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QUEST-IS'25
QUANTUM ENGINEERING SCIENCES & TECHNOLOGIES FOR INDUSTRY & SERVICES

BACQ
MetriQs-France

Applications-Oriented Benchmarks of Quantum Computers

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FRANCE 2030

anr agence nationale de la recherche

BACQ: A collaborative R&D project

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- **Key figures**
  - **3-year** project (Sept. 2023 – August 2026)
  - **6 partners : Thales**, Eviden, CEA, CNRS, Teratec, LNE
  - **7,2 FTE/year**
  - **3,9 M€ budget**

- **Access to QC and emulators**
  - Direct collaboration with **QPU providers**
  - **HQI** / CEA TGCC (HPC-QC)
  - **EuroHPC** (EU QC hosting sites)

- **Major outcomes after 3 years**
  - **First set of validated application-oriented benchmarks**
  - **Multi-criteria notation model for quantum computers**

- **Long term vision**

  LNE, as independent trusted third party:
  - **Makes the benchmarking tools publicly available via a Gitlab library**
  - **Collects and publishes the evaluation results**

- **Maximizing impact**
  - **Consultations** (Industry – Tech. providers and End-users - , Academia, Gov. agencies…)
  - **EU and international cooperation** (R&D teams, benchmarking initiatives…)
  - **Standardization** (AFNOR, CEN-CENELEC, ISO/IEC, IEEE)
  - **Publications & Communications**

BACQ: Application-oriented benchmarks for quantum computing

- ## Scientific approach

Benchmarks adapted to analog to gate-based machines NISQ to FTQC

1. Definition of **reference problems to be solved**

   [Optimization – Simulation of quantum physics – Linear system solving – Factorization]

2. Definition of **technical metrics** for their resolution

   [**Computational** and **energetic**]

3. **Aggregation of the metrics** and **multi-criteria analysis** to derive **high-level operational indicators**

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BACQ: The generic reference problems

Simulation of Quantum Physics
(Ising model in transverse field, BCS model)

Optimization
(including MAXCUT / Q-score)

Linear Systems Solving

Prime factorization

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BACQ: The technical metrics

- **[*Simulation of Quantum Physics*]**
  - Many-body Quantum Score
- **[*Optimization*]**
  - **Q-score MaxCut**
  - **Accuracy** indexed by noise level
  - Compilation-dependent criteria
  - Probability of obtaining the optimum
  - Min case/Max case gap with regards to the optimum
  - **Size of the problem** in number of variables, number of qubits to solve the problem, class of problem addressed
- **[*Linear Systems Solving*]**
  - Accuracy indexed by noise level
  - Compilation-dependent criteria
  - **Probability of solving** the problem, number of variables and precision in qubits
  - **Algorithm-dependent energetic criteria**
- **[*Factorization*]**
  - Probability to factorize
  - Size in bits of the calculated number
- **[*Generic*]**
  - **Computation time**
  - Latency
  - Throughput

More to be added…

BACQ: Aggregation of the metrics into high-level operational indicators

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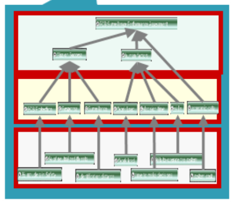
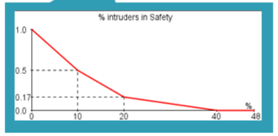
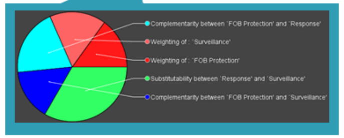
- Overall evaluation
  - Analytical N-Body
    - Q-score Many-Body
    - Many-Body Fidelity
  - Optimization (MaxCut, HOBO, S-Path)
    - Q-score MaxCut
    - Accuracy indexed by noise level
    - Probability of obtaining the optimum
  - Linear systems Solving (sparse/Dense matrix)
    - Accuracy indexed by noise level
    - Probability of solving the Problem
    - Algorithm-dependant Energetic criteria
  - Factorization
    - Probability to factorize
    - Size in Qubit of the calculated number

Problem Formalization: Metrics identification → Metrics normalization → Metrics aggregation

Performance assessment: Notation elaboration → Notation explanation



With Choquet integral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Building a future we can all trust

- **Aggregates** all the metrics into a unique score (allowing ranking the solutions)
- Takes into account: the **interacting metrics**
  the **user preferences**
- Fully **interpretable** and **explainable**

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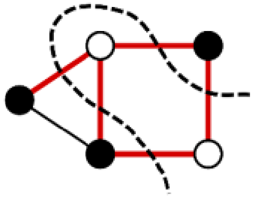
BACQ: Metrics development - Q-score

[*Optimization*]

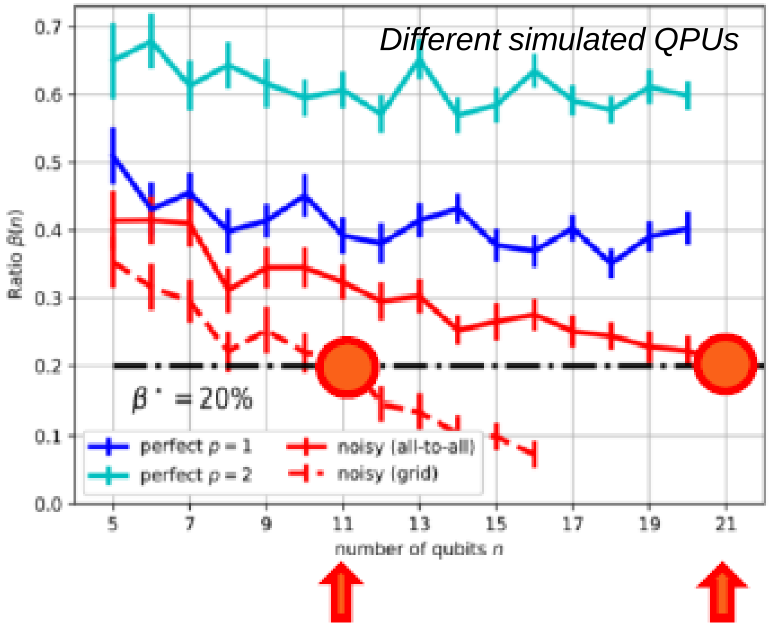
- **Q-score/MaxCut** addresses a complex **combinatorial optimization problem** (MaxCut) for which a quantum advantage is expected.

Problem to be solved : MaxCut

Find the set of vertices that maximizes the number of outgoing edges



- Methodology to assess if **a QPU** can solve a **given size of graphs**
  - Classically compute the average solution for a family of graphs of this size
  - Randomly choose n graphs among this family of graphs
  - Execute it on a quantum machine
  - Compute the quantum average and its standard deviation to the classical average



Q-score value

- **Q-score/MaxCut is the maximal size of graphs that the QPU can handle with an acceptable approximation rate**

- Q-score **is scalable** because the **reference** used to validate a success is an average on a random sample of graphs which is **easily computed classically**; despite individual graphs being complex to solve classically.

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BACQ: Metrics development - Fast Track Q-score

[*Optimization*]

- **Q-score/MaxCut originally implemented on gate-based machines**
  - Q-score definition, by Atos [DOI: 10.1109/TQE.2021.3090207]
- **Extend, Test and Validate the implementation of Q-score/MaxCut on a large variety of quantum machines**
  - Towards a “universal” benchmark
- **Q-score implementation and Fast-Track achievement:**
  - Q-score/MaxCut on **D-Wave** [annealer], by **TNO** [DOI: 10.1109/QSW55613.2022.00017]
  - Q-score/MaxCut implementation on **Quandela** emulator [photonic], by Quandela
  - Q-score/MaxCut on **Pasqal** emulator [neutral atoms], by Pasqal [arxiv:arXiv:2207.13030]
  - Q-score/MaxCut on **IQM** QPU [superconducting], by IQM [arXiv:2402.07315]
  - Q-score/MaxCut on **Quandela** QPU [Photonic], by Quandela [https://www.quandela.com/cloud/]
- **Ongoing activities:**
  - Q-score/MaxCut implementation with **Quantinuum & Universal Quantum** [trapped ions]
  - Brainstorming within BACQ collaboration to standardize the Q-score MaxCut benchmark
  - Discussion on publications

BACQ: Metrics development

Simulation of Quantum Physics Models

- **Why ?**

Quantum physics problems with **many interacting particles** arise in various fields of science:

- solid-state physics (superconductivity, correlated electrons, quantum magnetism, electronic transport, understanding new quantum phenomena & design of new materials with potential applications)
- chemistry (electronic structure of molecules, elucidating chemical reactions, catalyst design, …)
- high-energy physics (particle or nuclear physics, gauge theories)

…

Simulating these quantum many-body systems is notoriously difficult on a classical computer

- **Goal**

Develop metrics to quantify the capacity of a quantum machine **to simulate accurately** physically relevant quantum many-body problems

