COMPARATIVE BENCHMARKING OF **UTILITY-SCALE QUANTUM EMULATORS**

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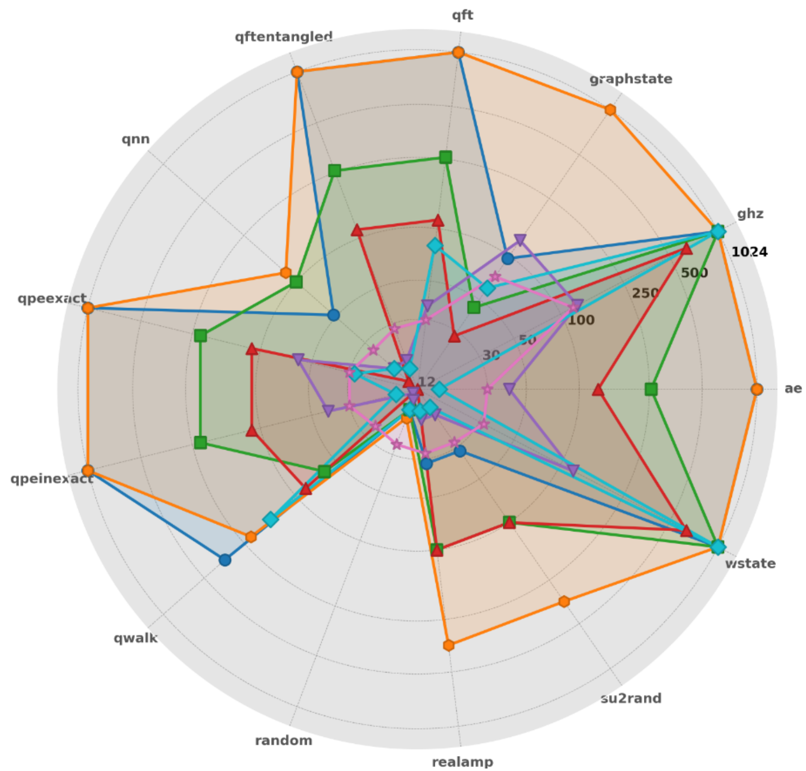


Université de Strasbourg
cnrs
CESQ CENTRE EUROPÉEN DE SCIENCES QUANTIQUES
EuRyQa
INVESTIR L'AVENIR
FRANCE RELANCE

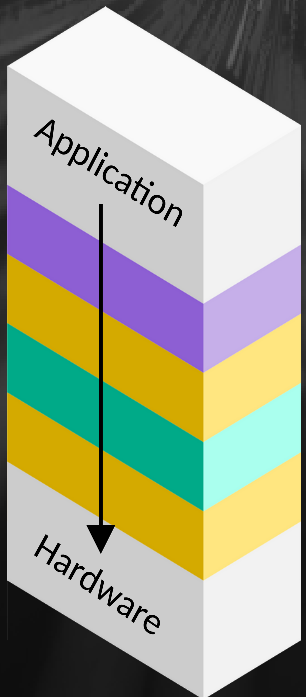
QPerfect

- Founded in Strasbourg, France 2023 + iLab Grand Prix
- Leader in quantum emulation with our flagship product: MIMIQ™
- Fast tracking practical fault-tolerant quantum computing (neutral atoms)

i-Lab Grand Prix 2023

La FRENCH TECH

The Quantum Logic Unit™-an "FTQC accelerator"



Bridging the gap from applications to early FTQC hardware

- Our application- and hardware-specific QEC strategies cut FTQC resource costs by 1000x or more
- Embedded software targeting >1k logical qubits & >1M logical gates by 2030
- **Anticipating a quantum-leap in digital infrastructure with cost-effective, application-specific quantum devices**

- **MVP:** full scale emulation of a 15:1 Magic state distillation circuit[1]
- **Strategic partnership** on quantum-secure transactions[2]

1 https://www.quera.com/press-releases/qperfect-and-quera-announce-collaboration-to-propel-simulations-of-quantum-error-correction-and-logical-quantum-algorithms
2 https://www.prnewswire.com/news-releases/btq-technologies-announces-strategic-partnership-with-qperfect-to-achieve-quantum-advantage-using-neutral-atom-quantum-processors-302477386.html

WHY BENCHMARK QUANTUM EMULATORS?

