Confidential

PASQAL

Quantum for HPC

Vivatech

June 2022

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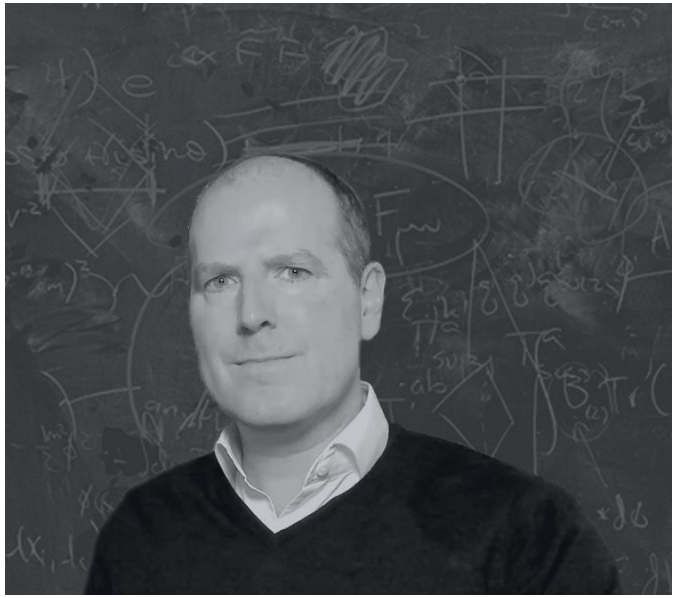
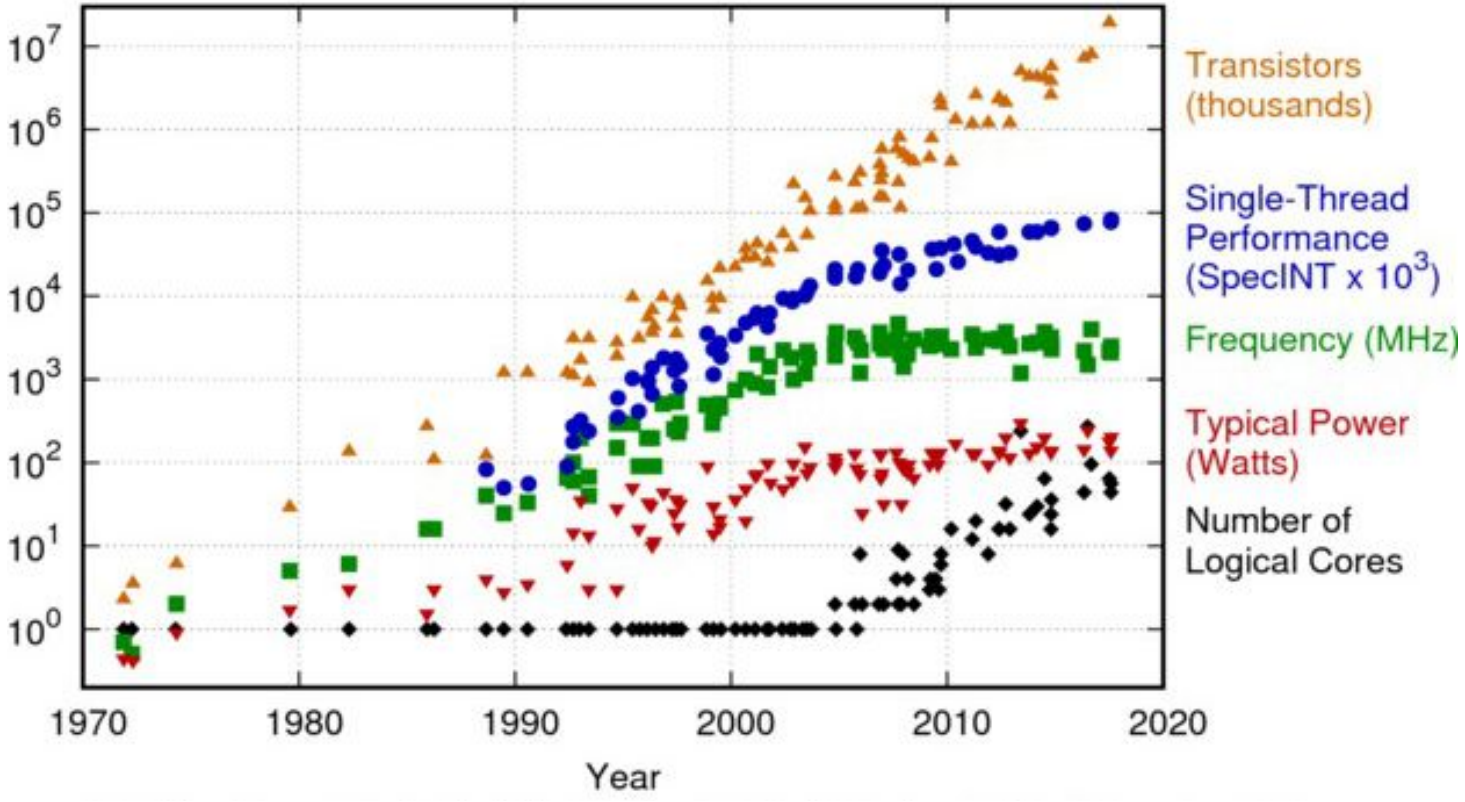
Hello world