- **Method**

- Target non-trivial **many-qubit entangled states**

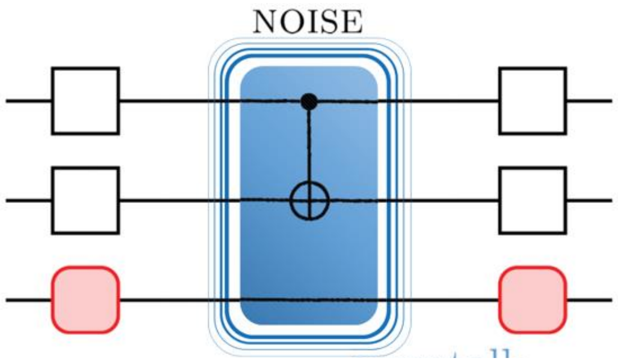
- Focus on many-body problems/states/Hamiltonians which are **exactly solvable**
(to allow for comparison between the theoretical [error-free] results and the measured ones)

Benchmarking of gate-based machines

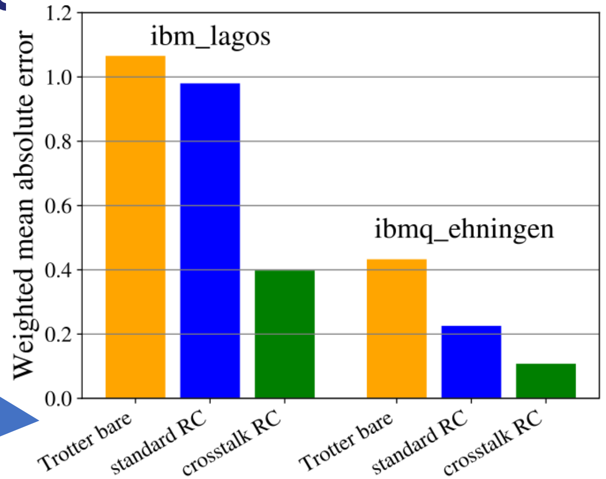
- Simulating quench in a BCS model on few qubits

$$\hat{H}_{\mathrm{BCS}} = -\sum_{j=0}^{L-1}\left(\epsilon_j - \frac{g}{2}\right)\sigma_j^z - \frac{g}{2}\sum_{\substack{i,j=0\\ i<j}}^{L-1}\left(\sigma_i^x\sigma_j^x + \sigma_i^y\sigma_j^y\right)$$

- Using a stack of error-mitigation techniques (randomized compiling+)
- Calculating average error over multiple obse and over simulation durations



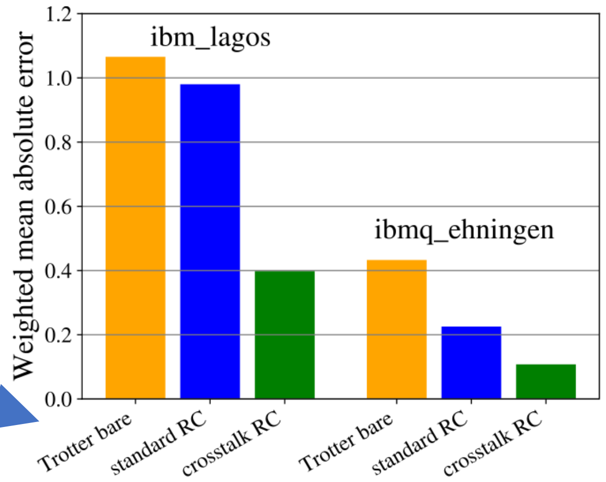
- Varying the error-mitigation techniques enables understanding the relevance of different error sources (e.g., crosstalk)



PRResearch **6**, 013142 (2024)

Benchmarking of gate-based machines

- **Varying the error-mitigation techniques enables understanding the relevance of different error sources (e.g., crosstalk)**



=> Next task: evaluate multiple machines (manufacturer, architecture, platform, generation)

BACQ: Metrics development

Simulation of Quantum Physics Models

- Models & Architectures
  - Ising chain with transverse field in quench
  - Analog quantum simulators or gate-based QPU
- Metrics development
  (work in progress by Eviden quantum Lab & CEA/DRF)
  - 1D chain is integrable and an exact theoretical **solution is available**
  - Compare simulation results from an analog machine with exact results
  - Noisy simulation using Eviden's Qaptiva emulator
  - Currently testing which indicators to measure/compare between simulated and exact values
    - Goal: Assess the machine's performance on larger chain sizes or longer simulation times
    - Set a **tolerance threshold** for the score obtained
  - First tests of Many-body Quantum Score in progress (H. Erbin et al.) on PASQAL QPU (Ruby) at TGCC CEA

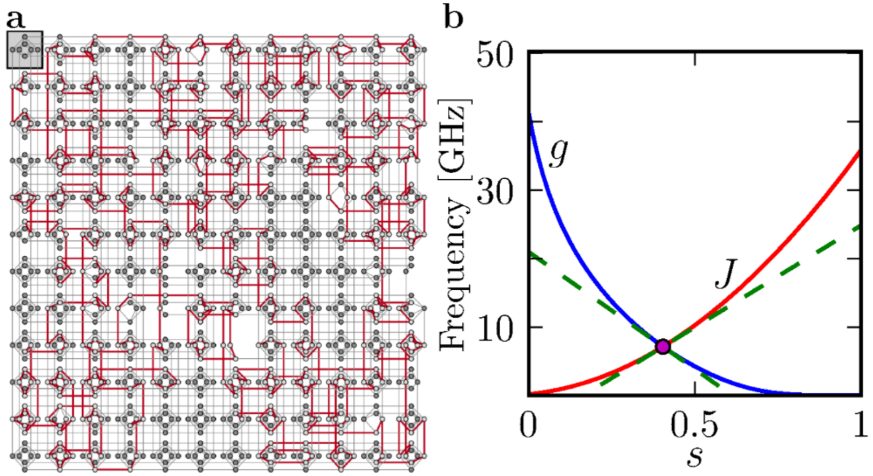


FIG. 1. **The quantum Ising chain implemented in a D-Wave computer. a.** An example of an Ising chain on the D-Wave "chimera graph". The red lines are active couplings between "spins". **b.** A typical annealing protocol for a D-Wave annealer. Here $J(s) = J_{\max} \cdot j(s)$, where $j(s)$ is a predetermined function increasing from $j(0) = 0$ to its maximal value $j(1)$ and $J_{\max} \in [-1, 1]$ is a free parameter that can be turned at will.

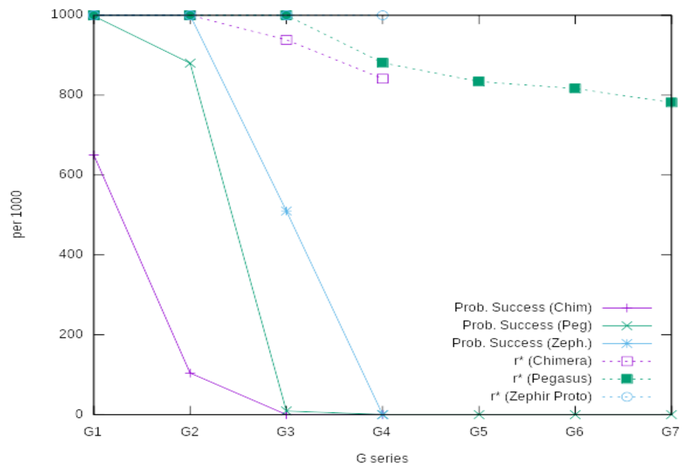
https://doi.org/10.1038/s41598-018-22763-2

BACQ: Optimization problems

- **Gate-based and analog QC applications for optimization**

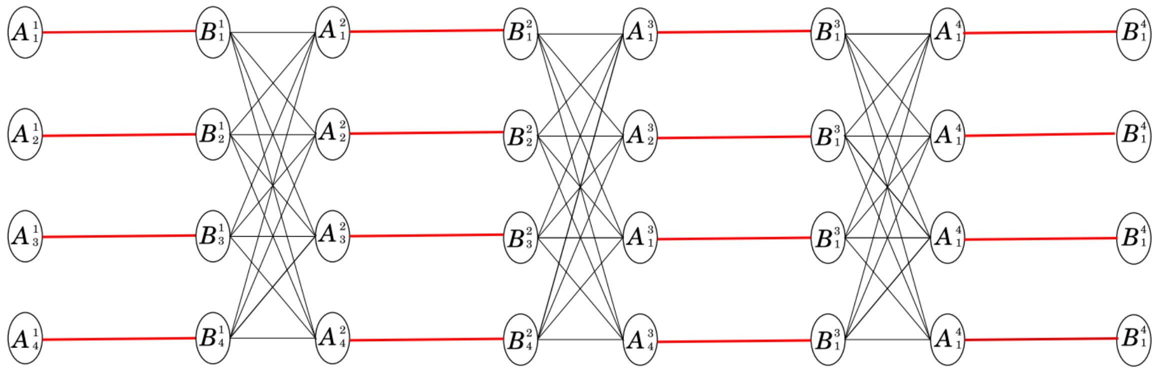
- Idea: Develop metrics to evaluate quantum computers on **several classes of optimization problems**

