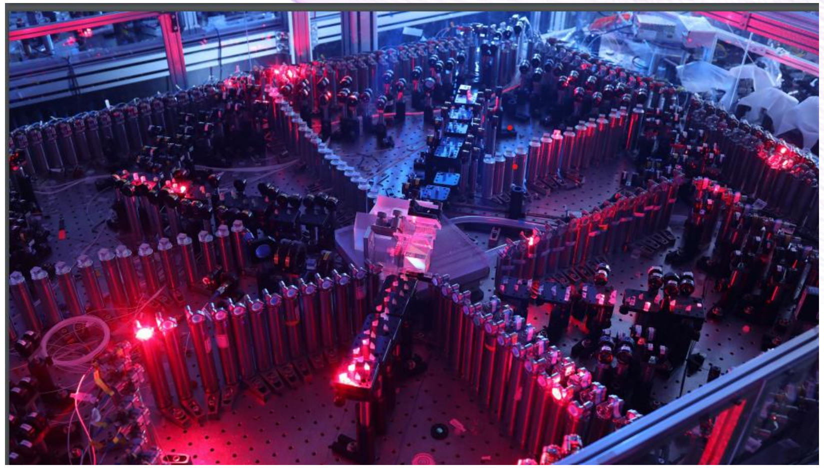
- **Gate-based NISQ devices**
  Tens of qubits in matter-based affected by various noise sources systems (Pauli stochastic noise, drift effects, decoherence,…)

Why you should care about noisy intermediate-scale quantum (NISQ) devices

- Several groundbreaking experiments claiming quantum advantage
- Becoming increasingly difficult to spoof classically



Arute et al. 2019



Zhong et al. 2020

Why you should care about NISQ

- Convincing evidence of ***useful*** quantum advantage in NISQ algorithms, especially when coupled with error mitigation techniques

RESEARCH ARTICLE

QUANTUM COMPUTING

Quantum advantage in learning from experiments

Hsin-Yuan Huang[1,2]*, Michael Broughton[3], Jordan Cotler[4,5], Sitan Chen[6,7], Jerry Li[8], Masoud Mohseni[3], Hartmut Neven[3], Ryan Babbush[3], Richard Kueng[9], John Preskill[1,2,10], Jarrod R. McClean[3]*

Quantum technology promises to revolutionize how we learn about the physical world. An experiment that processes quantum data with a quantum computer could have substantial advantages over conventional experiments in which quantum states are measured and outcomes are processed with a classical computer. We proved that quantum machines could learn from exponentially fewer experiments than the number required by conventional experiments. This exponential advantage is shown for predicting properties of physical systems, performing quantum principal component analysis, and learning about physical dynamics. Furthermore, the quantum resources needed for achieving an exponential advantage are quite modest in some cases. Conducting experiments with 40 superconducting qubits and 1300 quantum gates, we demonstrated that a substantial quantum advantage is possible with today's quantum processors.

Article

Evidence for the utility of quantum computing before fault tolerance

https://doi.org/10.1038/s41586-023-06096-3
Received: 24 February 2023
Accepted: 18 April 2023
Published online: 14 June 2023
Open access
Check for updates

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Quantum computing promises to offer substantial speed-ups over its classical counterpart for certain problems. However, the greatest impediment to realizing its full potential is noise that is inherent to these systems. The widely accepted solution to this challenge is the implementation of fault-tolerant quantum circuits, which is out of reach for current processors. Here we report experiments on a noisy 127-qubit processor and demonstrate the measurement of accurate expectation values for circuit volumes at a scale beyond brute-force classical computation. We argue that this represents evidence for the utility of quantum computing in a pre-fault-tolerant era. These experimental results are enabled by advances in the coherence and calibration of a superconducting processor at this scale and the ability to characterize[1] and controllably manipulate noise across such a large device. We establish the accuracy of the measured expectation values by comparing them with the output of exactly verifiable circuits. In the regime of strong entanglement, the quantum computer provides correct results for which leading classical approximations such as pure-state-based 1D (matrix product states, MPS) and 2D (isometric tensor network states, isoTNS) tensor network methods[2,3] break down. These experiments demonstrate a foundational tool for the realization of near-term quantum applications[4,5].

