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LNE

The BACQ Project on Quantum Computing Benchmarks

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4 June 2024

STRATÉGIE NATIONALE QUANTIQUE

MetriQs France

FRANCE 2030

anr agence nationale de la recherche

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MetriQs-France

National Program for
Measurement, Evaluation, and Standardization
of Quantum Technologies

Develop, exploit, and promote **measurement capabilities of reference** - *validated, harmonized, widely recognized* -

→ Characterization and performance assessment of quantum technologies

→ Reliability, impartiality and comparability

>> Innovation + Establishment of the quantum industry

⇒ ***Trust in QT***
⇒ ***Adoption of QT***

➢ R&D Projects
Exploitation & Promotion Actions

- **R&D on metrology gaps: Application-oriented QC-benchmarks (BACQ)**, Characterization of quantum components and enabling technologies…
- **Standardization:** AFNOR, CEN-CENELEC, ISO/IEC, IEEE…
- **Collaborations** EU and International
- …

- Research Organizations
- Large industry
- Startups
- AFNOR & SDOs
- LNE**…**

➢ Measurement & Testing Infrastructure

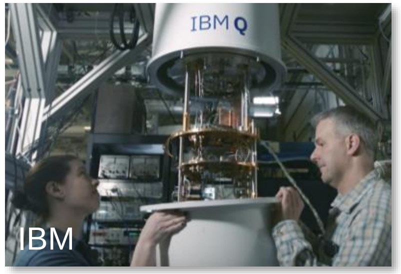
- **Quantum metrology platform** at LNE/French Metrology Network

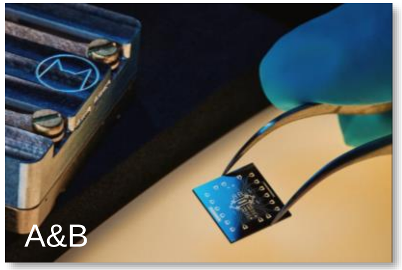
Solid-state qubits and enabling technologies (RF electronics and cryogenics); Quantum gravimeters; Atomic clocks.

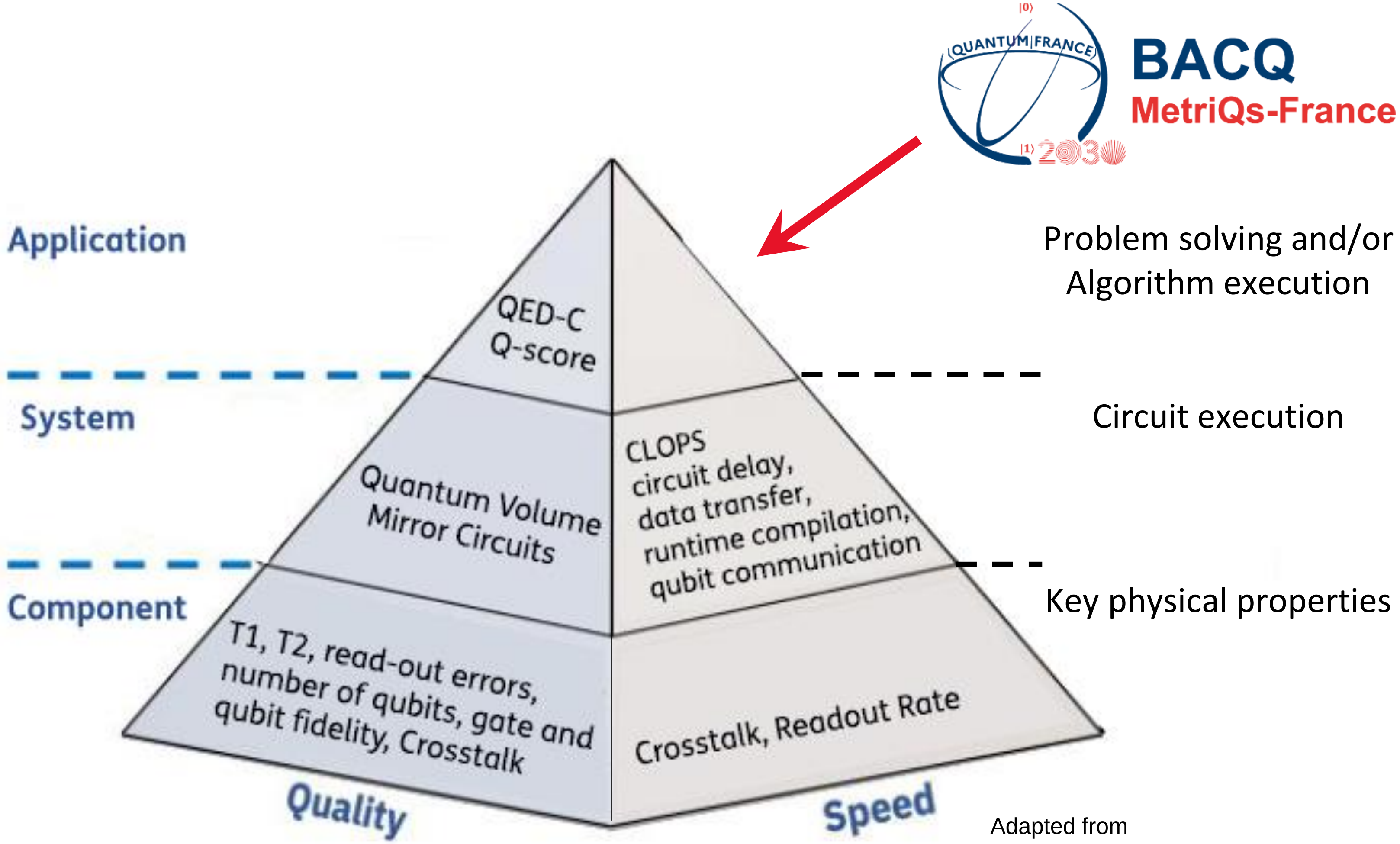
- Network of **trusted platforms for characterization and testing**

BACQ: Application-oriented benchmarks for quantum computing

MetriQs France







Adapted from
TNO and IBM

BACQ: Application-oriented benchmarks for quantum computing

BACQ
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- **Main goal:**

⇒ Developing a **measuring instrument** for the **objective evaluation** of the **quantum computing practical performance**

→ A set of **benchmarks close to real applications**, **meaningful for industrial end-users**

→ Unbiased, “universal”, long-lasting, widely-used and recognized, to serve as common reference

- **Purpose:**

→ Comparing different quantum computing technologies and modalities with classical computers

→ Assessing the advantages of a specific quantum computing technology for a specific application