	Polynomial	NP-hard	Non-quadratic
Unconstrained		Q-Score MaxCut	Prime Factorization (hamiltonian based)
Constrained	MCM/G series	Future extension	



- Q-Score MaxCut already an established benchmark data-point
- MCM/Gn series is an historically important class of problems to probe the efficiency of annealing heuristics
- Metrics: (Q-Score already self-supported as a benchmarking data-point)
  - **Probability of finding the optimum** or distance to optimum/solution
  - **Size of the problem**
  - **Complexity and sparsity of the problem**
  - **Complexity of pre/post processing if required**

G-Score, an evaluation of quantum optimization heuristics for constrained problems



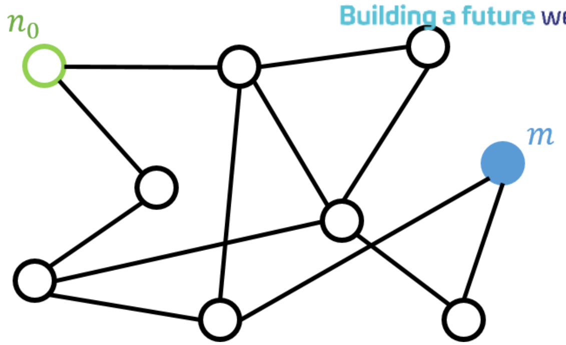
The G-score measures how many variables a (quantum) heuristic can effectively handle in a constrained optimization problem

1. **Based on a well known series of constrained problems [Sasaki&Hajek, 1988]**
2. **The score takes into account**
   A. The capability to significantly solve the problem to a point ns with probability pns
   B. In the first failed problem ns+1
   C. Hamming distance ratio rh
   D. The ratio of violated constraints rd for first failed problem

Heuristics	n_s	r_0	p_{ns}	S_G
Quantum Annealing (DW2000Q)	2	0.938	0.849	**54.7**
Quantum Annealing (DW-Advantage)	3	0.904	0.146	**70.5**
QA (DW-Advantage2)	3	0.936	0.315	**79.2**
NEC Vector Annealing V3	7	0.95	1,0	**717**

WalkScore for Optimization Problem : Solving a Graph Pathfinding Problem…

Find a destination node from a source node in a graph, with high enough success probability

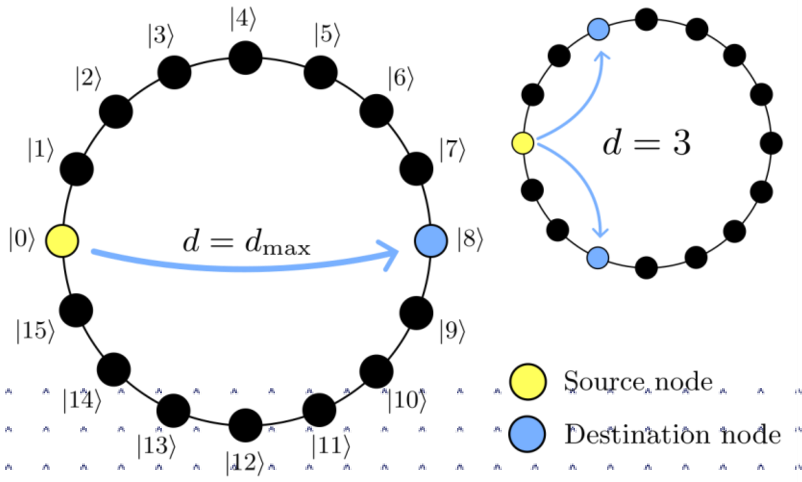


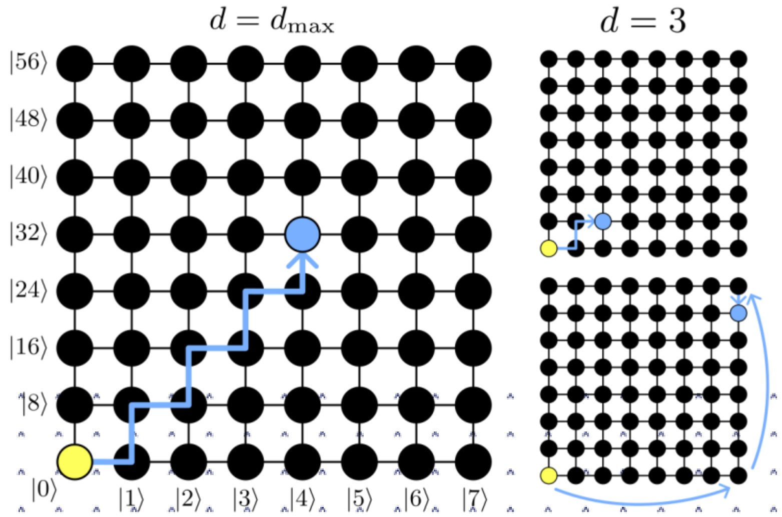
$(P_{cycle}^{n,d})$

Find the destination node, located at a distance d from the source, in the cycle graph of 2^n nodes, with a success probability $p \geq p_{cycle}^*(n, d)$

$(P_{torus}^{n,d})$

Find the destination node, located at a distance d from the source, in the 2D-torus graph of $2^n \times 2^n$ nodes, with a success probability $p \geq p_{torus}^*(n, d)$



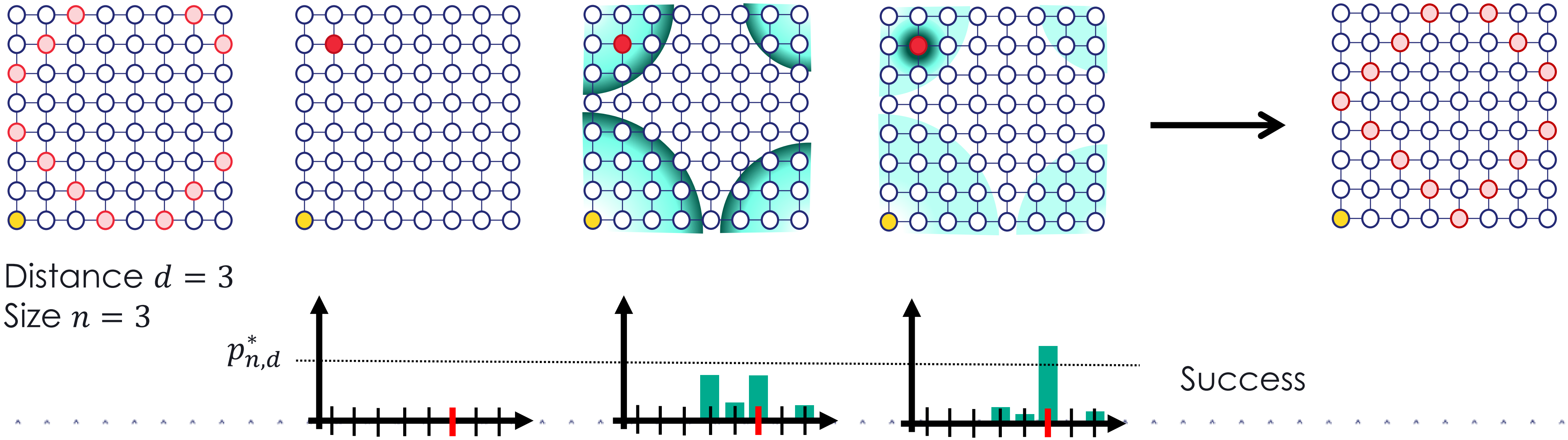


WalkScore for Optimization Problem:
…using an algorithm based on DTQW & Amplitude Amplification

> Goal :