Benno is the **CCO at PASQAL**, a full-stack quantum hardware player offering quantum processors based on neutral atom qubit technology. Benno is also the **Vice-President of the board at QuIC**, the European quantum industry association and a member of the Research and Innnovation Advisory Group (RIAG) of the **EuroHPC** Joint Undertaking. Previously Benno was the founder and **CEO of Qu&Co**, one of Europe's leading quantum-software businesses focused on quantum simulation and quantum-enhanced machine learning for chemistry, materials science, multiphysics simulation and finance. In December 2021 Qu&Co and PASQAL merged. Benno is an experimental quantum physics who graduated from **Delft University** (NL) in 1998 and he holds an MBA from **INSEAD** (France). Benno is a serial entrepreneur and started his career at a.o. The **Boston Consulting Group** and private equity firm **Alpinvest**.

CPU processors have reached their limit, and parallel processing has taken over as the main driver of computational performance improvements... but for how long?

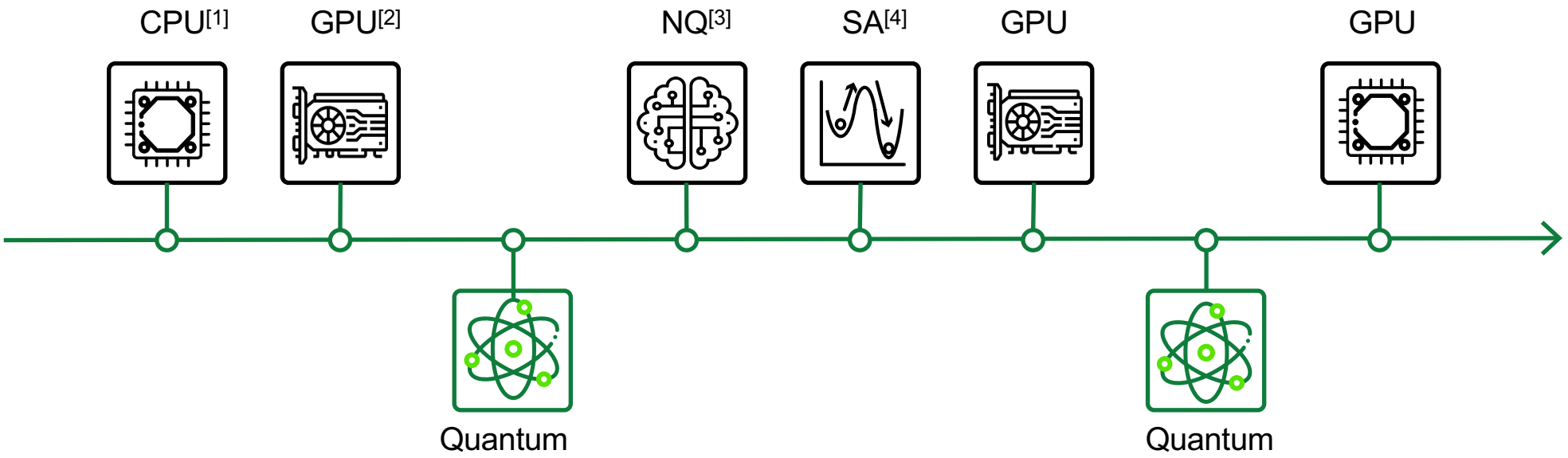
40+ years of microprocessor trends data[1]