⇒ **Measuring the <u>progress</u> of quantum technology towards a practical quantum advantage**

⇒ **Supporting the development of useful quantum computing technologies**

BACQ: A collaborative R&D project

BACQ MetriQs-France 2030

- **Key figures**

  - **3-year** project (Sept. 2023 – August 2026) + FastTrack action **Q-score / MaxCut** (from Feb. 2023)
  - **6 partners : Thales**, Eviden, CEA, CNRS, Teratec, LNE
  - **7,2 FTE/year**
  - **3,9 M€ budget**

- **Major outcomes**

  - **First set of validated application-oriented benchmarks**
  - **Multi-criteria notation model for quantum computers**
    (Analog to gate-based machines, NISQ to FTQC)

- **Maximizing impact**

  - **Consultations** (Industry – tech. providers and end-users, Academia, Governmental agencies…)
  - **Collaborations at EU and international** (R&D teams, benchmarking initiatives…)
  - **Standardization** (AFNOR, CEN-CENELEC, ISO/IEC, IEEE)
  - **Publications & Communications**

BACQ: Application-oriented benchmarks for quantum computing

- **Scientific & technical approach**

- Definition of **reference problems** to be solved
  [Optimization – Simulation of physics – Linear system solving – Factorization]

  For **all quantum machines**, analog to gate-based machines, NISQ to FTQC

- Definition of **technical metrics** for their resolution (computational and **energetic**)

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

BACQ: Main progress to date

- **Q-score**
  - Advances in the use of the metrics for optimization problems (MaxCut, MaxClique) on various QPUs (Quandela / photonics, IQM / supercond., Pasqal / neutral atoms, Quantinuum / trapped ions, TNO…).

  → *A special dedicated session at this TQCI Quantum Benchmarks seminar.*
- **Myriad-Q**
  - Elaboration of the aggregation model for the BACQ metrics started, with first use with variants of Q-score metrics for optimization problems.
- **Collaborations**
  - Consultation with various stakeholders (e.g., French Académie des Technologies, Institutional and Governmental Agencies, GIFAS…).
  - Collaboration and dialogue engaged with more than +20 QPUs providers, all over the world.
  - Exchanges with other benchmarking initiatives (EU, US…)

  → *To be extended and reinforced at this TQCI Quantum Benchmarks seminar.*
- **Communication**
  - Paper published on ArXiv https://arxiv.org/abs/2403.12205: Description of the project and first results.
- **Standardization**
  - Standardization project on QC Benchmarks at EU CEN-CENELEC JTC22. Topic discussed in several other standardization groups or committees.

- **Other progress to be reviewed in the following** (quantum physics simulation…)

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

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BACQ - Application-oriented Benchmarks for Quantum Computing

arxiv preprint: https://arxiv.org/abs/2403.12205

Reference: arXiv:2403.12205v1 [quant-ph]

14 pages

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EVIDEN an atos business

cea

cnrs

Teratec

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MYRIAD: Principle of aggregation of the metrics into high-level operational indicators

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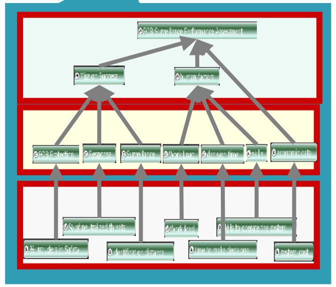
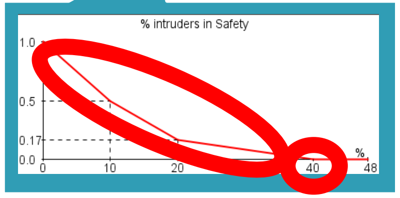
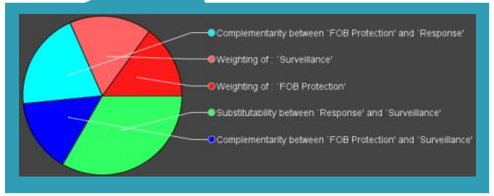
MYRIAD at a glance:

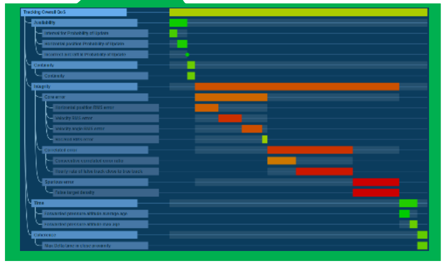
Problem Formalization | **Performance assessment**

KPI identification → KPI normalization → KPI aggregation → Notation assessment → Notation explanation