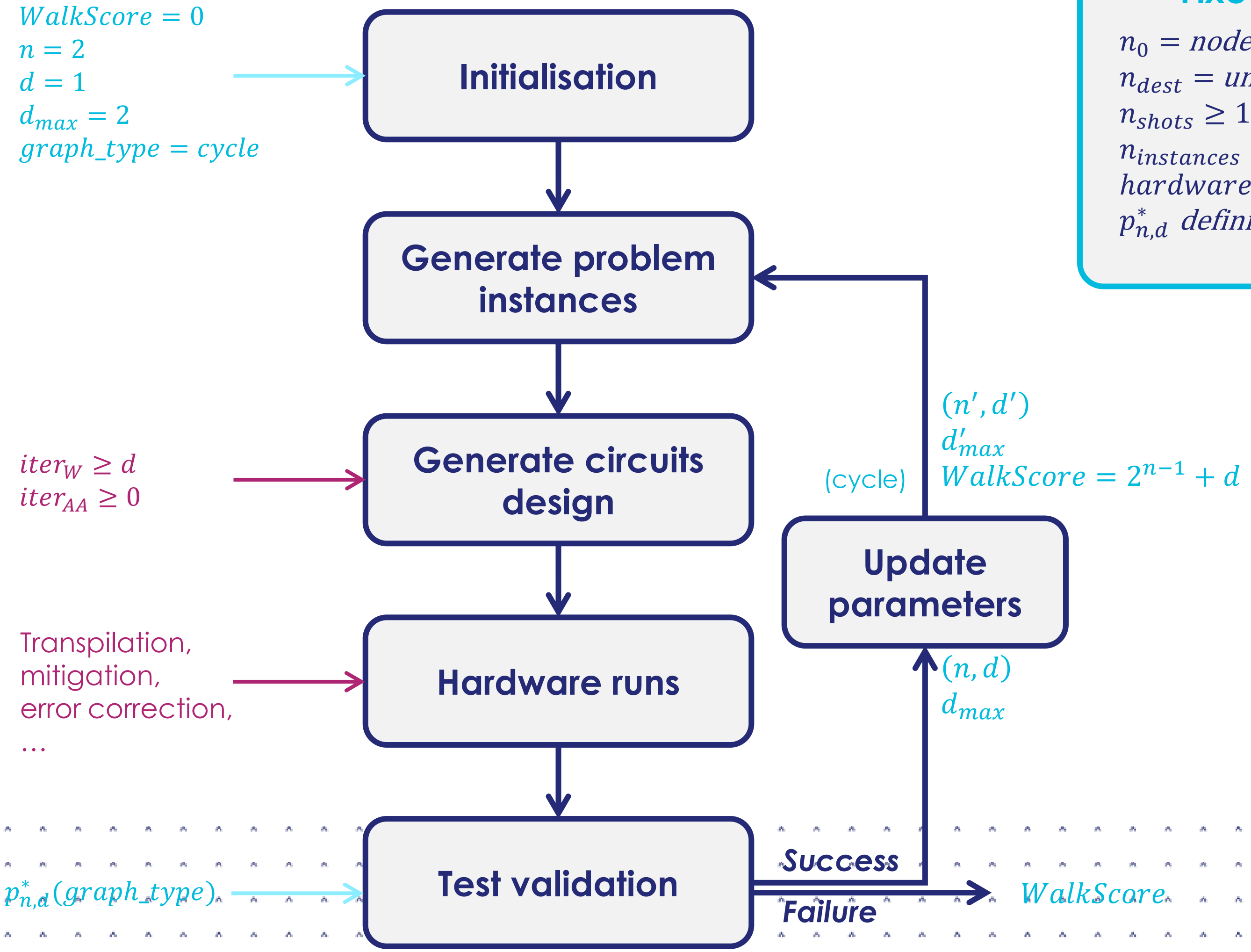
- Highlight hardware progress to leverage promising quantum routines for optimization applications
- Focus on Quantum Walks and Amplitude Amplification

> Global protocol description



$$S_{\text{cycle}} = 2^{\tilde{n}-1} + \tilde{d} \quad \text{and} \quad S_{\text{torus}} = 2^{\tilde{n}} + \tilde{d} \quad \text{s.t} \begin{cases} \forall n, d \in \mathbb{N}, n \leq \tilde{n}, d \leq \tilde{d} \Rightarrow \left(P^{(n,d)}_{\text{graph}}\right) & \text{successful} \\ \left(P^{(n,d)+1}_{\text{graph}}\right) & \text{unsuccessful} \end{cases}$$

WalkScore for Optimization Problem: protocol description



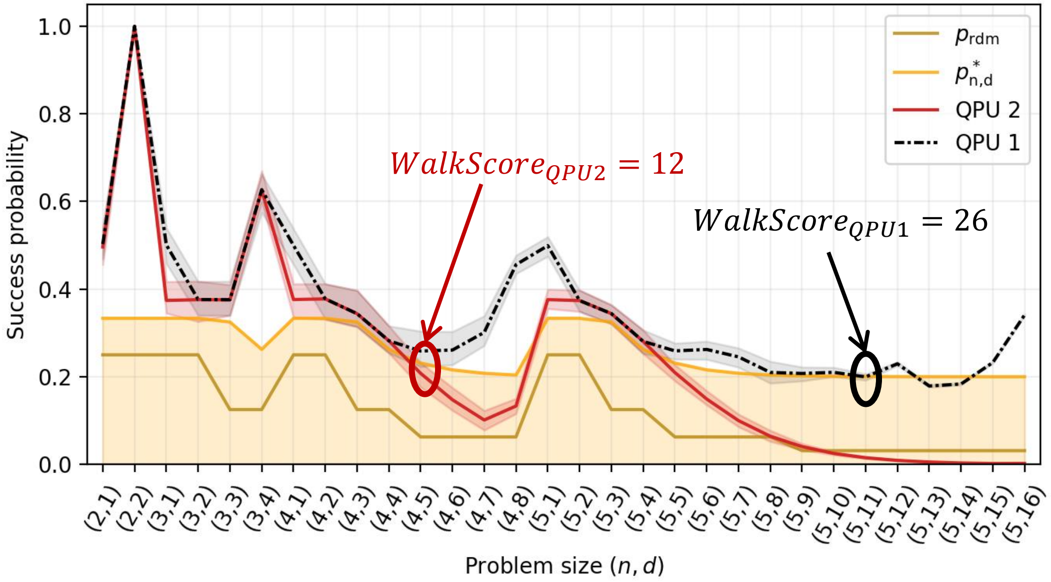
Fixed input parameters

$n_0 = node\ 0$
$n_{dest} = uniformly\ sampled$
$n_{shots} \geq 1000$
$n_{instances} \geq 10$
$hardware = \cdots$
$p^*_{n,d}$ *definition*

Parameters at hand

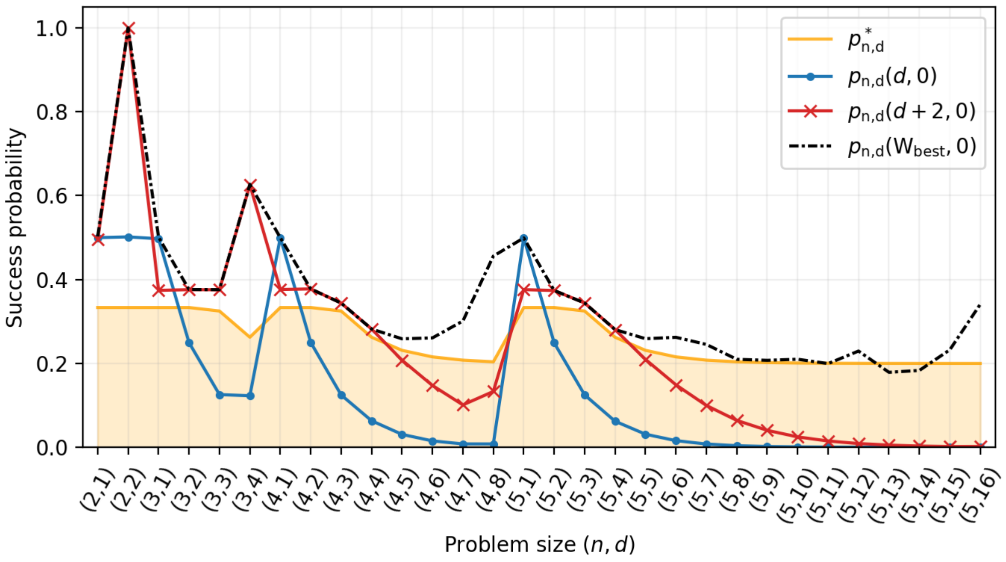
$n_{max} = \cdots$
$iter\_W = \cdots$
$iter\_AA = \cdots$
Transpilation routine, etc.

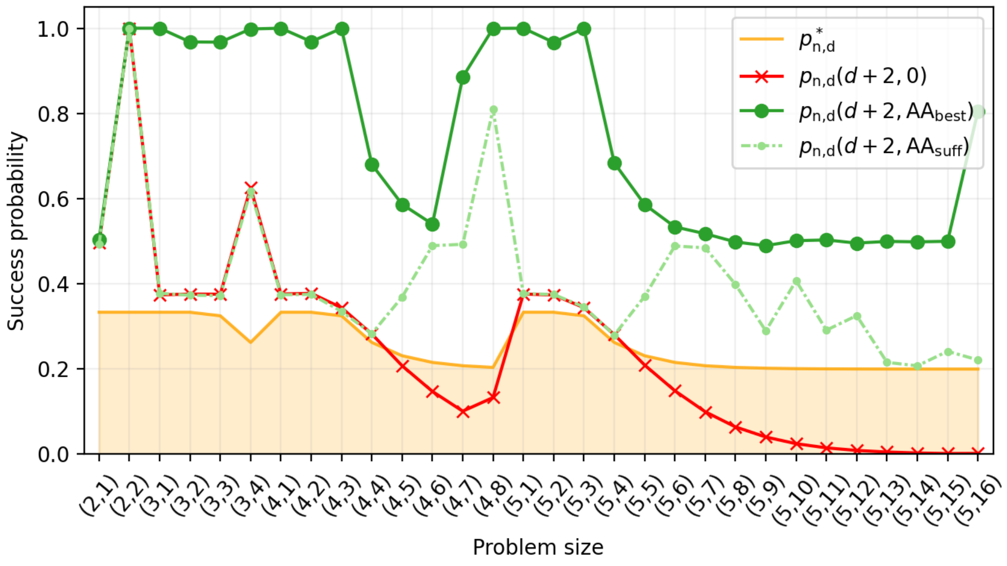
(cycle) $$p^*_{n,d} = \begin{cases} 1/3 & \text{If } d \leq 2 \\ \frac{1}{5} + \frac{1}{2^d} & \text{If } d > 2 \end{cases}$$