FACT OR FICTION?

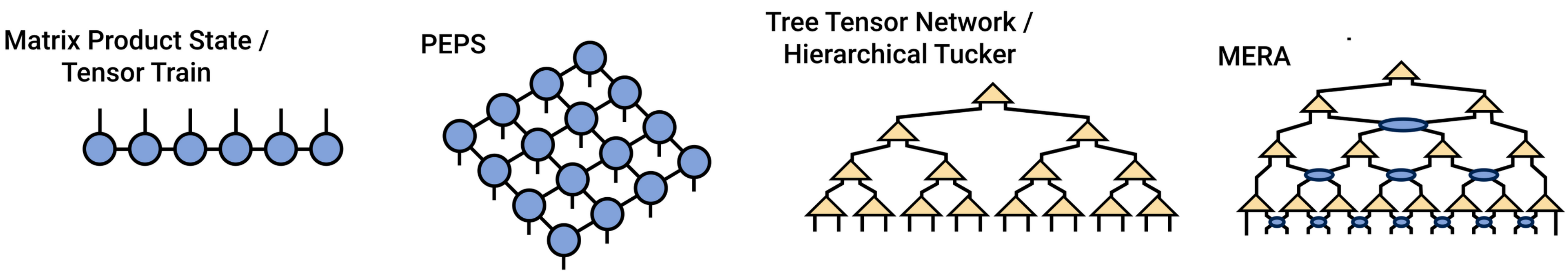
- Classical computers can only simulate ~40 qubits or less
- Tensor network simulations are inherently approximate
- Quantum computers can already perform computations that would take classical computers [insert number of years]

To know where quantum computers truly excel, we must also understand the limits of classical computers

TENSOR NETWORK EMULATORS

e.g., Matrix-product-states: The gold standard for simulating quantum computers

$$|\psi\rangle = \sum_{n_1 \ldots n_4} \sum_{i,j,k} A_i^{n_1} A_{ij}^{n_2} A_{jk}^{n_3} A_k^{n_4} |n_1 n_2 n_3 n_4\rangle$$



Other large scale emulators: Sparse matrices, Decision diagrams, Extended Clifford . . .

BENCHMARK STUDY DESIGN

1) Benchmark library: A standardized set of *scalable* benchmark algorithms covering a range of common quantum computing tasks

MUNICH QUANTUM TOOLKIT

arXiv:2204.13719
https://github.com/cda-tum/MQTBench

- Comprehensive open-source benchmark suite for quantum circuits
- Covers commonly used quantum circuit primitives and application-oriented tasks
- 13 circuit classes scalable up to 1024 qubits in OpenQASM format
- Transpilation of all circuits to a minimal gate set (u, cx) https://doi.org/10.5281/zenodo.15220683

BENCHMARK STUDY DESIGN

2) Emulator selection: Selection of 7 actively developed emulators capable of simulating circuits with 100 qubits or more

Matrix product states

Factorized ket

Tensor networks

Decision diagrams

Unified benchmarking framework with 12+ backends – *FENIQS*, by QPerfect

https://github.com/qperfect-io/feniqs_lite

BENCHMARK STUDY DESIGN

3) Performance metrics:

Scale
Maximum number of qubits with fidelity > 0.99 within 300 seconds

Accuracy (Mirror Circuit Fidelity)
Probability of sampling the initial state after running the circuit and its inverse *[Nature Phys. 18,75–79 (2022]*

Speed
Minimum time to execute the circuit, including import and sampling

All benchmarks performed using AMD EPYC 4244P 6-core processor with 12 threads, 130 GB RAM