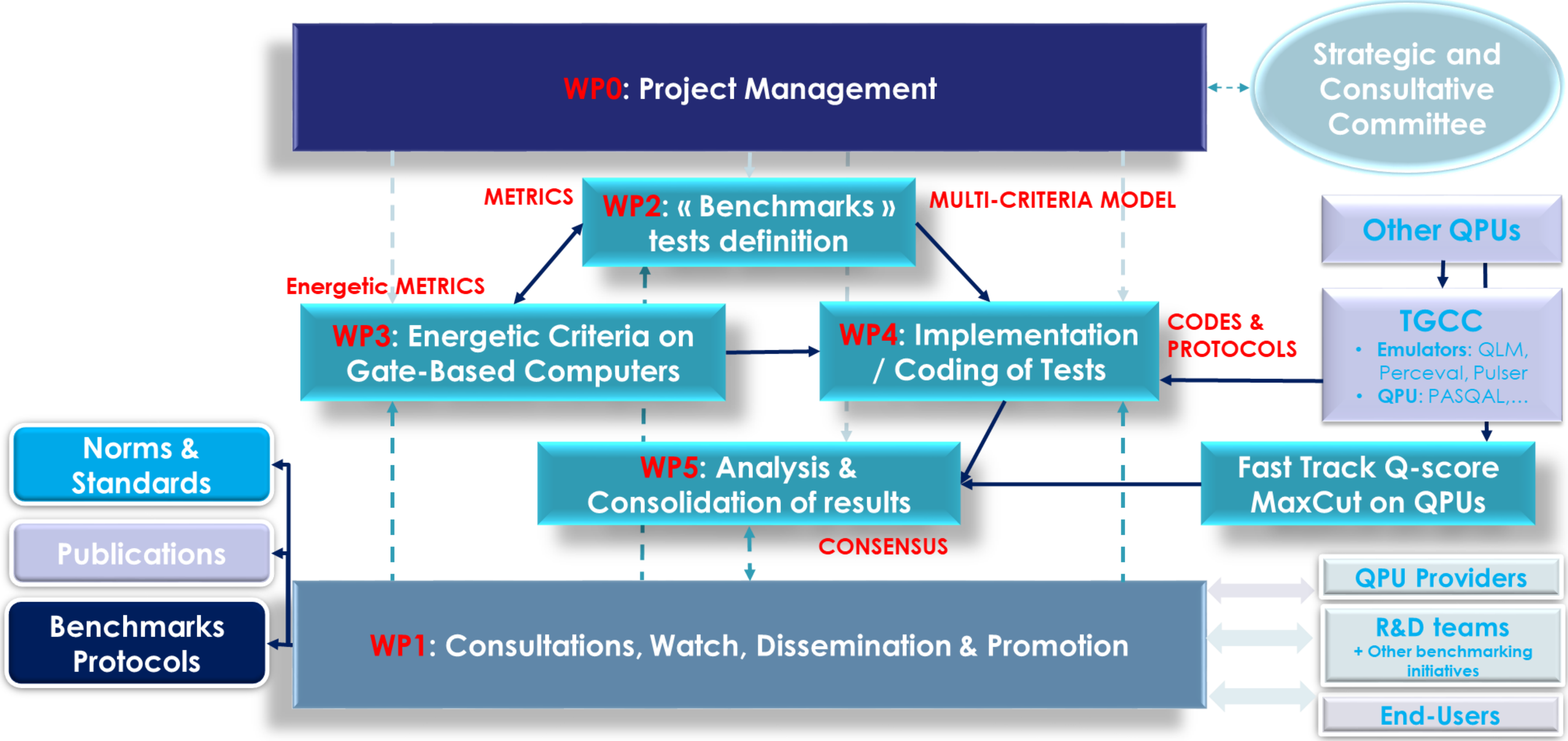




MYRIAD added values:

- Aggregate all KPIs into a unique quality score …
- … making it possible to rank solutions
- Representation of interacting criteria
- Model constructed from preferences of experts
- The model is fully interpretable
- Explanation of the evaluations
- The model can be shared among stakeholder

BACQ: Work Break Structure



BACQ: Collaboration with QPU providers

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Photonic

- Psiquantum (Palo Alto, US)
- **Quandela (Massy, France)**
- QuiX (Enschede, The Netherlands) via TNO
- Xanadu (Toronto, Canada)

Superconducting circuits

- Alice & Bob (Paris, France)
- Google (Santa Barbara County, US)
- IBM (US)
- **IQM (Espoo, Finland)**
- OQC (Oxford, UK)
- Anyon Systems (Waterloo, Canada)

Trapped ions

- AQT (Innsbruck, Austria)
- **Quantinuum (Cambridge, UK)**

Spin qubits

- C12 (Paris, France)
- Quobly (Grenoble, France)

Neutral atoms

- Pasqal (Massy, France)
- QuEra (Boston, US)

Annealing

- D-Wave (Burnaby, Canada) via TNO and FZJülich
- Fujitsu (Kanagawa, Japan) via Riken via CEA
- NEC (Tamagawa, Japan) via Riken via CEA

NV centers in diamond

- Quantum Brilliance (Acton, Australia)

* Indirect access via collaborators to be discussed
* Collaboration under discussion

BACQ: Collaboration with QPU providers

Image by rawpixel.com on Freepik

BACQ: The generic problems considered

BACQ MetriQs-France

A polyvalent suite of benchmarks addressing, to start:

Simulation of Quantum Physics
(Quantum many-body problems : Ising model in transverse field, quantum phase transitions, 2D Hubbard model)

Optimization
(including Q-Score/MAXCUT)

Linear Systems Solving

Prime factorization

4 June 2024

BACQ: The metrics

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Initial metrics considered by the partners:

❖ [*Simulation of Quantum Physics*]

- Quantum many-body problems:

Hubbard model, BCS model, spin models

❖ [*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 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

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EVIDEN an atos business
cea cnrs Teratec

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

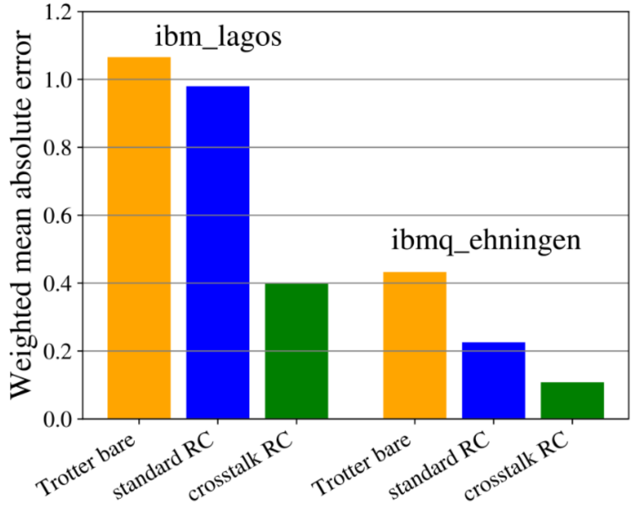
- Target non-trivial **many-qubit entangled states**

- Focus on many-body problems/states/Hamiltonians which are **exactly solvable**

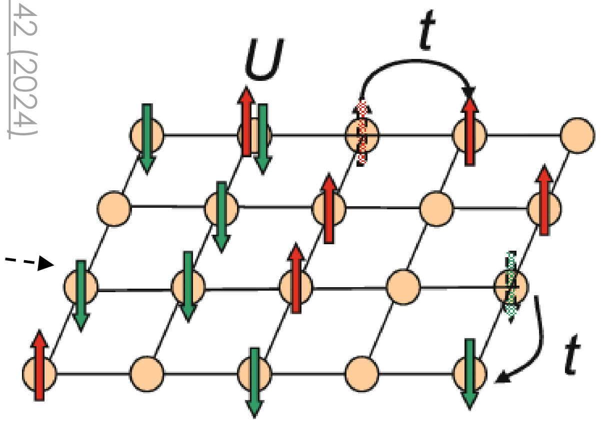
(to allow for comparison between the theoretical [error-free] results and the measured ones)

BACQ: Metrics development

Simulation of Quantum Physics Models



Phys. Rev. Research 6, 013142 (2024)



- Models
  - Interacting electrons (BCS model & Hubbard model)
  - Quantum spin-1/2 models (Ising in transverse field etc.)
- Architectures
  - Analog **quantum simulators** (very few benchmarks so far)
  - **Gate**-based machines
- Metrics (work in progress) will test the accuracy of
  - preparing a given **target entangled state of N qubits**
  - simulating the system **dynamics**
  - extracting **physical quantities** of interest