Why you should care about NISQ

- NISQ devices can be useful to understand noise models and demonstrate basic fault-tolerant operations

- Important for scaling up!

Experimental demonstration of fault-tolerant state preparation with superconducting qubits

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Robust quantum computation requires encoding delicate quantum information into degrees of freedom that are hard for the environment to change. Quantum encodings have been demonstrated in many physical systems by observing and correcting storage errors, but applications require not just storing information; we must accurately compute even with faulty operations. The theory of fault-tolerant quantum computing illuminates a way forward by providing a foundation and collection of techniques for limiting the spread of errors. Here we implement one of the smallest quantum codes in a five-qubit superconducting transmon device and demonstrate fault-tolerant state preparation. We characterize the resulting codewords through quantum process tomography and study the free evolution of the logical observables. Our results are consistent with fault-tolerant state preparation in a protected qubit subspace.

Article

Demonstration of fault-tolerant universal quantum gate operations

https://doi.org/10.1038/s41586-022-04721-1
Received: 26 November 2021
Accepted: 4 April 2022
Published online: 25 May 2022
Check for updates

Lukas Postler[1], Sascha Heußen[2,3], Ivan Pogorelov[1], Manuel Rispler[2,3], Thomas Feldker[1,4], Michael Meth[1], Christian D. Marciniak[1], Roman Stricker[1], Martin Ringbauer[1], Rainer Blatt[1,5], Philipp Schindler[1]✉, Markus Müller[2,3] & Thomas Monz[1,4]

Quantum computers can be protected from noise by encoding the logical quantum information redundantly into multiple qubits using error-correcting codes[1,2]. When manipulating the logical quantum states, it is imperative that errors caused by imperfect operations do not spread uncontrollably through the quantum register. This requires that all operations on the quantum register obey a fault-tolerant circuit design[3–5], which, in general, increases the complexity of the implementation. Here we demonstrate a fault-tolerant universal set of gates on two logical qubits in a trapped-ion quantum computer. In particular, we make use of the recently introduced paradigm of flag fault tolerance, where the absence or presence of dangerous errors is heralded by the use of auxiliary flag qubits[6–10]. We perform a logical two-qubit controlled-NOT gate between two instances of the seven-qubit colour code[11,12], and fault-tolerantly prepare a logical magic state[8,13]. We then realize a fault-tolerant logical T gate by injecting the magic state by teleportation from one logical qubit onto the other[14]. We observe the hallmark feature of fault tolerance—a superior performance compared with a non-fault-tolerant implementation. In combination with recently demonstrated repeated quantum error-correction cycles[15,16], these results provide a route towards error-corrected universal quantum computation.