HYPERPARAMETER OPTIMIZATION

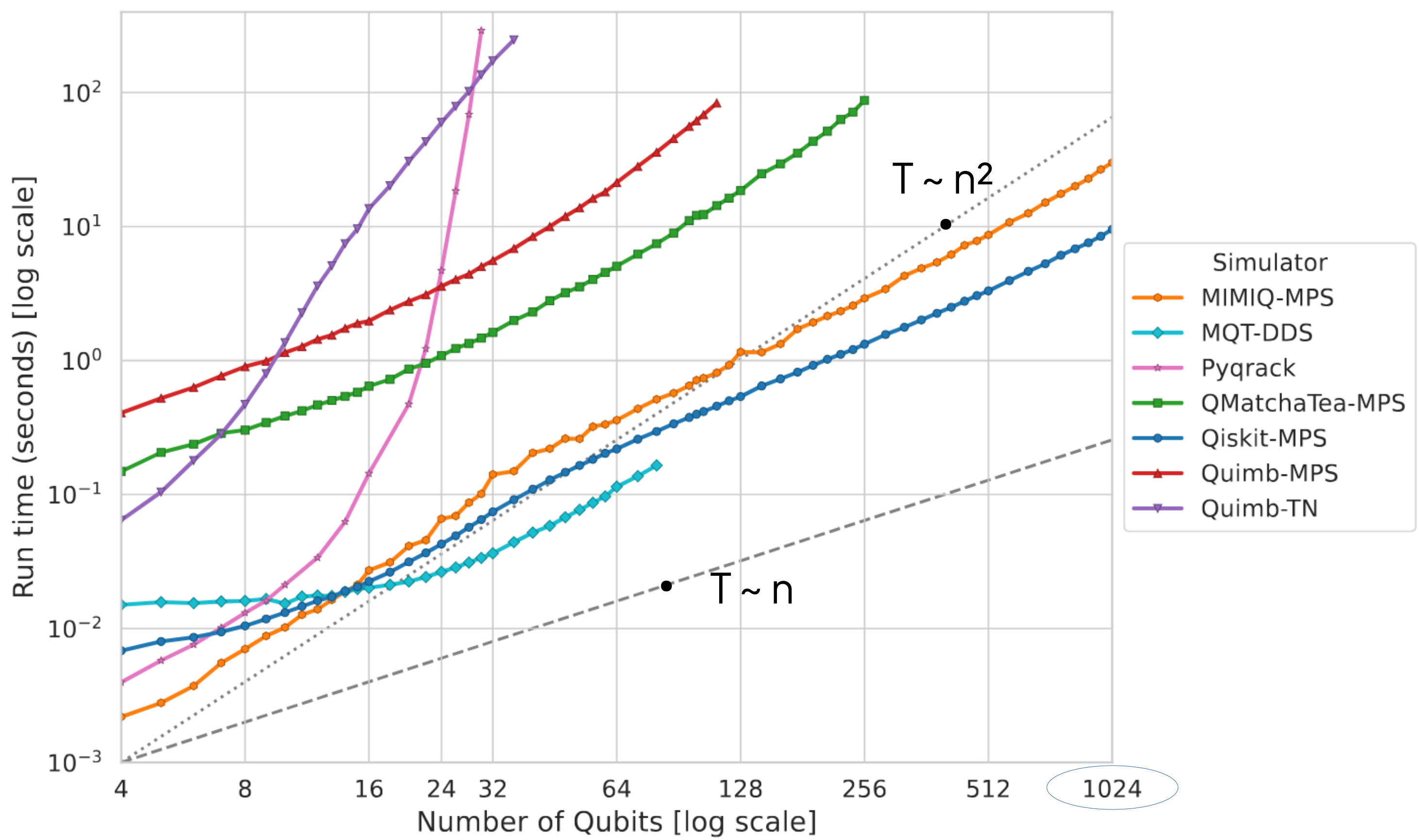
- Selected emulators expose tunable parameters and manual tuning is tedious and potentially biased

- Covariance Matrix Adaptation Evolution Strategy (CMA-ES) – automated search for optimal discrete and continuous parameters