  ➟ *QScore many-body and many-body fidelity*

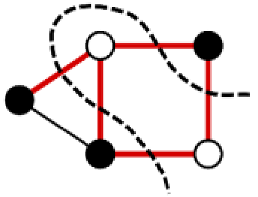
BACQ: Metrics development - Q-score

[*Optimization*]

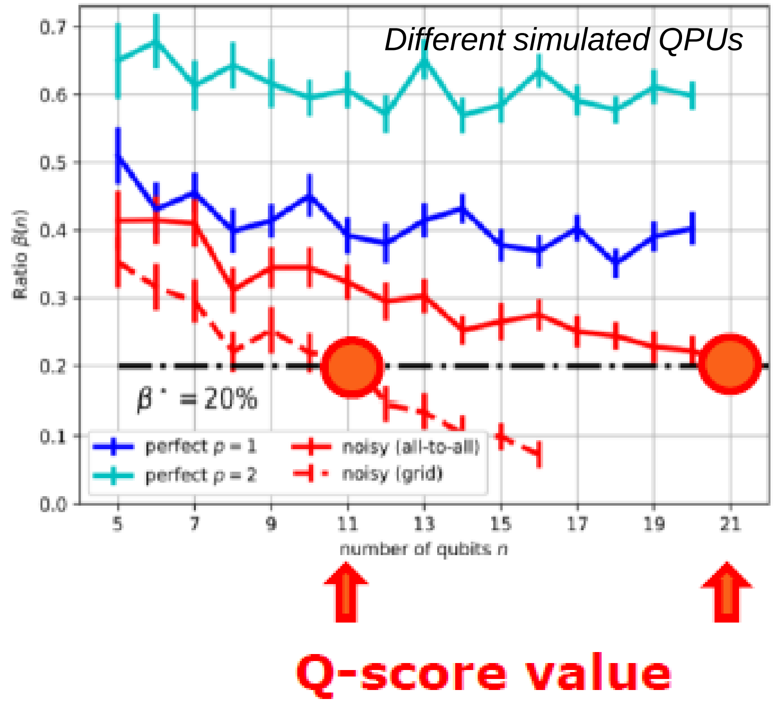
- **Q-score/MaxCut** addresses a complex **combinatorial optimization problem** (MaxCut) for which a quantum advantage is expected.

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/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.

BACQ: Metrics development – Fast Track Q-score/MaxCut

EVIDEN BACQ MetriQs-France

[*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** [trapped ions]
  - Brainstorming within BACQ collaboration to standardize the Q-score MaxCut benchmark
  - Discussion on publications

BACQ: Metrics development

Simulation of Quantum Physics Models

- Models & Architectures
  - Ising chain with transverse field in quench
  - Analog **quantum simulators**
- Metrics developpement *(work in progress by Eviden quantum Lab)*
  - 1D chain is integrable and an exact theoretical **solution is available**
  - Compare simulation results from an analog machine with exact results
  - Currently testing which indicators to measure/compare between simulated and exact values
    - Example: testing the area between the theoretical curve and the noisy curve of an observable over time
    - Goal: Assess the machine's performance on larger chain sizes or longer simulation times
    - Set a **tolerance threshold** for the score obtained

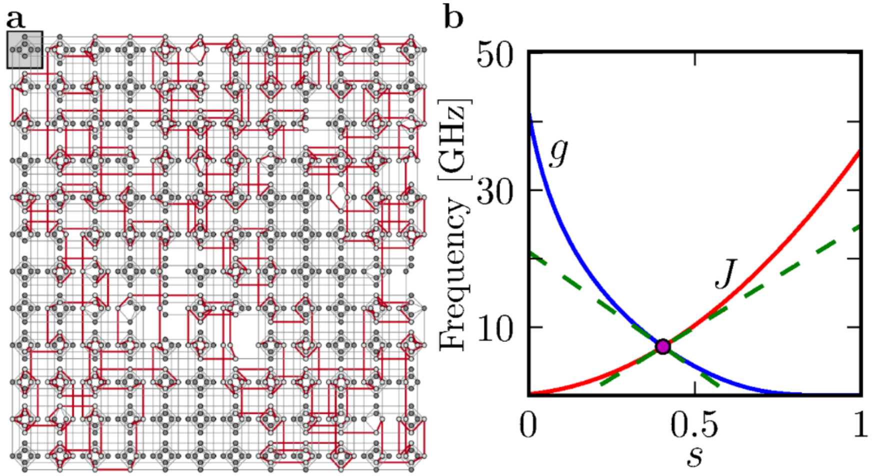


FIG. 1. **The quantum Ising chain implemented in a D-Wave computer. a.** An example of an Ising chain on the D-Wave "chimera graph". The red lines are active couplings between "spins". **b.** A typical annealing protocol for a D-Wave annealer. Here $J(s) = J_{\max} \cdot j(s)$, where $j(s)$ is a predetermined 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

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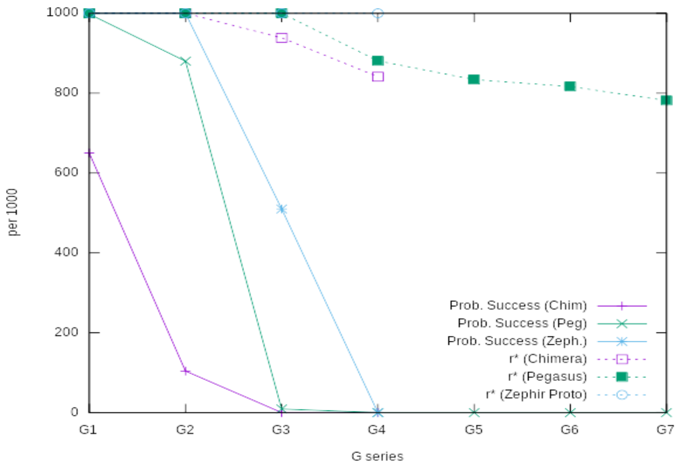
- **Gate-based and analog QC applications for optimization**

> 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)

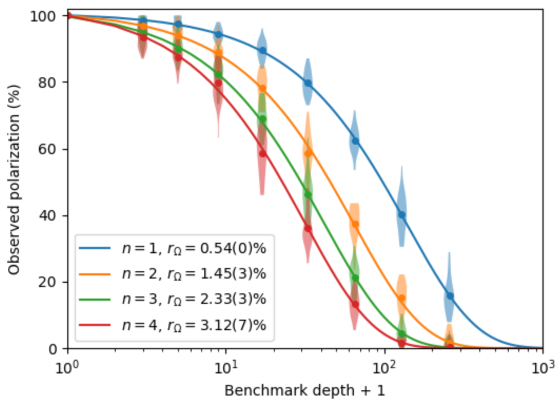
- **Probability of finding the optimum** or distance to optimum/solution
- **Size of the problem**
- **Complexity and sparsity of the problem**
- **Complexity of pre/post processing if required**

