A Review and Collection of Metrics and Benchmarks for Quantum Computers: definitions, methodologies and software

Deep Lall
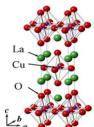
Institute for Quantum Standards and Technology, National Physical Laboratory
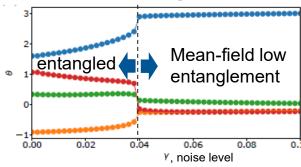
Quantum Software and Modelling Team

Quantum algorithms for materials simulations

APL Quantum 2, 016121 (2025);
Nature Comp. Sci. 1, 410 (2021);

pyTTN tensor network library for closed and open quantum systems (https://gitlab.npl.co.uk/qsm/pyttn)

Theory in support of experiments: material origins of noise in superconducting qubits
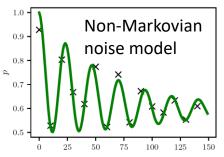
M. Lucas., J. Saunders, S. E. de Graaf *et al*, Nature Comms. 14, 3522 (2023);

M. M. Hegedüs *et . al*, Science Adv. (2025)

**Qubit characterisation and benchmarking:
towards good practice approaches and standards**

A Review and Collection of Metrics and Benchmarks for Quantum Computers: definitions, methodologies and software, arXiv:2502.06717 (2025)

Effects of noise in quantum algorithms
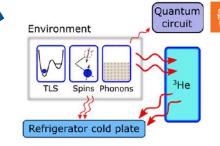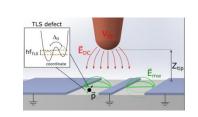

NPJ Quantum Information 11, 84 (2025); QST 9 015015 (2023); Quantum 6, 804 (2022); PRA 104 022403 (2021)

Qubit characterization

Quant. Sci. Technol. 9, 035017 (2024)

Acknowledgements

Contributors

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Motivation

- The emerging quantum computing hardware spans a **wide range of different technologies**, both for circuit based and non-circuit-based quantum computers. This makes it difficult to compare the performance of the different architectures.

- Manufacturer reported quantum computer performance metrics are often **difficult to reproduce**. Often, parts of the methodologies used to obtain these performance metrics are not reported.

- There is the **need for objective performance comparisons** based on well defined metrics by which emerging quantum processors can be fairly measured and compared.

Existing work on metrics and benchmarks

NPL National Physical Laboratory | **QMI** Quantum Metrology Institute

A number of proposed algorithms may achieve quantum advantage ⟷ Noise in the hardware is main obstacle

Metrics and benchmarks needed to objectively quantify and guide progress towards quantum advantage

- **Development of benchmarks and metrics active area of research**: SAND2019-0963R (2018), arXiv:1912.00546; arXiv:2112.09457; entropy (2022); arXiv:2407.08828v1 (2024), arXiv:2407.10941v2 (2024), arXiv:2408.12064 (2024), https://metriq.info/; …

- **Standardization working groups established**: https://quantumconsortium.org/; https://standards.ieee.org/ieee/7131/10681; https://www.darpa.mil/program/quantum-benchmarking; CEN/CLC JTC22/WG3 benchmarking task force (NPL); IEC/ISO JTC 3 Quantum technologies (NPL), AhG 5 Quantum Computing and Simulation

Work commissioned by the NQCC on "Open Standards for Emerging Quantum Processors":
Define metrics and the associated methodologies by which emerging quantum processors can be fairly measured and compared.

A Review and Collection of Metrics and Benchmarks for Quantum Computers: definitions, methodologies and software

Deep Lall[*1], Abhishek Agarwal[*1], Weixi Zhang[*1,2], Lachlan Lindoy[1], Tobias Lindström[1], Stephanie Webster[1], Simon Hall[1], Nicholas Chancellor[3,4], Petros Wallden[2], Raul Garcia-Patron[2,5], Elham Kashefi[2,6], Viv Kendon[7], Jonathan Pritchard[7], Alessandro Rossi[1,7], Animesh Datta[8], Theodoros Kapourniotis[9], Konstantinos Georgopoulos[9], and Ivan Rungger[†1,10]

arXiv:2502.06717

Aims

- Collect metrics and benchmarks for quantum computers used in practice
- Necessary properties: **transparency, reproducibility, comparability, objectivity**
- Using the chosen set of metrics, one should be able to determine:
  - what are the key areas that need improving for the specific QC (hardware vendor)
  - what algorithms may successfully run on the QC (end user)
  - which QC to use (everybody)

How did we achieve these aims?