1: source: https://www.karlrupp.net/2018/02/42-years-of-microprocessor-trend-data/

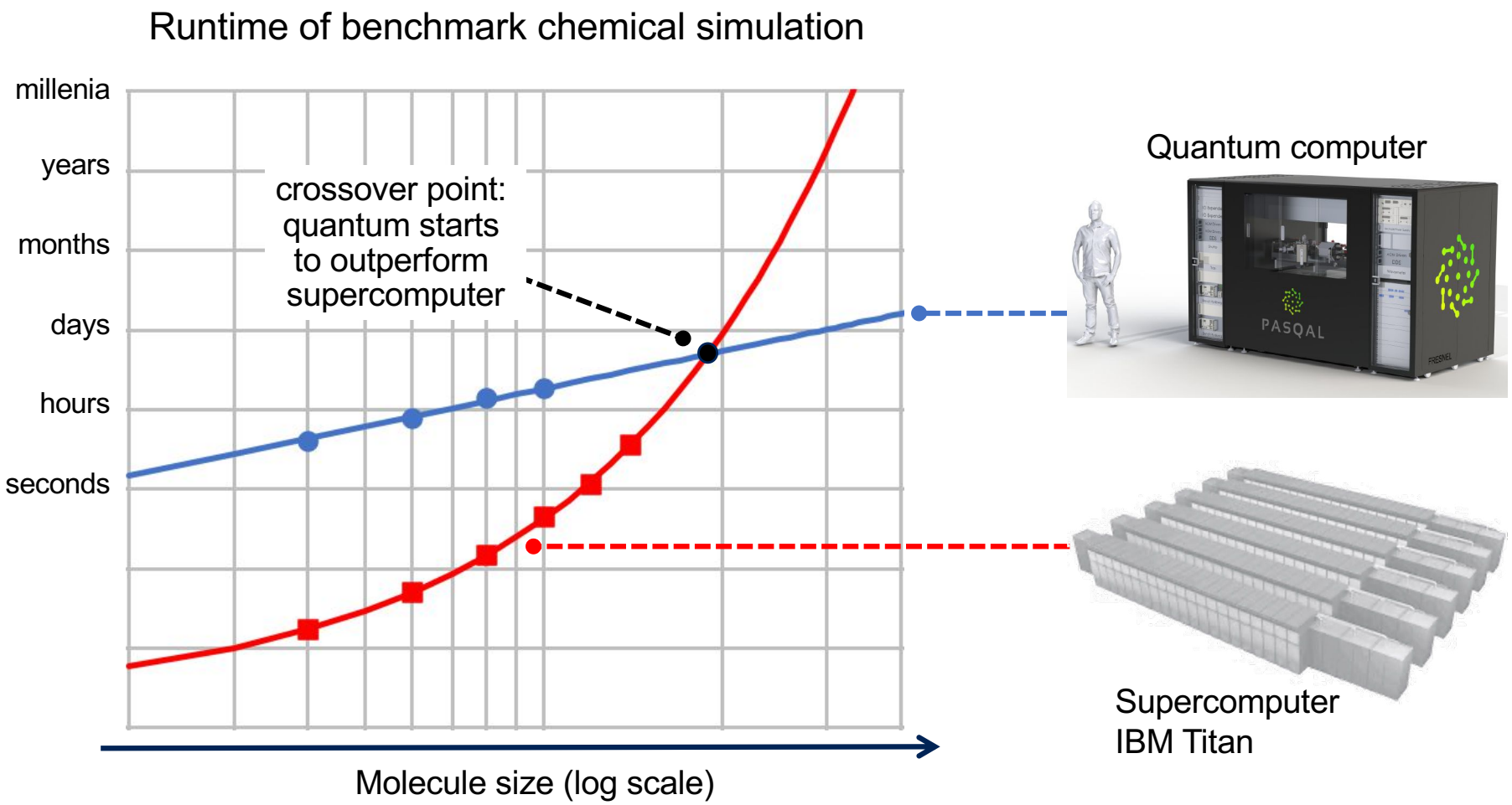
Future HPC workflows will likely combine multiple types of specialized compute resources; each of them best positioned to solve a specific mathematical challenge