Circuit	MIMIQ-MPS	Qiskit-MPS	Quimb-MPS	QMatchaTea-MPS	Quimb-TN
qft	[4/4/1e-5], [vmpoa/T/F]	[4/1e-10/AM],[1/T]	[4/1e-10], [F/AU]	[4/1e-10], [1/T/T]	F
qftentangled	[4/4/1e-5],[vmpoa/T/F]	[4/1e-10/AM],[1/F]	[4/1e-10], [F/AU]	[4/1e-10],[1/T/T]	T
ghz	[4/4/1e-5], [vmpoa/T/F]	[4/1e-10/P],[0/T]	[4/1e-10],[F/AU]	[4/1e-10], [0/F/F]	F
wstate	[4/4/1e-5], [vmpoa/T/F]	[4/1e-10/P],[0/T]	[4/1e-10] [F/AU]	[4/1e-10],[0/F/F]	F
qpeexact	[4/4/1e-5],[vmpoa/T/F]	[4/1e-10/P],[1/T]	[4/1e-10],[F/AU]	[4/1e-10],[1/T/T]	F
qpeinexact	[4/4/1e-5],[vmpoa/T/F]	[4/1e-10/P],[1/T]	[8/1e-10],[F/AU]	[4/1e-10], [1/T/T]	F
qwalk	[32/8/1e-5],[vmpoa/T/F]	[32/1e-5/P],[0/F]	[8/1e-10],[F/SS]	[8/1e-10], [0/T/T]	T
ae	[64/4/1e-3],[vmpoa/T/F]	[32/1e-5/P],[1/F]	[32/1e-6],[F/AU]	[32/1e-2],[1/T/T]	F
realamp	[32/4/1e-5],[vmpoa/T/F]	[1024/1e-6/P],[1/T]	[32/1e-10],[F/AU]	[64/1e-10],[1/T/T]	T
su2rand	[32/4/1e-5],[vmpoa/T/F]	[1024/1e-6/P],[1/T]	[32/1e-10],[F/AU]	[64/1e-10],[1/T/T]	T
qnn	[384/4/1e-5],[dmpo/T/F]	[256/1e-5/P],[1/T]	[256/1e-10],[F/AU]	[256/1e-10],[2/T/T]	T
graphstate	[256/16/1e-5],[vmpoa/T/T]	[2048/1e-10/P],[1/T]	[512/1e-10],[T/AU]	[1024/1e-10],[1/F/T]	F
random	[512/8/1e-5],[vmpoa/T/T]	[2048/1e-5/P],[1/T]	[128/1e-10],[F/AU]	[1024/1e-10],[0/T/T]	T

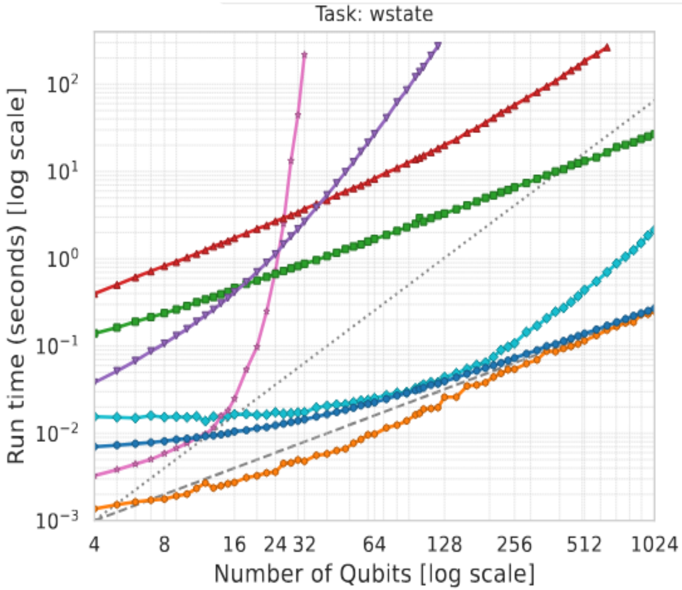
Optimal parameters differ widely across algorithms