BACQ: Metrics elaboration

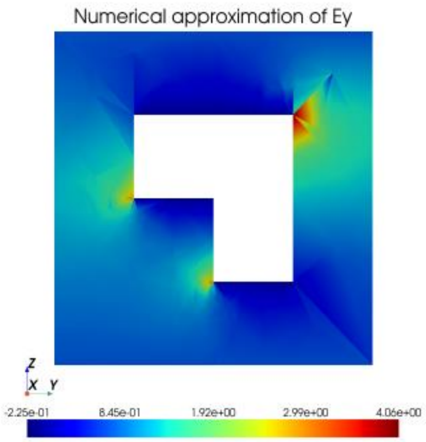
[*Optimization* / *Linear systems solving*]

- **Focus on NISQ & FTQC QPUs**

- 1st phase:
  - **Evaluation of physical characteristics** of a selected set of QPUs to better understand **noise** origins & **noise** modelling.
- 2nd phase:
  - Identification of **error correction codes** supported by each QPU.
  - Evaluate **resource overhead** for each type QPU (cat qubits, uniformly depolarizing)
- 3rd phase:
  - Study of the **compilation** (according to connectivity constraints).
  - Test and measures on real QPU machines..



Mirror Randomized Benchmarking example



Linear System Solving example

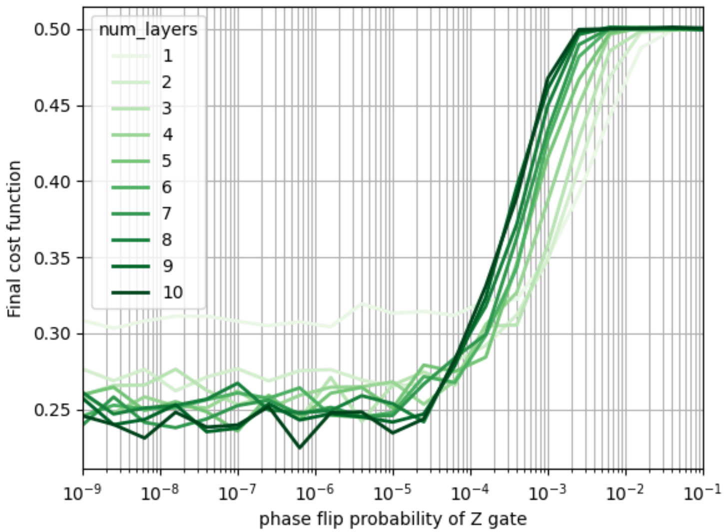
Finite Element Method
for electromagnetic simulation
(credits Elise Fressart, Thales)

BACQ: Metrics elaboration

[*Optimization* / *Linear systems solving*]

Related work:

Variational quantum algorithms on cat qubits
A.S. Bornens, M. Nowak, 2023

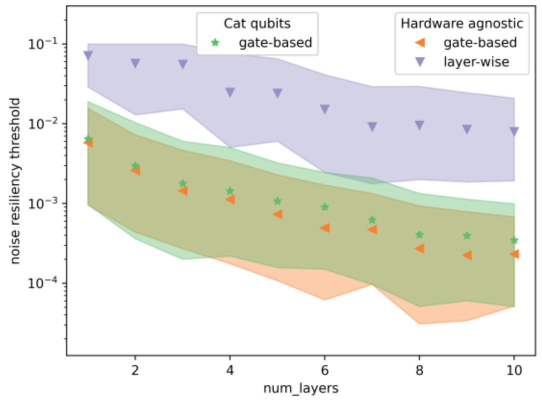


VQA convergence

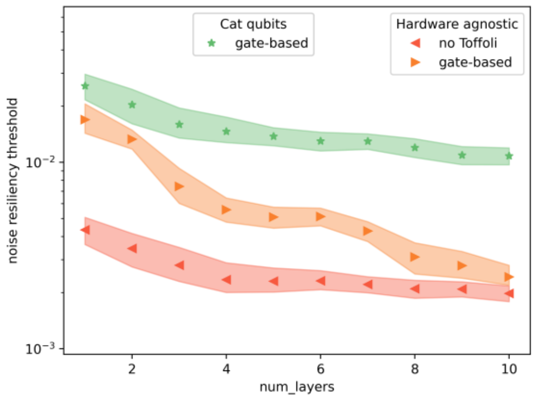
Extracting

Noise Resiliency Thresholds

QAOA □



VQLS □



Perspectives

□ **FTQC algorithm** for the finite elements

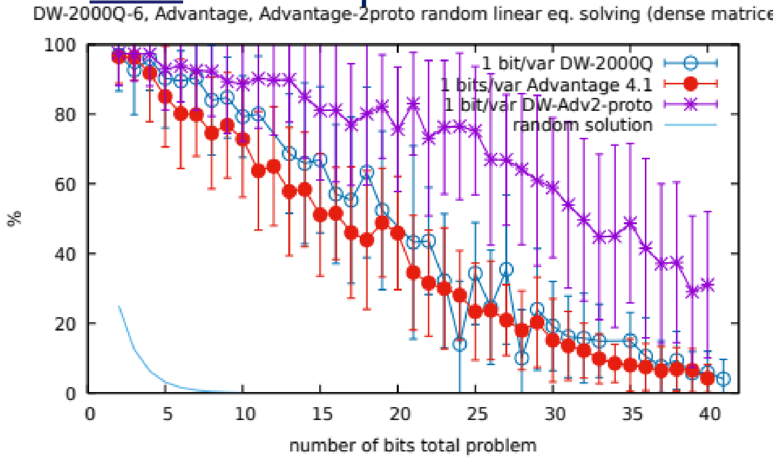
Quantum algorithms and the finite element method,
A. Montanaro et al., 2015

last algorithm step = hadamard test

BACQ: Linear System solving

- **Gate-based and analog application for optimization, linear system solving and (Hamiltonian-based) integer factorization**

> Idea: Develop metrics to evaluate **linear systems** (at different sizes) solving on both gate-base and analog



	1bit/var	2 variables	3 variables
DW-2000Q	20 var @ 50%		
DW-ADV	19→38* var @ 50%		3% @ 3b/v
DW-ADV2-proto	32 var @ 50%	29% @ 3b/v	6% @ 3b/v

(*) with minor embedding preprocessing

> 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: 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