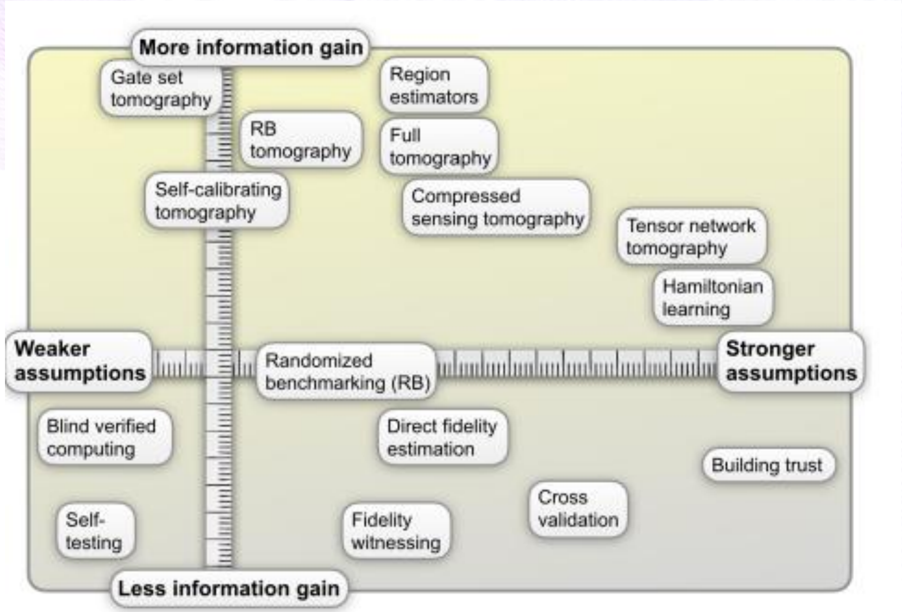
Benchmarking and Certification

- Benchmarking is important for assessing the quality of NISQ devices

- Some benchmarks are powerful tools, as they come with complexity theoretic **guarantees** of quantum-over-classical advantage
- Others come with **guarantees** of security

- A “zoo” of quantum information benchmarking protocols exists, each with their own set of **assumptions**, **information gain**, and **scalability**

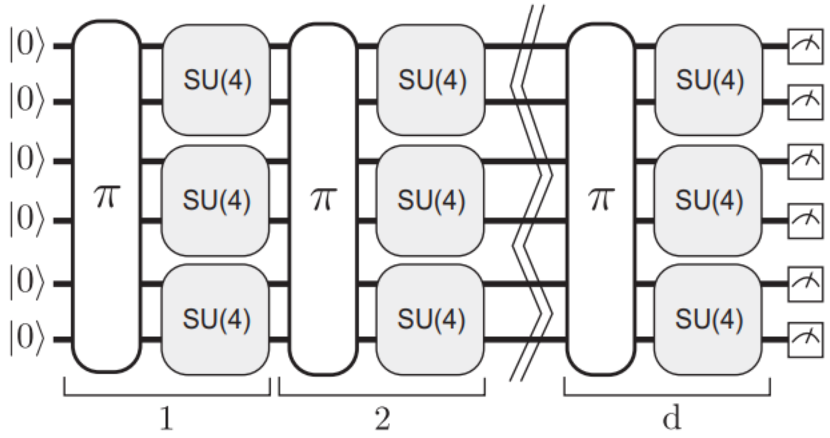
- We will focus on benchmarks being widely implemented on current NISQ Devices



Eisert et al. 20’

Benchmarking Generic Performance

Quantum Volume



- Random 2-qubit gates
- Any-to-any-connectivity

PHYSICAL REVIEW A **100**, 032328 (2019)

Validating quantum computers using randomized model circuits

Andrew W. Cross,* Lev S. Bishop,† Sarah Sheldon, Paul D. Nation, and Jay M. Gambetta
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(Received 17 June 2019; published 20 September 2019)

Problem 1 (HOG, or Heavy Output Generation). *Given as input a random quantum circuit C (drawn from some suitable ensemble), generate output strings $x_1, \ldots, x_k$, at least a $2/3$ fraction of which have greater than the median probability in C's output distribution.*

- Strong complexity-theoretic evidence that HOG cannot be performed efficiently on a classical computer Aaronson and Chen 16'

- *Quantum volume idea:* test if the output probabilities of random quantum circuits satisfy the HOG criterion

Benchmarking Generic Performance

Photonic Quality factor (PQF)

Quantum Volume is not natural for benchmarking Photonic NISQ devices

a) Many algorithms on photonic NISQ devices don't require qubit encodings!

b) Generic photonic NISQ circuits – Boson samplers – are different than random quantum circuits
Aaronson and Arkhipov 14'

c) Quantum Volume is not tailored for noise sources affecting photonic NISQ devices (photon loss, distinguishability,…)

d) Need for a new metric: **Photonic quality factor (PQF)**
Mezher and Mansfield 22'

Solving graph problems with single photons and linear optics

Rawad Mezher, Ana Filipa Carvalho, and Shane Mansfield
Phys. Rev. A **108**, 032405 – Published 6 September 2023