Diversity in computational resources employed in a future HPC workflow



1: CPU = Central Processing Unit (like the processor in most laptops)
2: GPU = Graphics Processing Unit, nowadays mostly used for parrallel computing
3: NC = Neuromorphic Computing, containing electronic analogue circuits aiming o exploit massive parallelism
4: SA = Simulated Annealing a probabilistic technique for approximating the global optimum of a given objective function

Quantum-computers can store and process quantum-information natively, which promises up to exponential performance improvements for certain computational problems

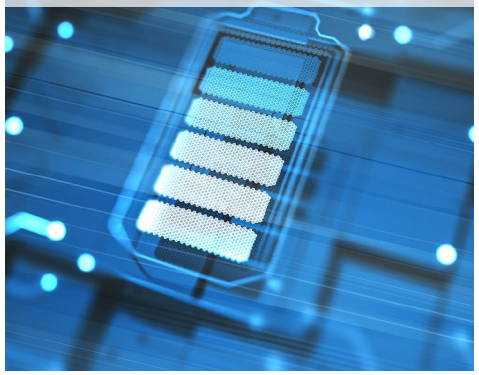


source: research paper by PASQAL and Schrödinger Inc., sept '20 (https://arxiv.org/abs/2009.12472)

Quantum computing will impact a broad set of industries; the earliest applications are expected within R&D departments enabling the development of next gen products/services

Some examples of products and services which will be impacted by quantum computing