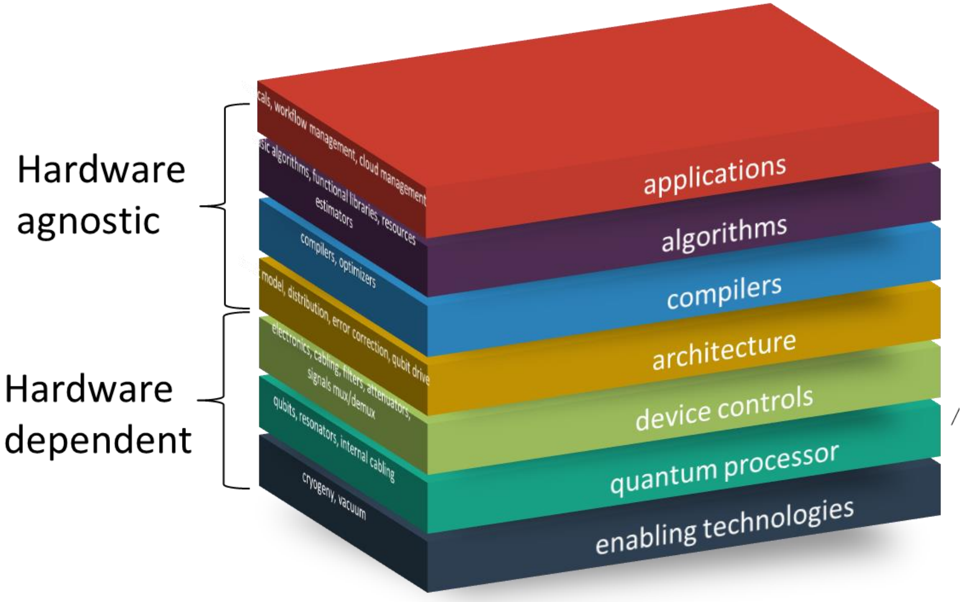
  - Size of the problem

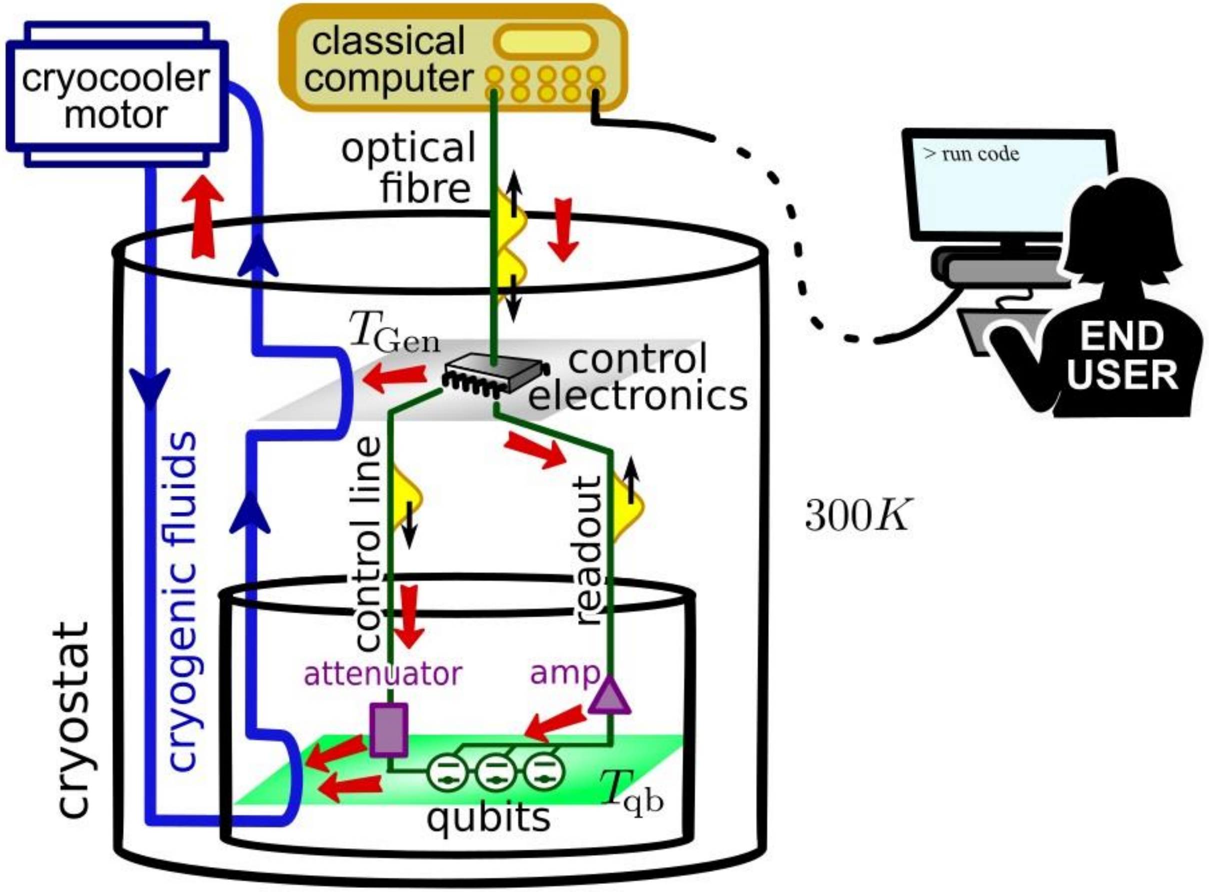
  - Complexity and sparsity of the problem