An error-mitigated photonic quantum circuit Born machine

Alexia Salavrakos, Tigran Sedrakyan, James Mills, Rawad Mezher

Photonic quantum generative adversarial networks for classical data

Tigran Sedrakyan, Alexia Salavrakos

Fock state-enhanced expressivity of quantum machine learning models

Beng Yee Gan[1a], Daniel Leykam[1] and Dimitris G. Angelakis[1,2,3c]

Benchmarking Generic Performance

Photonic Quality factor (PQF)

Common sources of noise in photonic NISQ devices

- Photon loss
- Distinguishability of single photons
- Multi-photon emissions
- Chip errors

…

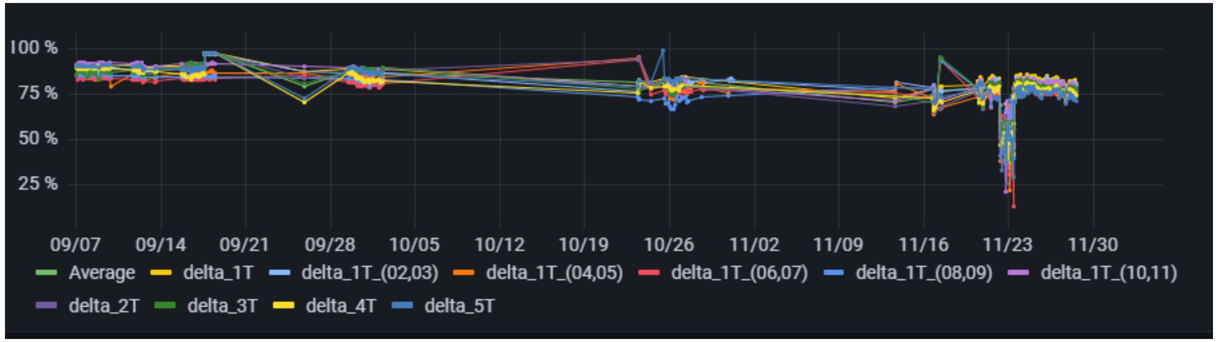
Assessing the quality of near-term photonic quantum devices

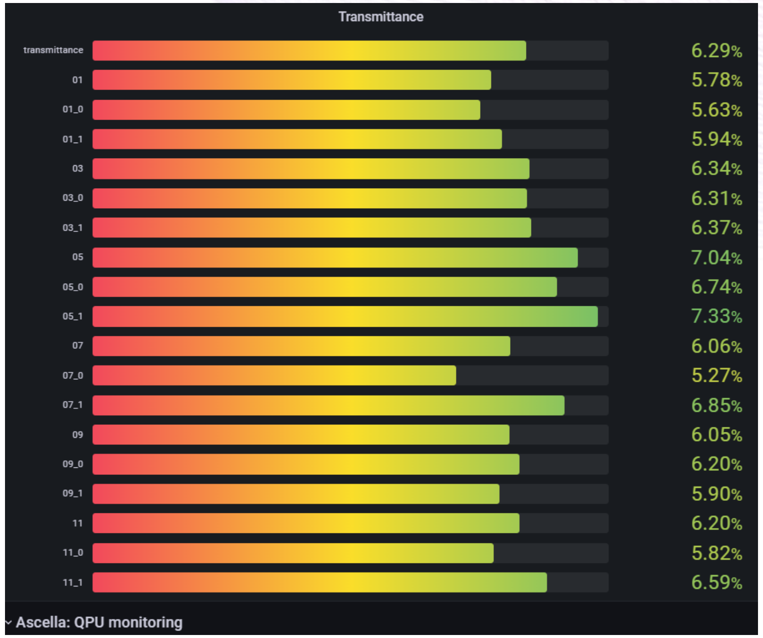
Rawad Mezher, Shane Mansfield

A versatile single-photon-based quantum computing platform

Nicolas Maring, Andreas Fyrillas, Mathias Pont, Edouard Ivanov, Petr Stepanov, Nico Margaria, William Hease, Anton Pishchagin, Aristide Lemaître, Isabelle Sagnes, Thi Huong Au, Sébastien Boissier, Eric Bertasi, Aurélien Baert, Mario Valdivia, Marie Billard, Ozan Acar, Alexandre Brieussel, Rawad Mezher, Stephen C. Wein, Alexia Salavrakos, Patrick Sinnott, Dario A. Fioretto, Pierre-Emmanuel Emeriau, … Niccolo Somaschi + Show authors