Walkscore: Simulation Tests Results

> Simulations on qiskit : ideal quantum computer, cycle graphs





→ Variation in number of QW steps
→ No Amplitude Amplification

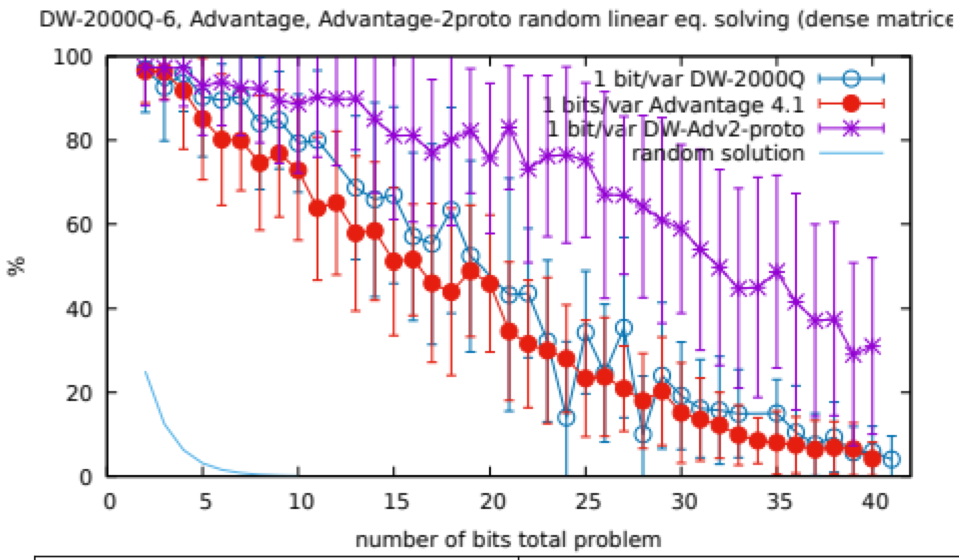
→ Variation in number of Amplitude Amplification steps
→ Fixed number of QW steps to $d+2$

***WalkScore* value depends on hardware capabilities and algorithmic choices !**

Capabilities of solving a system of linear equations

Two scores are defined

- The optimistic one evaluates an unrealistic case of a system with binary solutions
  - Only 1 bit of resolution is required



QPU	Solving capability (bits)
DW-2000Q	20
DW-Advantage	18
DW-Advantage-2	32

- The realistic one reflects the actual solving capabilities on the most realistic problems the evaluated quantum computer can solve
  - Highest resolution for the unknowns, minimum 2 unknows and 2 equations for the system
  - **DWave Advantage** achieves 2 unknowns with 4 bits of resolution (solving with 8 significant bits)
  - **Dwave Advantage-2** achieves 3 unknows with 4 bits of resolution (solving with 12 significant bits)

BACQ: Prime factorization

(Hamiltonian-based) integer factorization

- Idea: Develop metrics to evaluate the capabilities of quantum computers on **prime factorization**
  - Prime factorization is a very hyped potential utilization of QC
  - Make it work on gate-based and analog QC
  - Shor's algorithm will not work before FTQC
  - Once FTQCs are available, we can still use this first method 1) for analog 2) as a base of HOBO problem
  - SotA: factorization of 8,219,299 = 32,749×251 on D-Wave Advantage
- Metrics:

  - Probability of finding the optimum or distance to optimum/solution

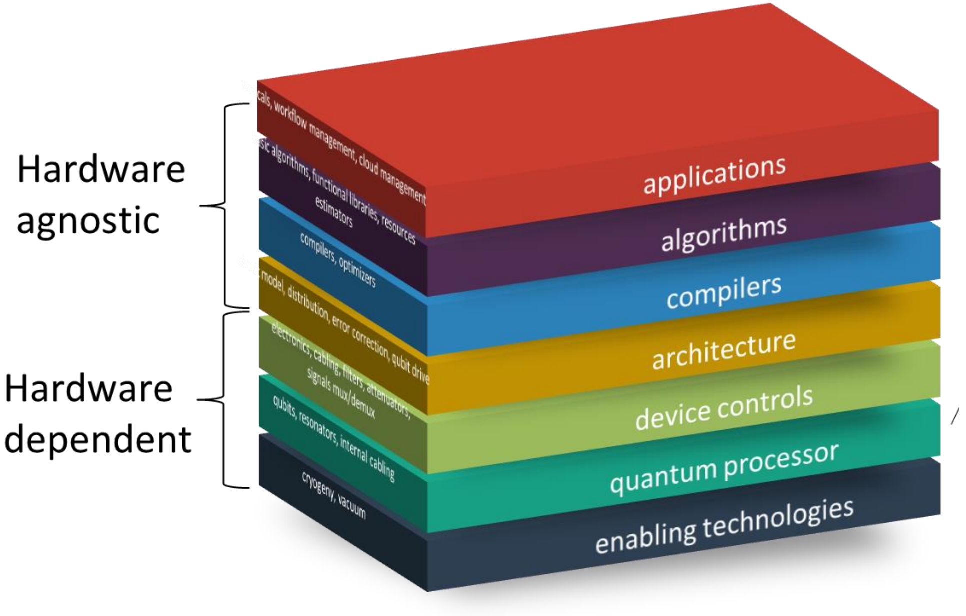
  - Size of the problem

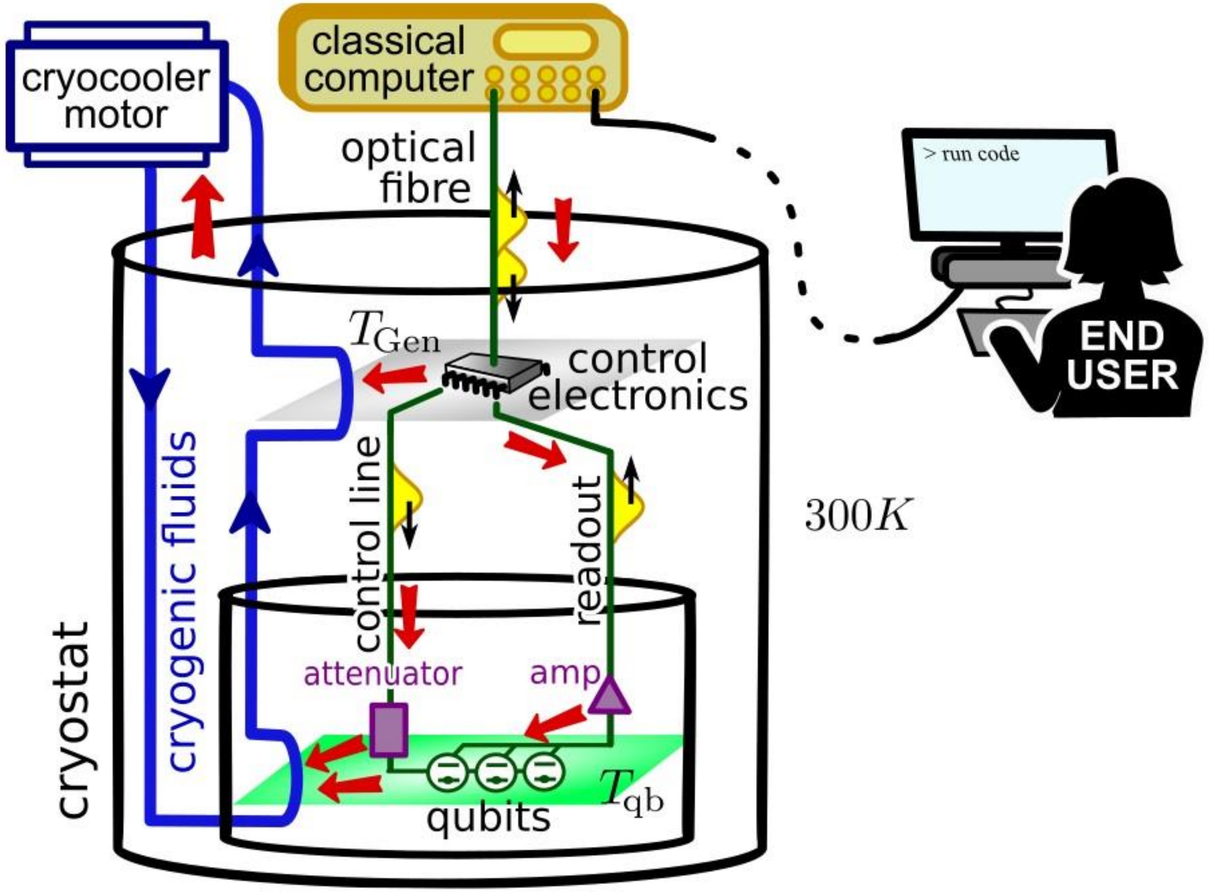
  - Complexity and sparsity of the problem