- Developed a review of metrics and benchmarks for quantum computers
- Selected metrics that together **comprehensively** evaluate device performance
- Methodology, assumptions, limitations provided for each metric
- **Open-source software** provided

Choice and organisation of metrics

- Aim: **comprehensive & holistic evaluation of device performance**
- Metrics grouped based on performance aspect they measure

Hardware architecture properties: What are the device's architectural properties and what operations is it able to perform?

Quality metrics: How close are the outputs of computations on the device to those of the ideal noiseless device?

Speed metrics: How fast are operations and algorithms executed on the device?

Stability metrics: How stable and reliable is the device over time?

Non-gate-based quantum computer metrics: What algorithms are non-gate-based quantum computers targeting and what is their performance?

Performance Metrics for Quantum Computers

M1. HARDWARE ARCHITECTURE PROPERTIES

M1.1. Number of usable qubits
M1.2. Pairwise connectivity
M1.3. Native gate set
M1.4. Capability to perform mid-circuit measurements

M2. - M5. QUALITY METRICS

HARDWARE MANUFACTURER → *END-USER*

M2. QUBIT QUALITY METRICS

M2.1. Qubit relaxation time (T_1)
M2.2. Qubit dephasing time (T_2)
M2.3. Idle qubit purity oscillation frequency

M3. GATE EXECUTION QUALITY METRICS

M3.1. Gate set tomography-based process fidelity
M3.2. Diamond norm of a quantum gate
M3.3. Clifford randomized benchmarking average gate error
M3.4. Interleaved Clifford randomized benchmarking gate error
M3.5. Cycle-benchmarking composite process fidelity
M3.6. Over- or under-rotation angle
M3.7. State preparation and measurement fidelity

M4. CIRCUIT EXECUTION QUALITY METRICS

M4.1. Quantum volume
M4.2. Mirrored circuits average polarization
M4.3. Algorithmic qubits
M4.4. Upper bound on the variation distance

M5. WELL-STUDIED TASK EXECUTION QUALITY METRICS

M5.1. Variational Quantum Eigensolver metric
M5.2. Quantum Approximate Optimization Algorithm metric
M5.3. Fermi-Hubbard model simulation metric
M5.4. Quantum Fourier Transform metric

HARDWARE COMPONENTS → *APPLICATIONS*

M6. SPEED METRICS

M6.1. Time taken to execute a general single- or multi-qubit gate
M6.2. Time to measure qubits
M6.3. Time to reset qubits
M6.4. Overall device speed on reference tasks

M7. STABILITY METRICS

M7.1. Standard deviation of a specified metric evaluated over a time interval

M8. - M10. NON-GATE-BASED QC METRICS

M8. METRICS FOR QUANTUM ANNEALERS

M8.1. Single qubit control errors
M8.2. Size of largest mappable fully connected problem
M8.3. Dimensionless sample temperature

M9. METRICS FOR BOSON SAMPLING DEVICES

M9.1. Hardware characterization and model as metrics
M9.2. Quantum advantage demonstration as metric

M10. METRICS FOR NEUTRAL ATOM DEVICES

M10.1. Analogue process fidelity
M10.2. Trap lifetime
M10.3. Reconfigurable connectivity

What is included for each metric

Metric title

Short definition of the metric.

Long description

Long description of the metric.

Measurement procedure

Description of the methodology to measure the metric.

Assumptions and limitations

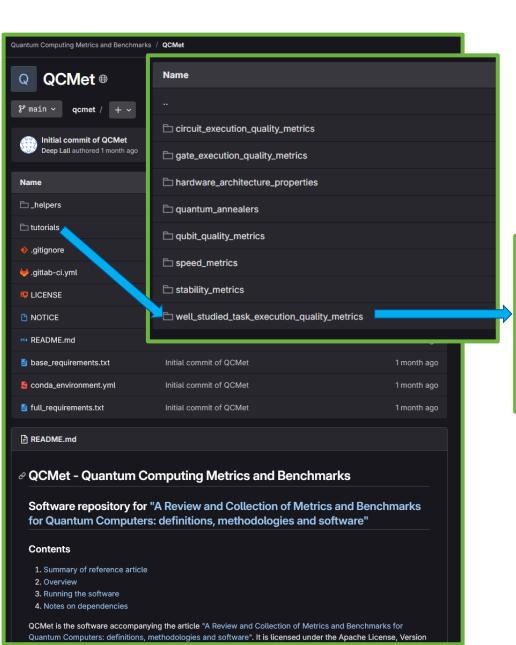Where relevant, a list of assumptions underpinning the metric is provided, as well as practical limitations.
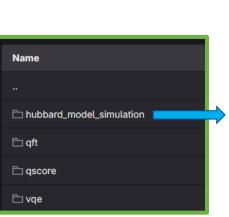
Source code