Nature Photonics (2024) | Cite this article





Data from *Ascella* QPU

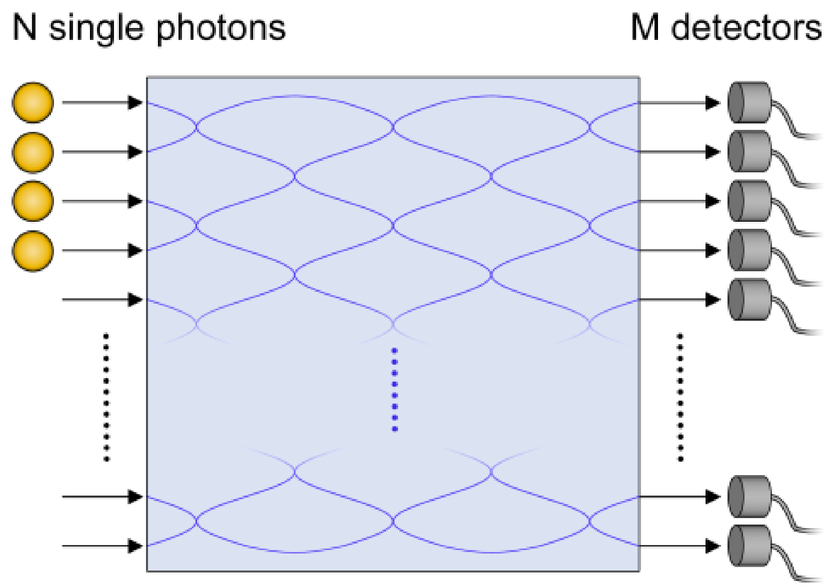
Benchmarking Generic Performance

Photonic Quality Factor (PQF)

PROTOCOL

1. Configure a Haar random $M \times M$ unitary U and pass a N photons through it, collect output statistics by running the experiment many times, $M = N^{2+\gamma}$
2. Repeat for different Haar chosen U
3. Do the tests t_{loss}, $t_{d,1}$ $t_{d,2}$, $t_{d,3}$, $t_{d,4}$ on collected data (computing certain output probabilities)
4. *If all tests pass*, increase the number of modes and repeat

Our PQF benchmark is the largest N for which all our tests pass



Sample complexity (number of experiments) needed for the tests $\boldsymbol{t_{loss}}$, $\boldsymbol{t_{d,1}}$ $\boldsymbol{t_{d,2}}$, $\boldsymbol{t_{d,3}}$, $\boldsymbol{t_{d,4}}$ is polynomial in N and M, thus our method is scalable

Scheshnovic 16'; Walschaers et al. 16'; RM and SM. 22'

Benchmarking generic performance

Photonic Quality factor (PQF)

Efficient classical strategy	t_{loss}	$t_{d,1}$	$t_{d,2}$	$t_{d,3}$	$t_{d,4}$
Distinguishable particles (Walschaers et al.)	N/A	X	X	X	X
Lossy Boson sampling (Oszmaniec et al.)	X	N/A	N/A	N/A	N/A
Mean field strategies (Tichy et al.)	N/A	✓	X	X	?
Google's greedy sampler (Villalonga et al.)	N/A	?	?	?	X
Renema et al.'s algorithm (constant loss and distinguishability)	X	?	?	?	X
Brute force permanent approximation (Gurvits)	N/A	X	X	X	X