Battery Development



CO2 Storage Engineering

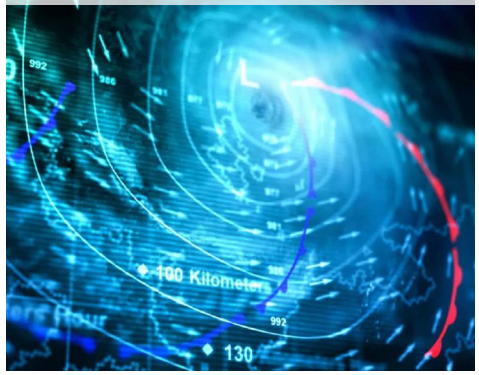
Smart Infra Management

Financial Trading

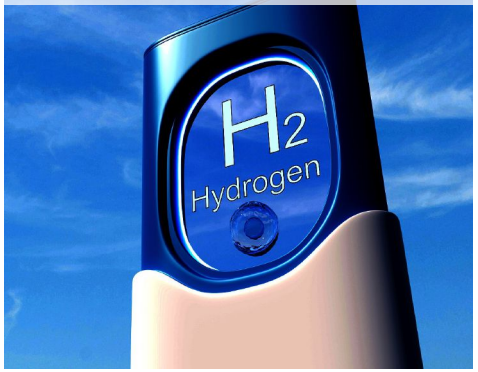
Anomaly Detection

Aerodynamics Optimization

Weather Forecasting



Fuel Cell Development



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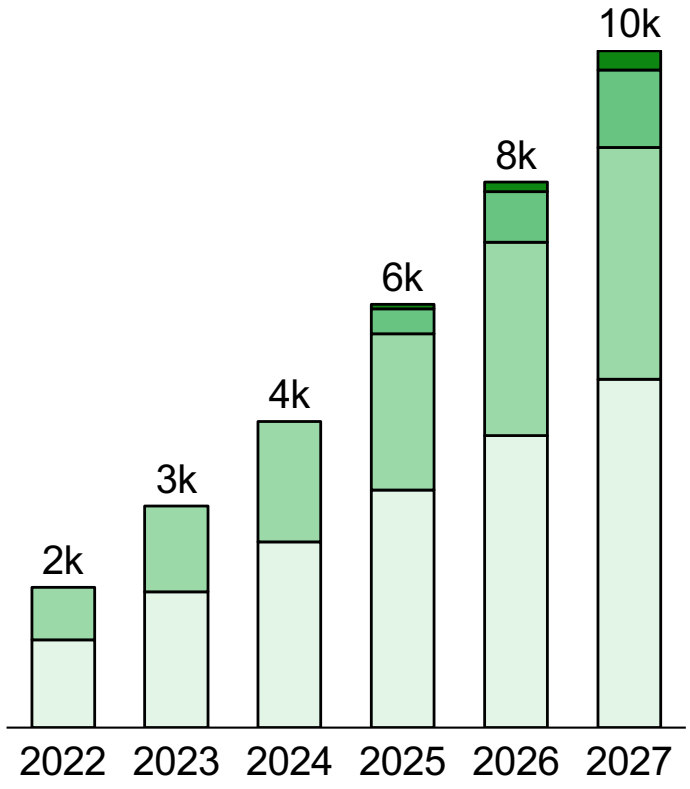
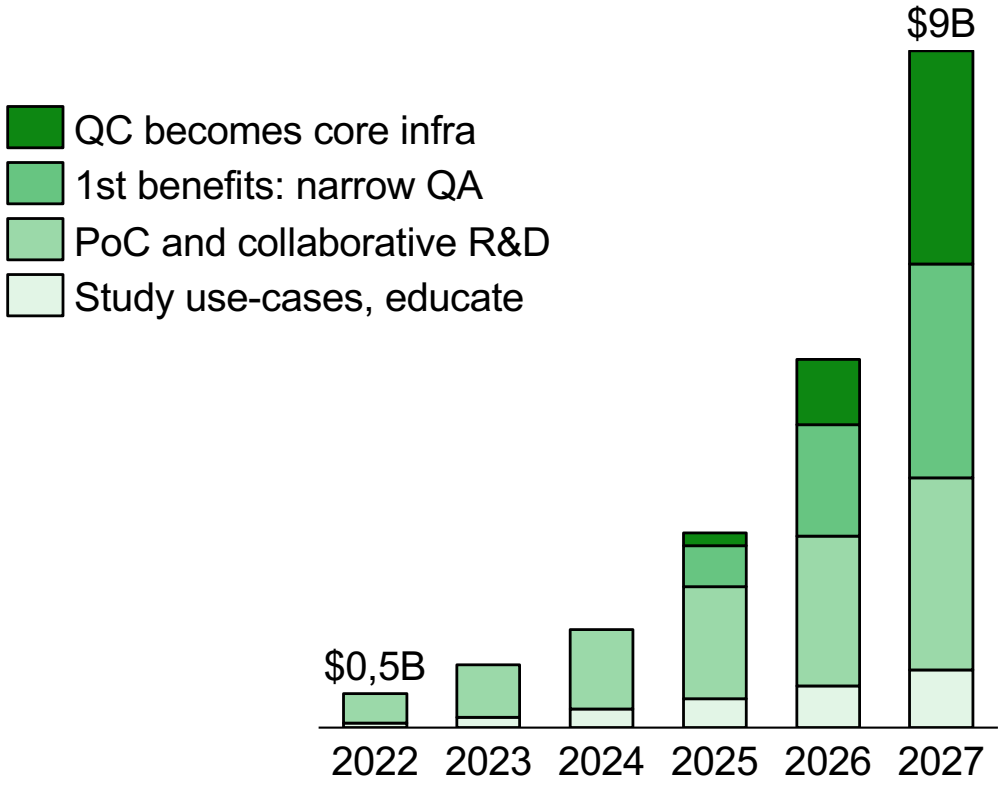
By 2027 ~10,000 companies are expected to engage with quantum and the adressable market will be in the order of $9B