  - Complexity of pre/post processing if required

BACQ: Metrics elaboration - Energetics

Defining **Resource Efficiency** as the ratio of **Performance Metrics / Resource Cost**





In BACQ, focus on resources at the HW-agnostic layers for linear system solving, with test on a gate-based machine

BACQ: Metrics elaboration – Energetic Benchmarks for Gate-Based

Goal: propose and simulate energetic benchmarks

- Energy is critical for competitivity and sovereignty
- Currently no energetic benchmark for quantum computing => France can take a leadership
- Challenges: methodologic (interdisciplinarity), strategic (acceptation of the benchmark)

MNR (metrics noise resource)

- Under study: a simple gate-based quantum machine
- Build up of a systemic *hardware-agnostic* approach

D3.1 List of control parameters and algorithmic resources for a gate-based quantum machine performing a simple task. Design and exploitation of an Algorithmic Resource Estimator for the studied problem (M18)

D3.2 Optimization of the algorithmic efficiency for a fixed noise and effective relation to the energetic performance of the machine (M36)

Working group Quantum Energy Initiative @ IEEE

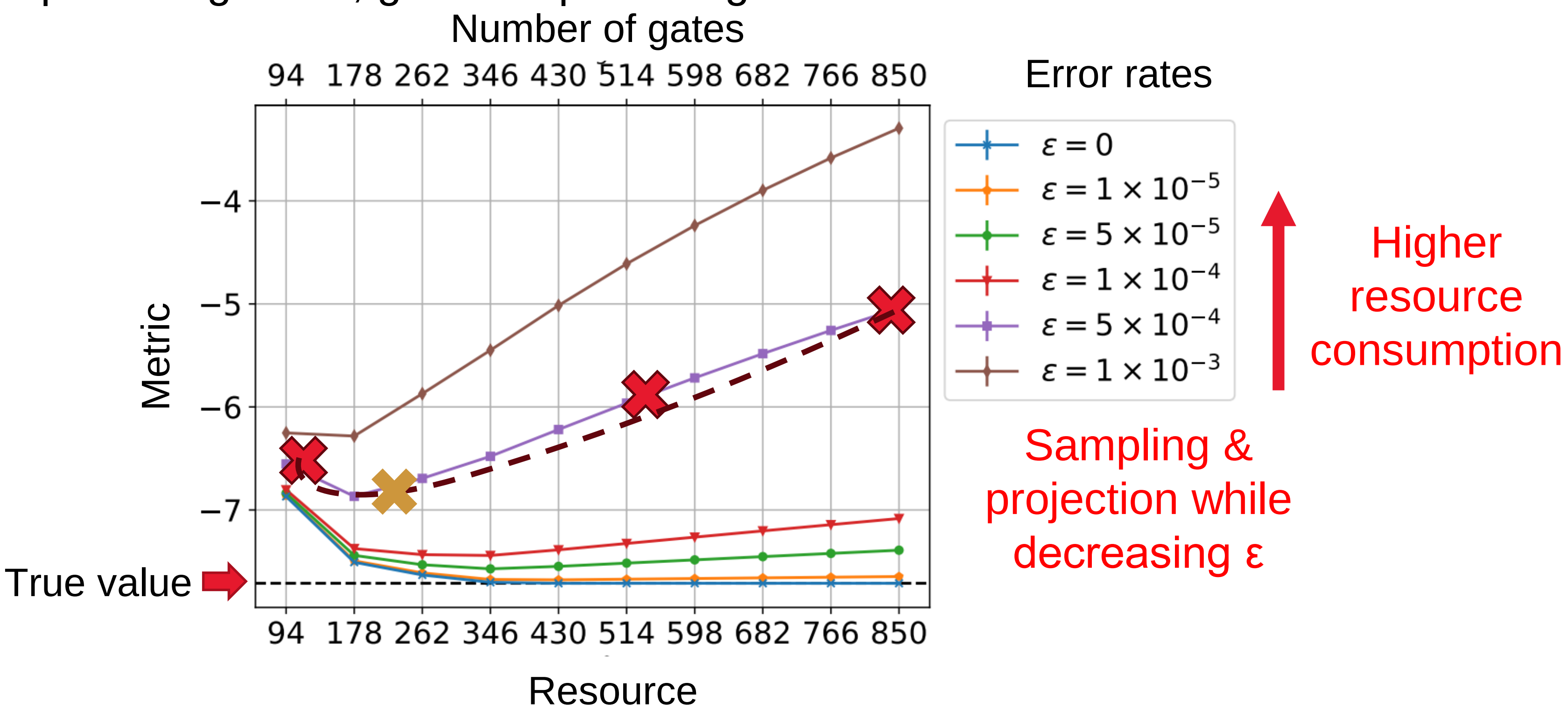
- D3.3 (M12, M24, M36): Proposition of frameworks and contribution of the validation of the standard

#QEI the quantum energy initiative

IEEE SA STANDARDS ASSOCIATION

Hardware agnostic resource estimator from MNR tradeoff

- What is the minimum energy consumption required to reach a target metric/ tolerance?
- In principle works for any algorithm where accuracy increases with circuit size and error accumulates with circuit size.
- Eg for : gate depolarizing noise, global depolarizing noise



Hardware agnostic resource estimator from MNR tradeoff

en_opt(nqbits, dep_list, n_samples, tol, err_rates, rds, tol_flag = False, *args):

Number of qubits

Number of layers
[list]

Number of sampling points

Tolerance
Or
convergence criteria

Possible error range
[list]

Number of random seeds used per sampled point

If True, measure tolerance i.e. gain in metric per error rate, else compare with target metric

Target metric (optional); if tol_flag is False

True if converged

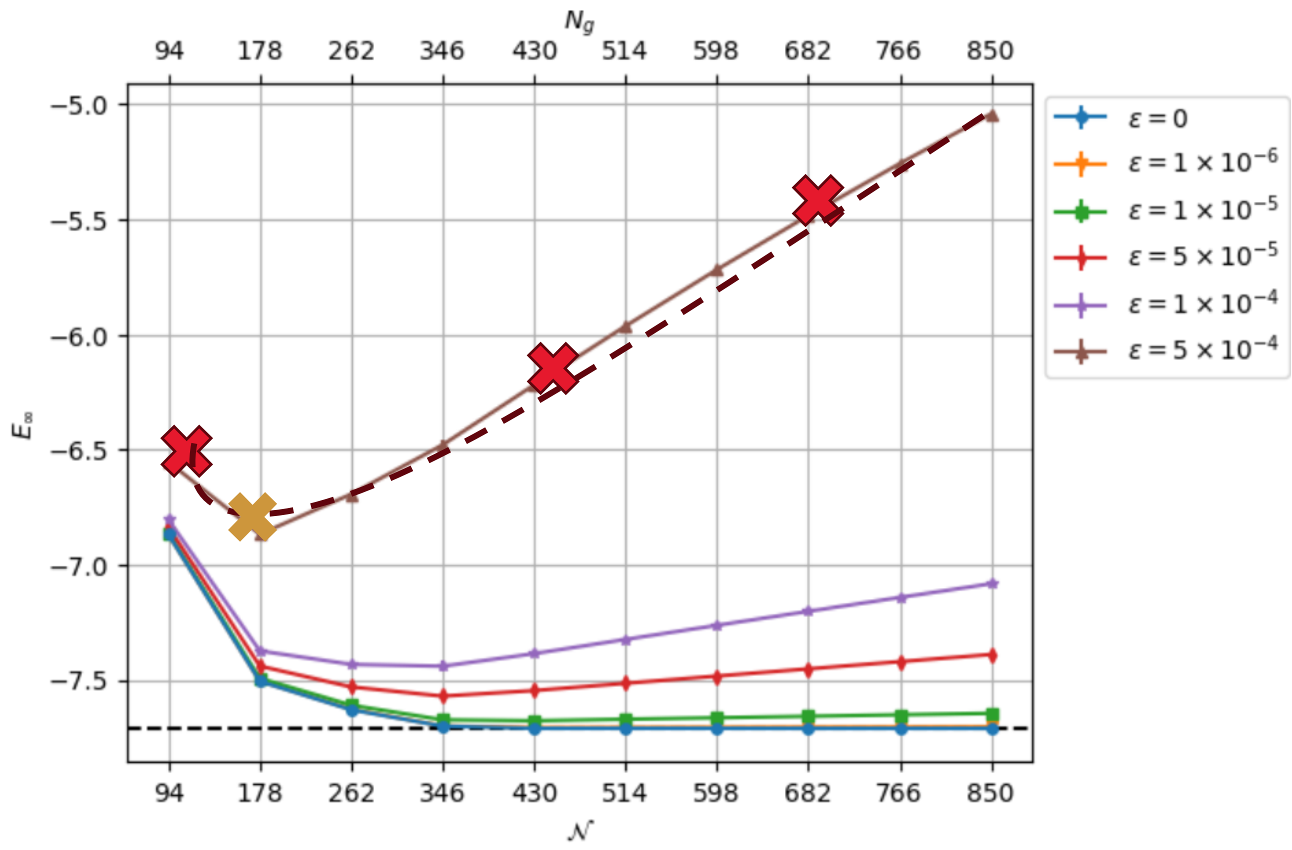
Optimal set of error rate and number of layers / gates