N/A – Not Applicable
X – Fail
✓ – Pass
? – Unknown

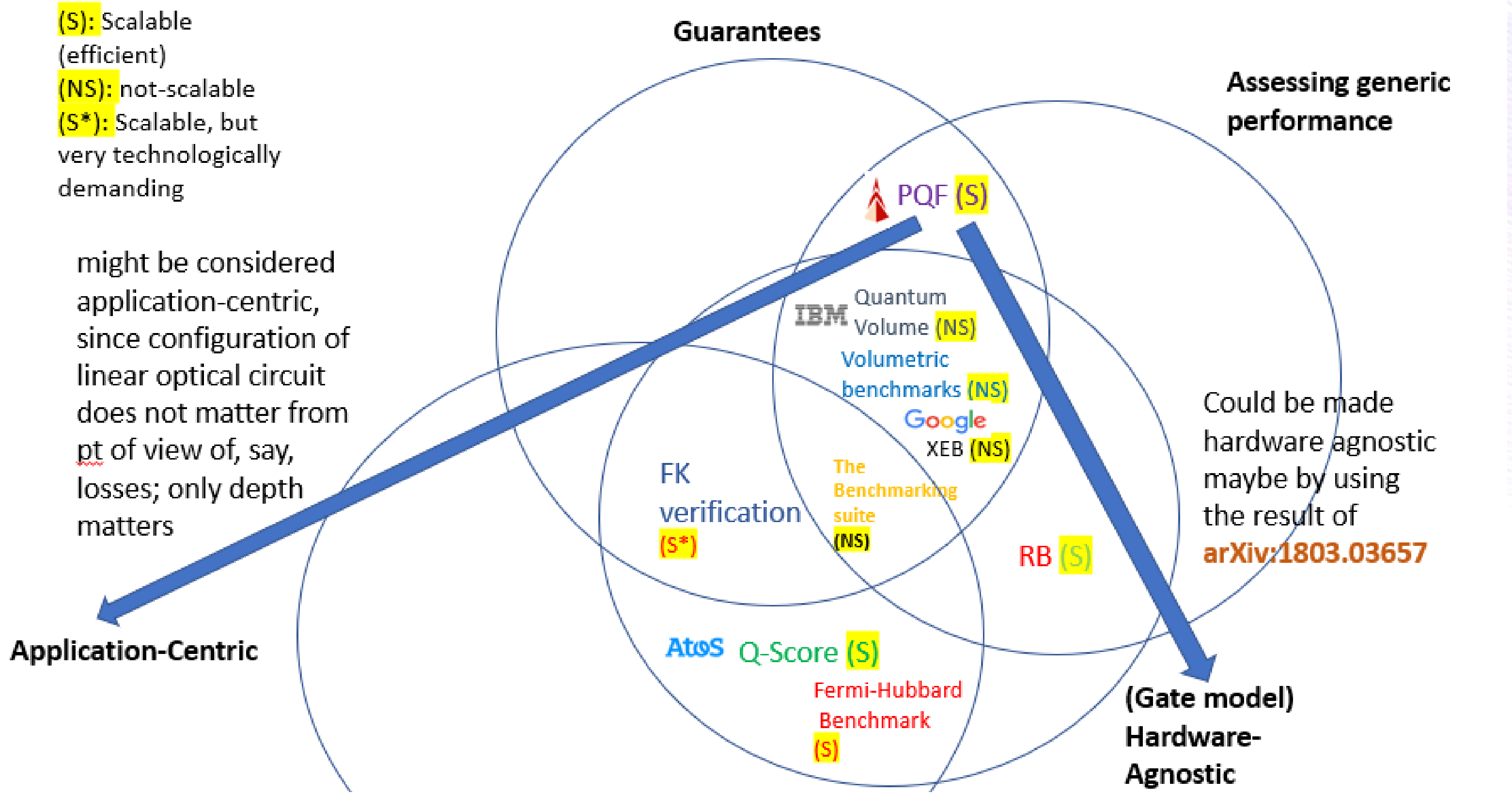
- PQF is evolutive
- More noise sources can be integrated by adding more tests

Benchmarking Generic PerformanceF

Photonic Quality factor (PQF)

- *Ascella* QPU has a **PQF = 3**

Where does PQF sit ?