  - Complexity of pre/post processing if required

BACQ: Metrics elaboration - Energetics

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

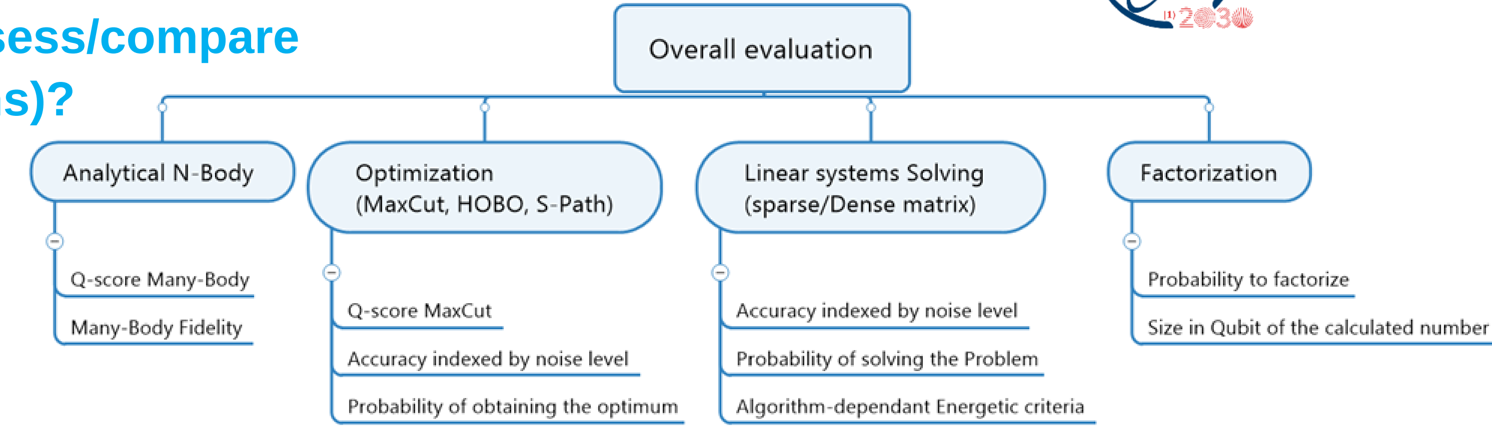




In BACQ, focus on resources at the HW-agnostic layers for linear system solving, with test on a gate-based machine

MYRIAD-Q: multi-criteria approach for quantum benchmarking

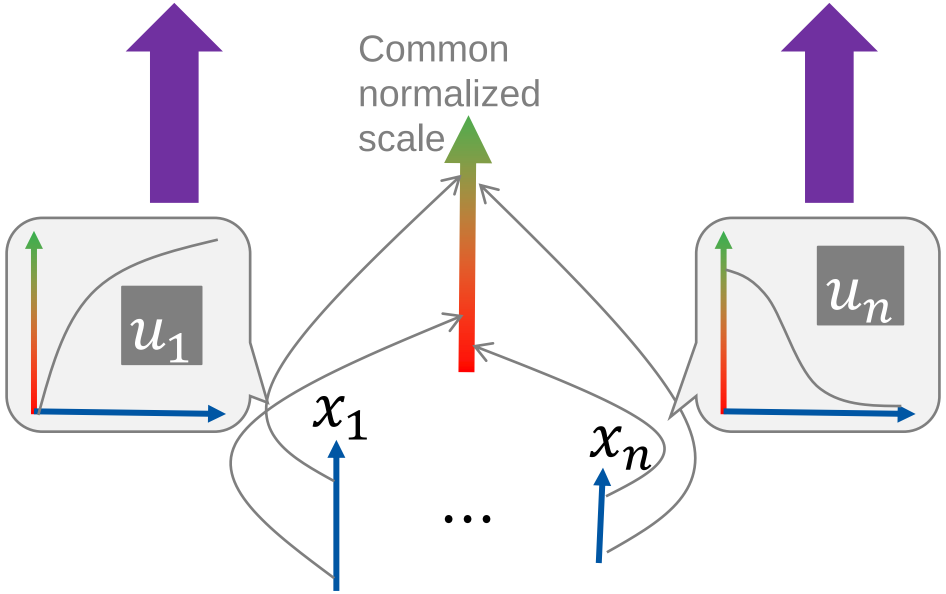
- **How to combine many metrics to assess/compare quantum solutions (QPU – algorithms)?**
  - Potentially many metrics from different benchmarking problems
  - Metrics are given in different units
  - Different priorities among metrics



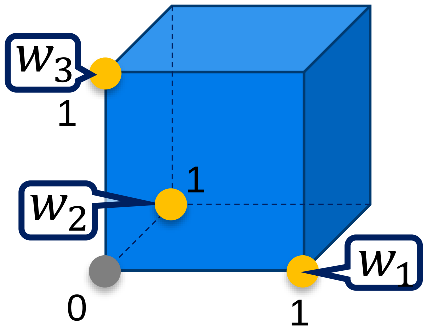
- **Approach: use of Multi-Criteria Decision Support.**

  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

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



MYRIAD-Q: multi-criteria approach for quantum benchmarking



$$H(a) = \sum_{i=1}^{n} w_i \, a_i$$

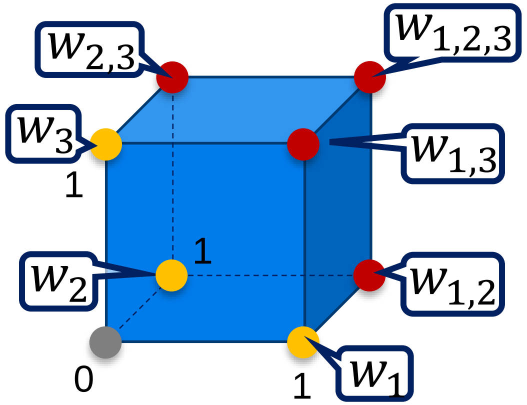
- **Standard aggregation method: Weighted Sum**

Extension to represent interaction among criteria

Choquet integral

$$H(a) = \sum_{S \subseteq N} w_S \min_{i \in S} a_i$$

MYRIAD



$$H(a) = \sum_{S \subseteq N} w_S \prod_{i \in S} a_i$$

Multi-linear extension

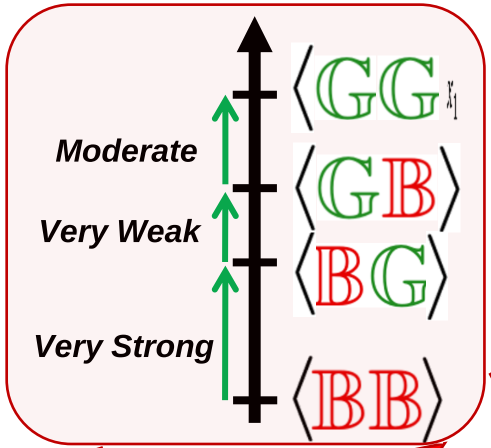
QPACK

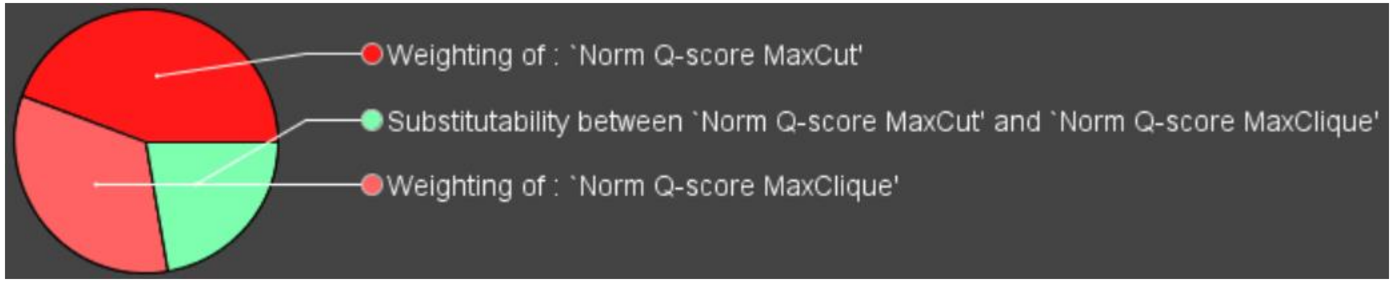
$$S = \frac{1}{2}(S_{\text{runtime}} + S_{\text{scalability}})(S_{\text{accuracy}} + S_{\text{capacity}})$$