Return convergence_flag, $(\epsilon_{\text{opt}}, N_{\text{opt}})$

Hardware agnostic parameters for minimal resource consumption

Hardware agnostic resource estimator from MNR tradeoff

1. Start with least energy – highest error provided.
2. Pick samples and fit a curve.
3. Each sampled point has multiple runs with different seeds (runs parallel).
4. Result selected are the minimum from all seeds.
5. Sample at the projected minima.
6. If |sampled value at minima – target| > tolerance, move to the next curve.
7. Sampled points on the next curve near the sampled minima from the previous.
8. Repeat from 3, until tolerance is reached.



BACQ: Aggregation of the metrics into high-level operational indicators

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2030

- Overall evaluation
  - Analytical N-Body
    - Q-score Many-Body
    - Many-Body Fidelity
  - Optimization (MaxCut, HOBO, S-Path)
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Problem Formalization: Metrics identification → Metrics normalization → Metrics aggregation

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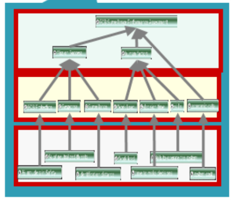

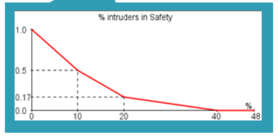

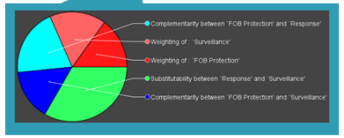

With Choquet integral

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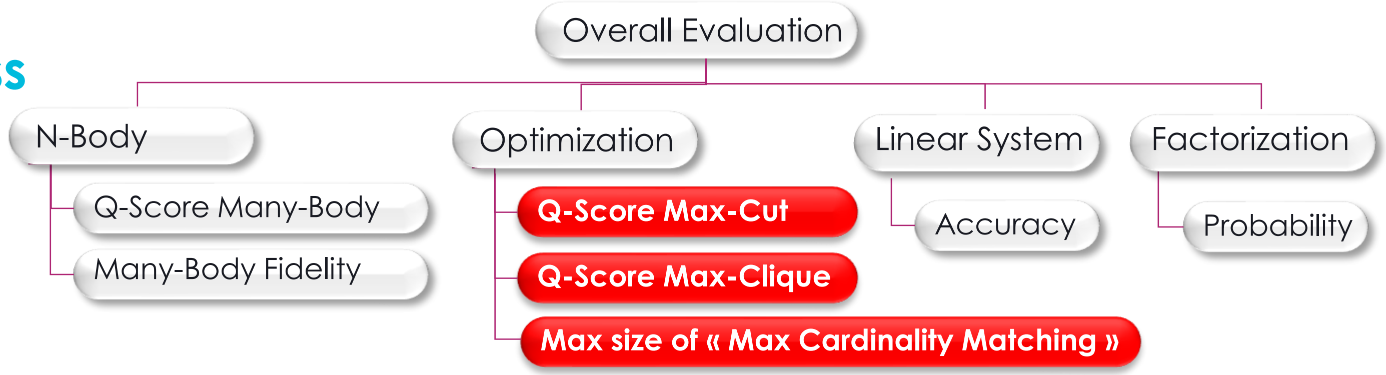
- **Aggregates** all the metrics into a unique score (allowing ranking the solutions)
- Takes into account: the **interacting metrics** the **user preferences**
- Fully **interpretable** and **explainable**

LNE THALES EVIDEN an atos business cea cnrs Teratec

Q-MYRIAD: multi-criteria approach for quantum benchmarking

> How to combine many metrics to assess /compare quantum solutions (QPU – algorithms)?

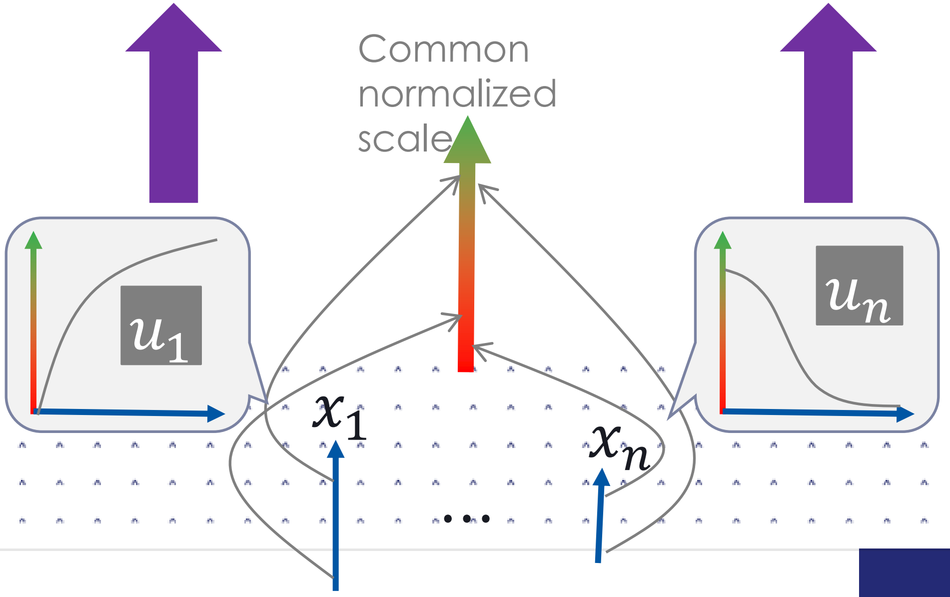
- Potentially many metrics from different benchmarking problems
- Metrics are given in different units
- Different priorities among metrics



> Approach: use of Multi-Criteria Decision Support. 2-step approach:

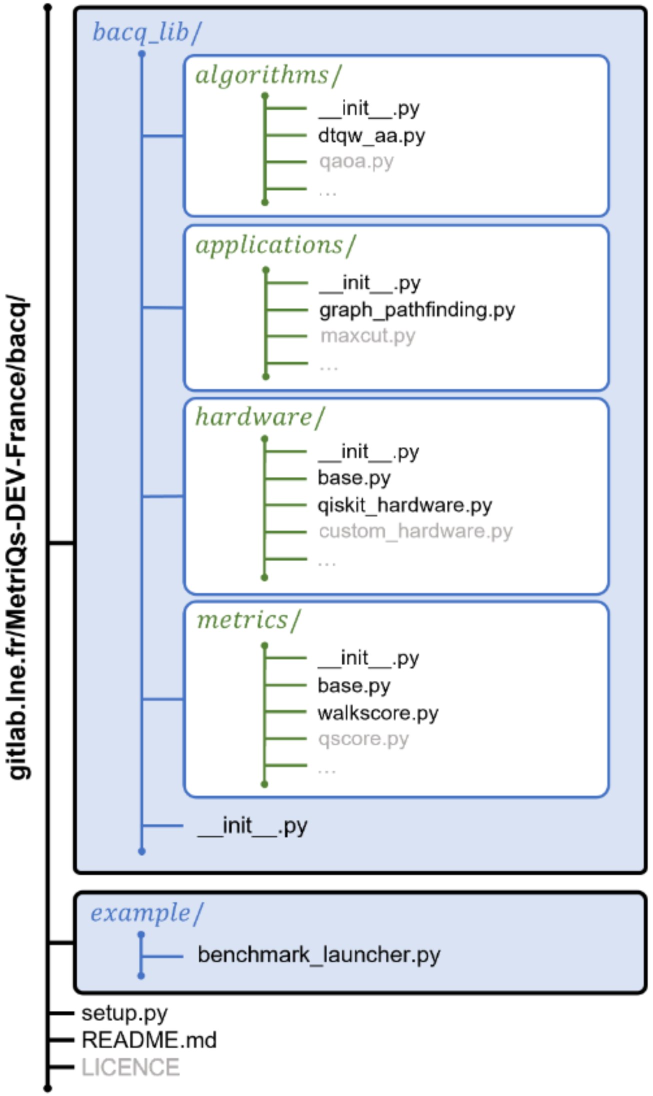
- Step 1: normalization of metrics
  - $x_i \mapsto u_i(x_i)$
  - Output = normalized score in $\mathbb{R}_+$
- Step 2: aggregation of normalized scores