BENCHMARKING RESULTS – QFT

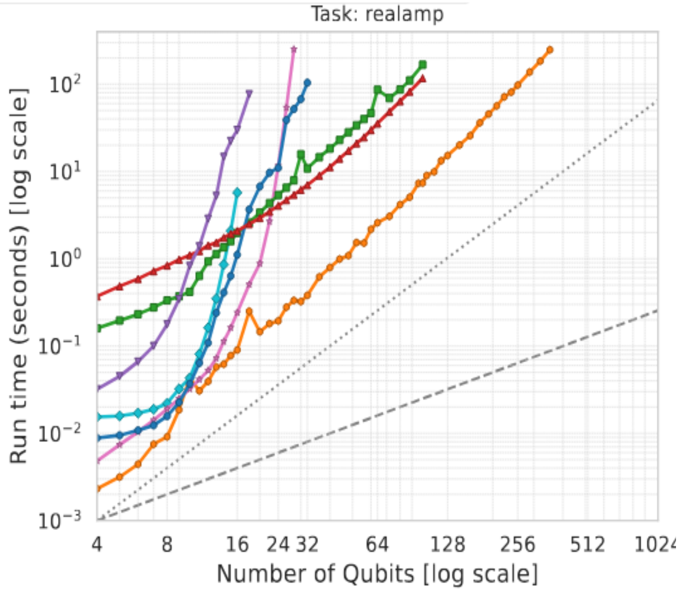


ALGORITHMIC COMPLEXITY

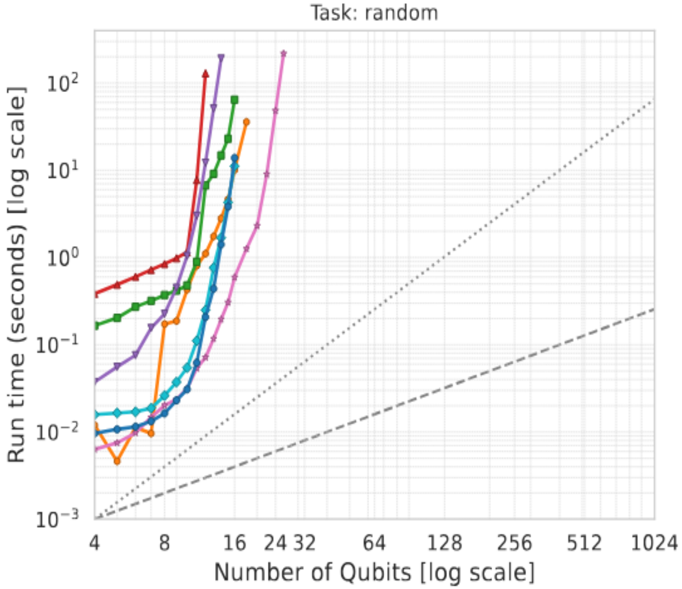
Easy



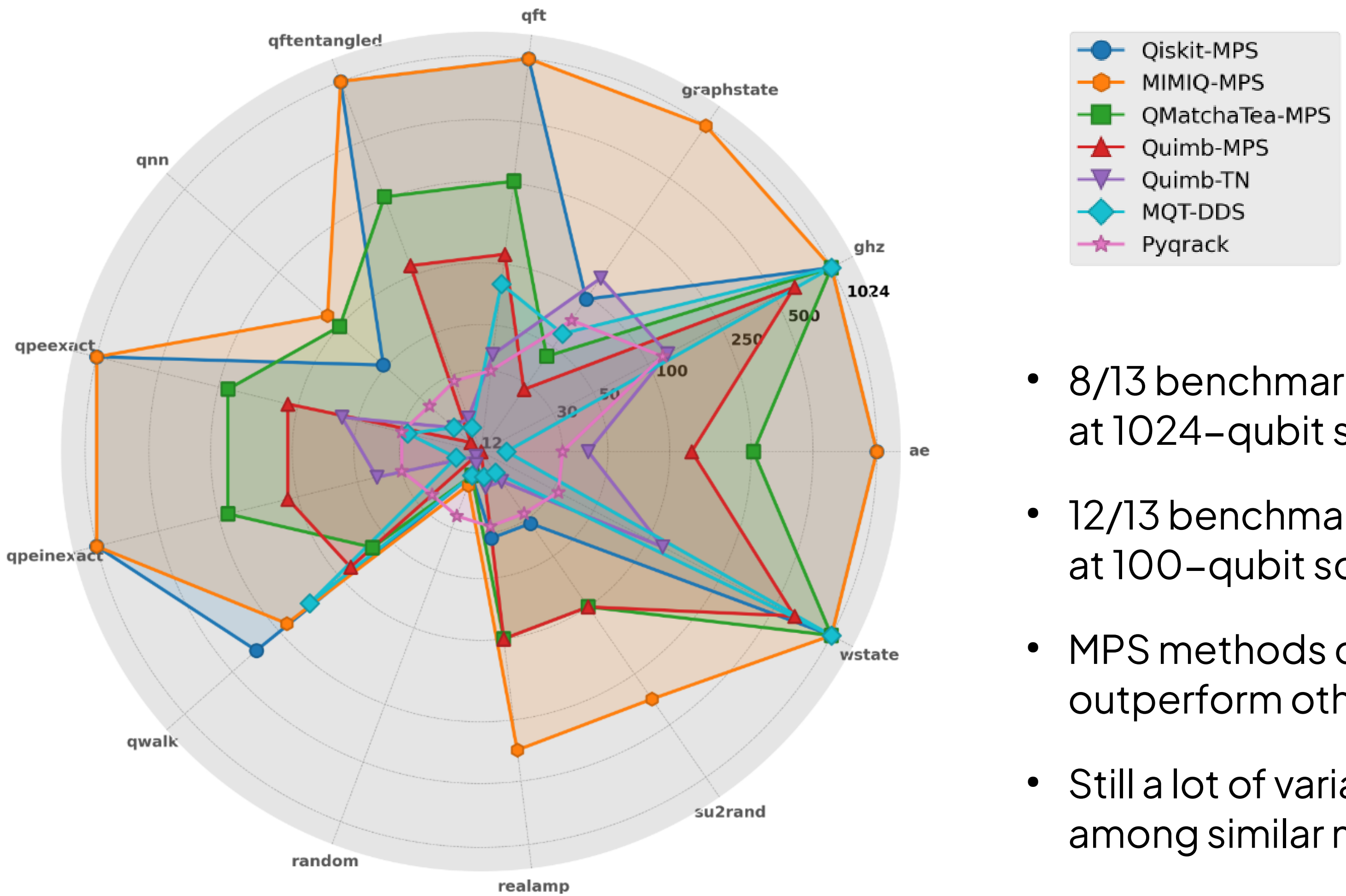
Medium



Very Hard



BENCHMARKING OVERVIEW



- 8/13 benchmark sets solved at 1024-qubit scale!
- 12/13 benchmark sets solved at 100-qubit scale!
- MPS methods consistently outperform other methods
- Still a lot of variation, even among similar methods

ELO RATING SYSTEM

A new way to measure the performance of quantum computing systems across benchmarks

Elo Rating System

If players A, B have ratings R_A and R_B, the expected score of players is

$$E_A = \frac{1}{1+10^{(R_B-R_A)/400}} \qquad E_B = \frac{1}{1+10^{(R_A-R_B)/400}}$$

After the game, players actually score S_A, S_B so their rating is updated

$$R'_A = R_A + K(S_A - E_A) \qquad R'_B = R_B + K(S_B - E_B)$$

where K is the maximum possible rating gain or loss per match

https://www.henrychesssets.com/elo-rating-system-definition-and-how-it-works-in-chess/

- Averaging over all "games" in our benchmark study

emulator	Elo Average	Std
MIMIQ-MPS	1,529	16
Qiskit-MPS	1,435	40
QMatchaTea-MPS	1,241	34
Quimb-MPS	1,132	51
Pyqrack	1,030	51
MQT-DDS	1,026	55
Quimb-TN	1,005	37

SUMMARY AND CONCLUSIONS

- The first comprehensive benchmarking of quantum emulators for simulating quantum algorithms in the “utility” regime (100 – 1024 qubits)
- Matrix product state-based simulators generally performed best, solving almost all benchmark problems in polynomial time. No single emulator dominated all algorithms.
- We need more difficult benchmarks !

Interested in comparing emulators for your specific use case using FENIQS?
Want to try the world’s most powerful quantum emulator MIMIQ ?

Contact us at: shannon.whitlock@qperfect.io

- On-going work:
  - Developing faster methods for hyperparameter optimization based on AI
  - Competitive platform for benchmarking quantum computer systems (?)