Properties	Choquet integral	Multilinear model
Idempotency	YES	NO
Interval Scale Invariance	YES	NO
Weak Difference Independence	NO	YES
Monotonicity in $\mathbb{R}_+$	YES	NO

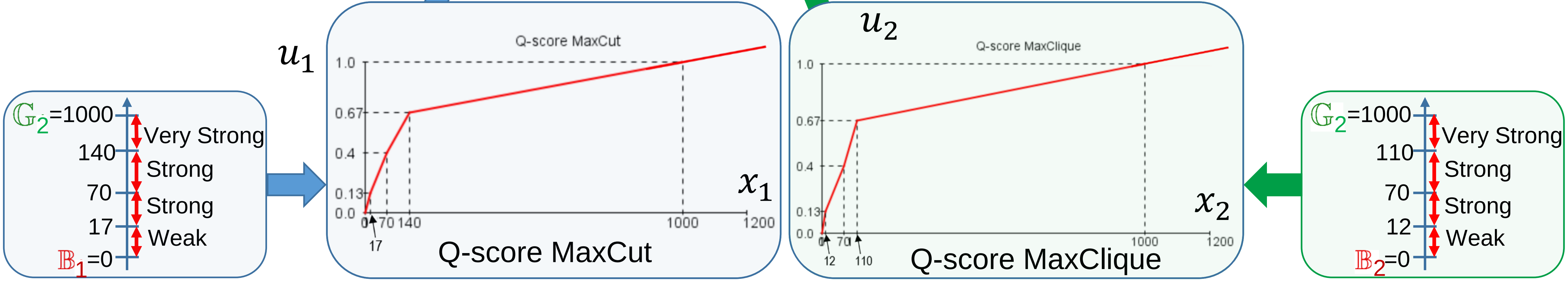
MYRIAD-Q: multi-criteria approach for quantum benchmarking

Illustration of the elicitation process with MYRIAD





$$u(\mathbf{x}) = w_1 u_1(x_1) + w_2 u_2(x_2) + w_{1,2} \min\big(u_1(x_1), u_2(x_2)\big)$$



MYRIAD-Q: multi-criteria approach for quantum benchmarking

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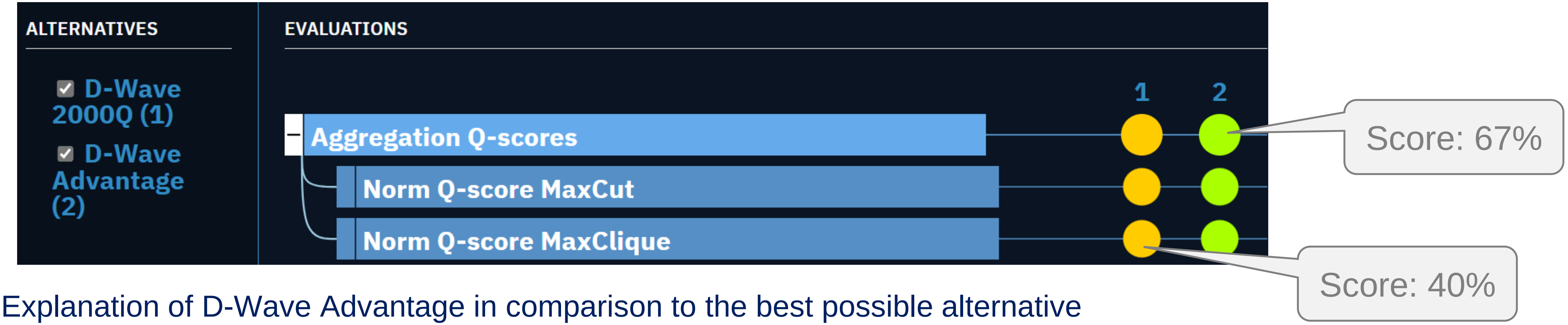
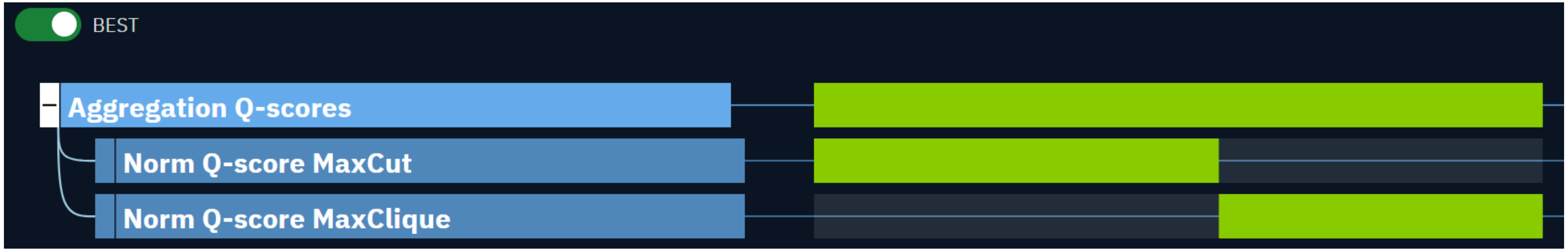
- **Evaluation & explanation with MYRIAD-Q**
  - Illustration with two quantum computers

	Q-score MaxCut	Q-score MaxClique
D-Wave 2000Q	70	70
D-Wave Advantage	140	110



  - Explanation of D-Wave Advantage in comparison to the best possible alternative



BACQ Kick-Off Meeting 13 Sept. 2023 @ Thales Research & Technology (France)

MetriQs France

National Program on Measurement, Evaluation and Standardization of Quantum Technologies

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Application-Oriented Benchmarks for Quantum Computing

THALES Building a future we can all trust

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F. Barbaresco *et al.*

ArXiv preprint: https://arxiv.org/abs/2403.12205

Reference: arXiv:2403.12205v1 [quant-ph]

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