Benchmarking Specific Quantum Gates

a) **Randomized benchmarking (RB)** is commonly used technique.
Magesan et al. 12'

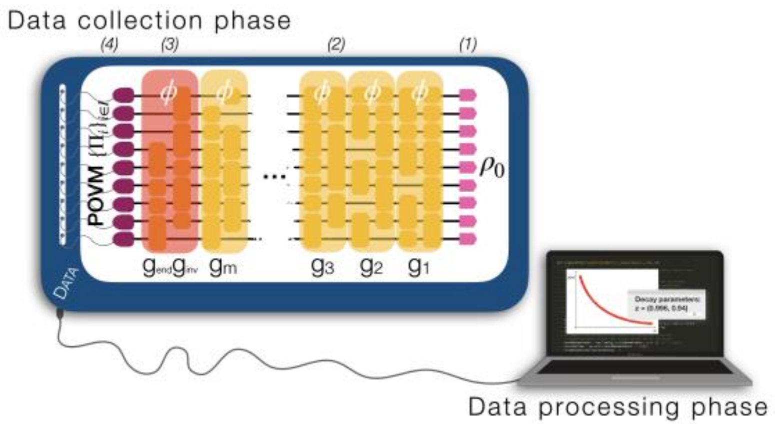
b) Allows estimation of average gate fidelity free of **State Preparation And Measurement (SPAM)** errors

c) Needs to implement a sequences of gates not natural for modular architecture (interferometer) to evaluate average fidelity F_{av}

d) We propose new way to directly measure F_{av}
Mezher and Wein, in prep.

$$F_{av} := \int d\psi \text{Trace}(|\psi\rangle\langle\psi|\Lambda(|\psi\rangle\langle\psi|))$$

Λ is a quantum channel (CPTP map)



Direct Average Fidelity Computation

- Complicated general expression
- But reduces to some nice special cases for specific gates!

Expression of average Fidelity for the **T-gate**

$$T := \begin{pmatrix} 1 & 0 \\ 0 & e^{i\frac{\pi}{4}} \end{pmatrix}$$

$$F_{av} = \frac{\sqrt{2}p_{0|0} + \sqrt{2}p_{1|1} + 2p_{+|+} - 2p_{+|+i}}{3\sqrt{2}}$$

where $p_{x|y}$ is the probability of measuring x when T-gate is applied on input state y with:

- 0, 1 are corresponding to $|0\rangle$ and $|1\rangle$
- $+$ is $\frac{|0\rangle+|1\rangle}{\sqrt{2}}$
- $+i$ is $\frac{|0\rangle+i|1\rangle}{\sqrt{2}}$

Direct Average Fidelity Computation

Platform (Device)	Gate	F_{avg} (%)	Date - Benchmark Details
Quandela (Ascella)	T-gate	99.6 ± 0.1	2023/05/31 – average and standard deviation on 5× 1M-sample measurements, for 14 different gate locations on chip
	CNOT	93.8 ± 0.6	2023/03/20-2023/05/07 — average and standard deviation of 114 consecutive 100k-sample measurements over 46 days
	Toffoli	86 ± 1.2	2023/01/06 – calculated on 100000-sample tasks
IonQ (AWS `ionq.qpu`)	T-gate	99.6 ± 1	2022/12/16 – calculated on 4096-sample tasks
	CNOT	91.7 ± 1.5	2022/12/17 – calculated on 4096-sample tasks
	Toffoli	90 ± 3.1	2023/01/18 – calculated on 256-sample tasks
Rigetti (AWS `rigetti.aspen-11`)	T-gate	88.7 ± 1	2022/12/16 – calculated on 4096-sample tasks
	CNOT	71.2 ± 1.5	2022/12/17 – calculated on 4096-sample tasks
IBM (`Quito` or `Belem` depending on availability)	T-gate	96 ± 1.5	2022/12/16 – calculated on 4096-sample tasks
	CNOT	86.4 ± 1.5	2022/12/17 – calculated on 4096-sample tasks

Maring et al. 23'
Mezher and Wein , in prep.