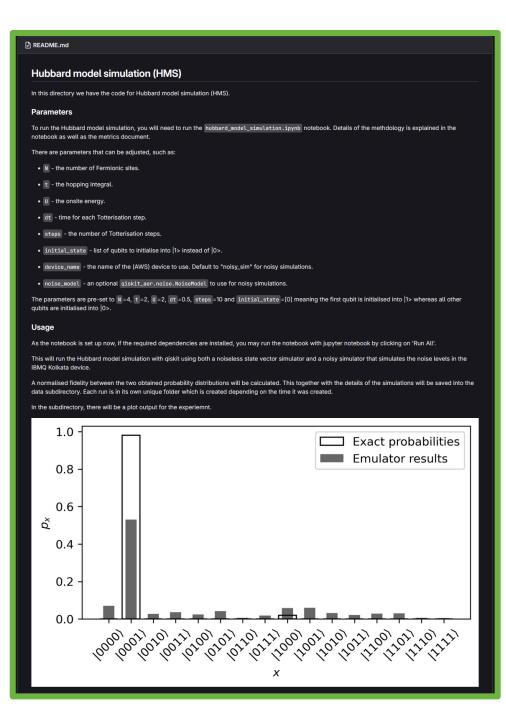Where available, this section provides links to free open source libraries suitable for measuring the metric.

References

- Consistent structure and information for all metrics
- Each metric is as self-contained as possible
- The length depends on metric, can vary between 1-4 pages depending on metric

Accompanying software - QCMet

Conclusions: Further development

Fast scalable metrics for large-scale devices

- Fast benchmarks for **1000+ qubit devices**
- Metrics that guide and track progress towards quantum error corrected **fault tolerant quantum computing**
- Benchmarks for **distributed quantum computers**

Speed and stability metrics

- **Quantify speed** for running gates to algorithms
- Quantify **stability at different timescales**

Metrics for other components/technologies

- Benchmarks for quantum software, such as low-level compilers
- Benchmarks for non-gate-based quantum computing approaches

Noise assumptions

- Metrics devoid of noise model assumptions
- Metrics quantifying specific kinds of noise such as **crosstalk or non-Markovian noise**

Conclusions: towards good practice approaches and standardization

i. the identification and agreement on the **categories of metrics** that comprehensively benchmark device performance

ii. the **identification and agreement on a set of well-established metrics** that together comprehensively benchmark performance

iii. the **identification of metrics specific to hardware platforms, including non-gate-based quantum computers**

iv. **inter-laboratory comparison** studies to develop best practice guides for measurement methodology

v. **agreement on what data and software should be reported** together with a metric value to ensure **trust, transparency and reproducibility**.
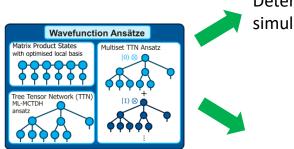
Summary

- Review and collection of metrics and benchmarks for quantum computer with defined metrics categories

- Open-source library containing methodology implementation

- Identified key areas for further development of metrics

- Proposed items for development of **good practice guides** as first step towards longer term development of standards

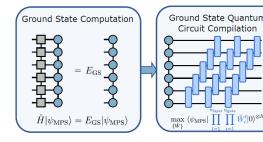# Our current research feeding into qubit quality and application-level benchmarks
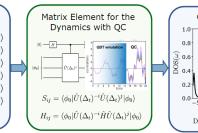
Tensor networks based classical and quantum algorithms for materials simulations & QEC
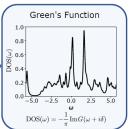

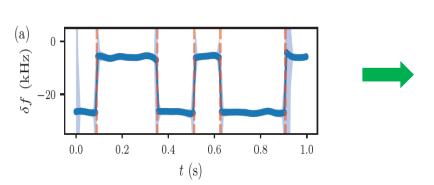Determining limit of classical simulability and quantum advantage
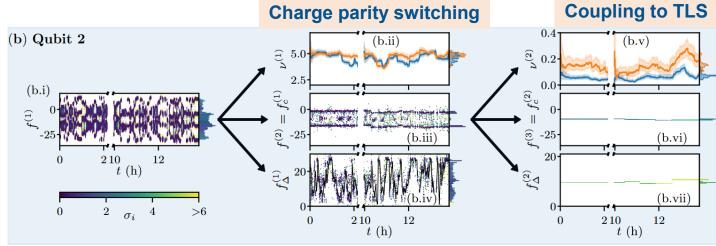
Towards hardware implementations

APL Quantum 2, 016121 (2025);

IBM Heron
Ben Jaderberg *et al.*,
arXiv:2503.09683

Automated fast-tracking of noise fluctuations:

Charge parity switching

Coupling to TLS

A. Agarwal *et al.*, arXiv:2505.23622

Thank you!