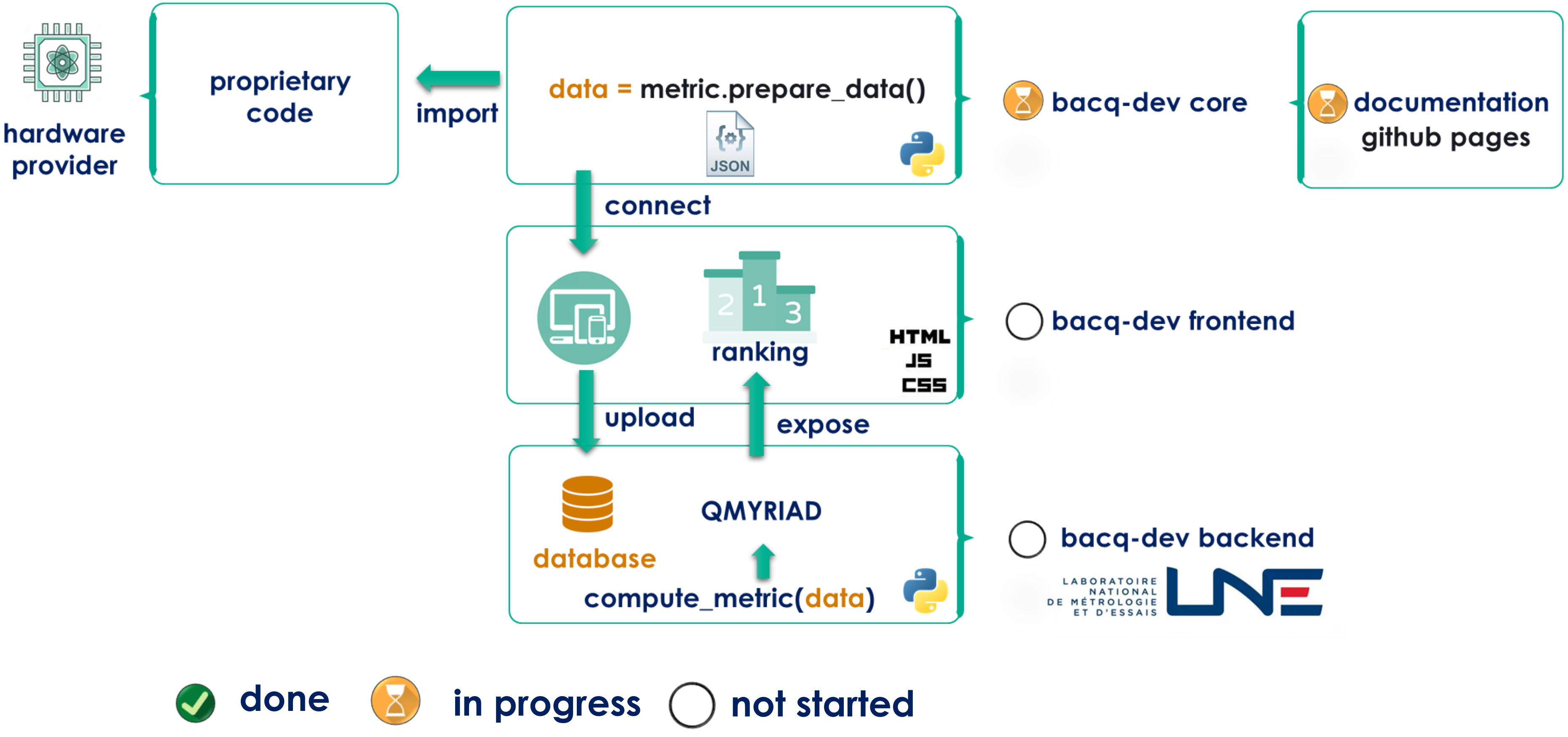
$$u(x) = H\big(u_1(x_1), \dots, u_n(x_n)\big)$$



bacq-dev overview

BACQ
MetriQs-France





BACQ: First results

BACQ
MetriQs-France

BACQ - Application-oriented Benchmarks for Quantum Computing

Delivering an application-oriented benchmark suite for objective multi-criteria evaluation of quantum computing performance, a key to industrial uses

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***Abstract*—With the support of the national program on measurements, standards, and evaluation of quantum technologies MetriQs-France, a part of the French national quantum strategy, the BACQ project is dedicated to application-oriented benchmarks for quantum computing. The consortium gathering THALES, EVIDEN, an Atos business, CEA, CNRS, TERATEC, and LNE aims at establishing performance evaluation criteria of reference, meaningful for industry users.**

***Keywords*—Quantum Computer, Quantum Algorithm, Quantum Emulator, Quantum Annealer, NISQ, FTQC, Benchmark, Multi-Criteria Decision**

I. Introduction

Quantum computing promises to revolutionize multiple technical fields and activity sectors, from optimization in logistics, to simulation for research in physics or chemistry, engineering or industry, passing through cryptography. Measuring the progress towards the quantum advantage and the realization of such promises, with objectivity and reliability, is of high interest for potential end-users and crucial for the future development of the domain, now subject of hype and high competition. The challenges, especially to achieve comparable measurements, comes from the diversity of the hardware platforms, their specificities in terms of physical characteristics and applications, their maturity that can still be low, and the potential rapid evolution of the technologies.

A number of initiatives exist to benchmark the performance of quantum computers. Examples include Quantum VOLUME [1] and CLOPS [2] from IBM, SupermarQ [3] from Super-Tech or Quantum LINPACK- [4] from Berkeley Lab. The metrics used in these previous approaches are very technical and require familiarity with the technology. They therefore do not make it possible to derive operational indicators of the performance of the different families of algorithms executed on the different existing quantum computers. Dedicated to the whole value chain setting up from quantum hardware development to industrial

https://arxiv.org/abs/2403.12205
ArXiv [quant-ph], 14 pages

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BACQ: EU and International Cooperation on QC benchmarking

In Europe

- TNO / QuAS (NL)
- TU Delft / QPack + QuAS (NL)
- Fraunhofer IKS / BenchQC Project (DE)
- CESGA / TNBS (NEASQC) (ES)
- **EQCBC** – European QC Benchmarking Coordination Committee (**FR**-DE-NL lead)

With the US

- QED-C / QC Benchmarking WG
- DOE / Sandia
- DARPA
- Hamiltonian Library
- Unitary Fund / Metriq

- EU-US Trade & Technology Council / QC Benchmark WG

With Japan Under construction …

More collaborations to come, towards globally harmonized and recognized benchmarks

International TQCI Seminar on Quantum Computers Benchmarks organized by TERATEC, LNE & THALES

https://teratec.eu/Seminaires/TQCI/2023/Seminaire_TQCI-230511.html

1st TQCI Seminar 2023, THALES R&T, Paris-Saclay Campus

2nd TQCI Benchmark Seminar Reims with TERATEC & LNE

https://teratec.eu/activites_quantiques/TQCI_240604_programme.html

2nd TQCI Seminar 2024, Reims

https://teratec.eu/Seminaires/TQCI/2025/Seminaire_TQCI-250625_UK.html

Systematic benchmarking of quantum computers: status and recommendations

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***Abstract*—Architectures for quantum computing can only be scaled up when they are accompanied by suitable benchmarking techniques. The document provides a comprehensive overview of the state and recommendations for systematic benchmarking of quantum computers. Benchmarking is crucial for assessing the performance of quantum computers, including the hardware, software, as well as algorithms and applications. The document highlights key aspects such as component-level, system-level, software-level, HPC-level, and application-level benchmarks. Component-level benchmarks focus on the performance of individual qubits and gates, while system-level benchmarks evaluate the entire quantum processor. Software-level benchmarks consider the compiler's efficiency and error mitigation techniques. HPC-level and cloud benchmarks address integration with classical systems and cloud platforms, respectively. Application-level benchmarks measure performance in real-world use cases. The document also discusses the importance of standardization to ensure reproducibility and comparability of benchmarks, and highlights ongoing efforts in the quantum computing community towards establishing these benchmarks. Recommendations for future steps emphasize the need for developing standardized evaluation routines and integrating benchmarks with broader quantum technology activities.**

***Index Terms*—Quantum computing, quantum algorithms, benchmarking, metrics.**

CONTENTS

LIST OF ABBREVIATIONS

ACES *Averaged circuit eigenvalue sampling* is a component-level benchmarking method that is capable of detecting and characterising correlations.

FTQC *Fault-tolerant quantum computing* relies on careful computational instructions such that errors do not spread during QC in an uncontrollable fashion. These

QUANTUM FLAGSHIP

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European Quantum Computing Benchmarking Coordination Committee

The European Quantum Computing Benchmarking Coordination Committee (EQCBC) was established to coordinate European activities in benchmarking quantum computers

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https://qt.eu/working-groups/european-quantum-computing-benchmarking-coordination-committee

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