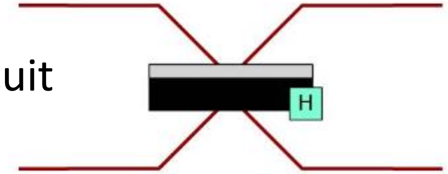
By choosing realistic noise models for distinguishability, and appropriate postprocessing, we obtain SPAM free estimates of F_{av}

Qubits, n	Gate, U	Raw Fidelity (%)	State Preparation Error (%)	Corrected Fidelity (%)
1	T-gate	99.6 ± 0.1	0	99.6 ± 0.1
2	CNOT	93.8 ± 0.6	9.0 ± 0.4	99.0 ± 0.8
3	Toffoli	86.0 ± 1.2	13.2 ± 0.5	90.0 ± 1.4

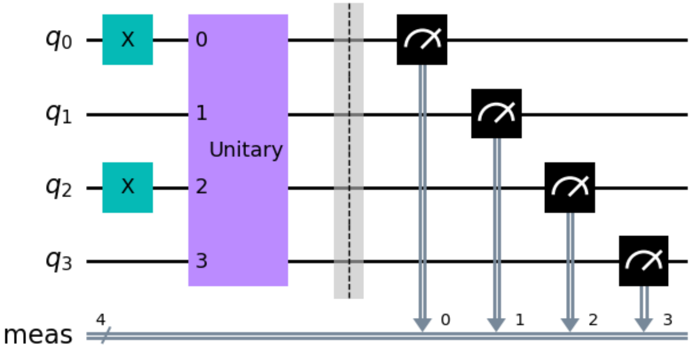
On the Need for Fair Comparisons

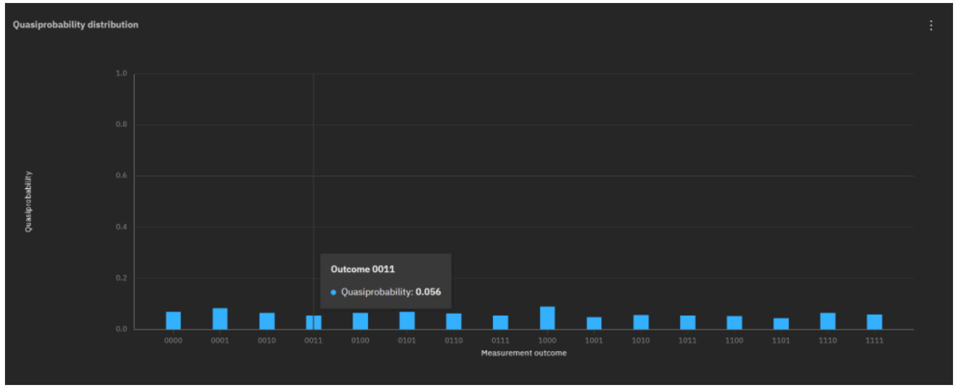
- One can also think of tasks which are **natural in photonics but not natural for gate-based circuits**

Hong-Ou-Mandel circuit



Encoding of Aaronson and Arkhipov





QPU output is noisy because circuit is very deep: *all outputs appear instead of exactly two*

Qubit gate-based circuit for Hong-Ou-Mandel

- 4-qubit circuit with a 4-qubit unitary
- Decomposable as 868 gates on 127 qubit *IBM Eagle*
- Of which 198 two-qubit gates

Takeaway

- Many types of benchmarks for quantum hardware
- Each with their own guarantees, information gain, scalability

- Some benchmarks are used for testing generic performance
  - Quantum Volume
  - PQF
- Others test the performance of a specific applications
- Others test performance of specific quantum gates
  - Randomized Benchmarking
  - direct average fidelity computation

- Some tasks which are natural in qubit gate-based circuits are difficult to implement in photonic circuits
- And vice versa