Addressable[1] market (# end-users[2])

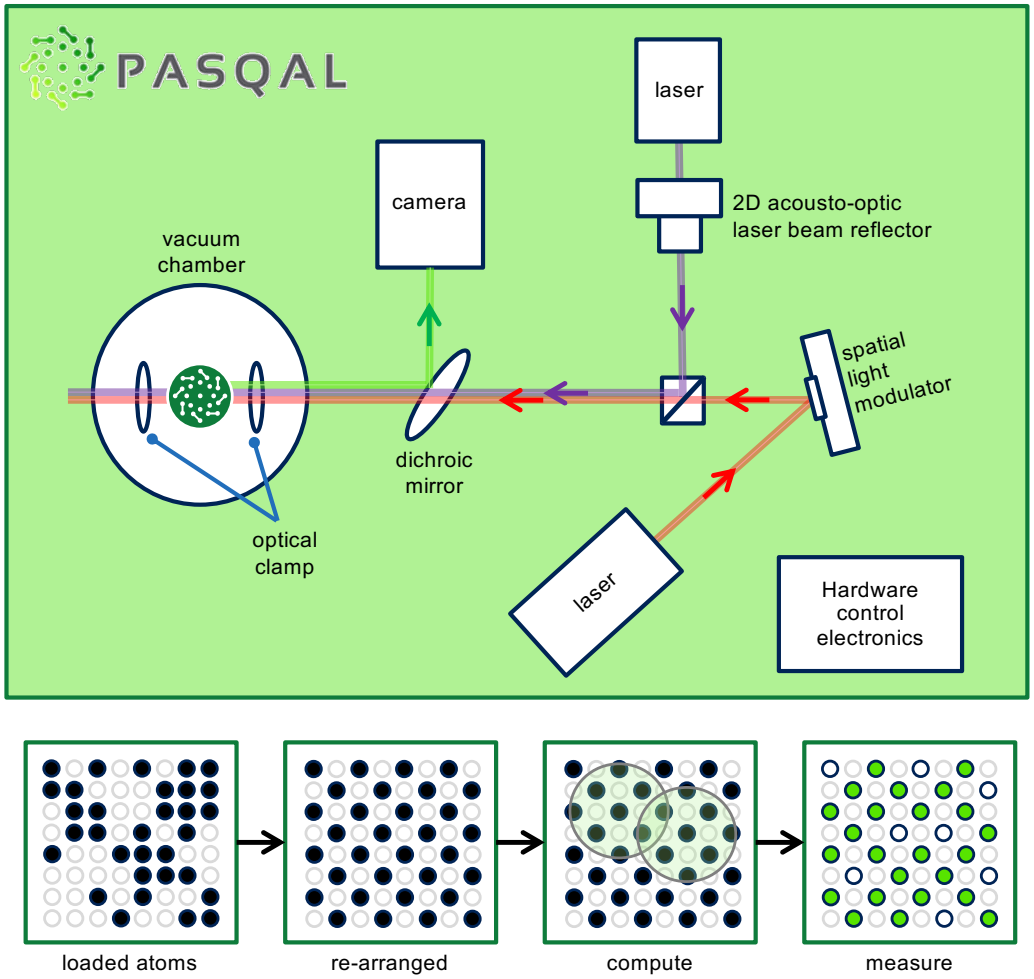


Addressable[1] market (revenues)



Source: OECD datasets, quantum market studies (Hyperion, BCG, McKinsey), Pasqal team analysis
1: excluding 'restricted' countries like China, Russia, Iran, ...
2: number of active quantum end-users (companies)

PASQAL manufacturers neutral-atoms type quantum processors offering superior scaling, state-of-the-art performance, low energy consumption and a high level of industrialization



- Current commercial system offers 100 qubits
- Clear blueprint to showcase 1000 qubits

Source: arXiv:2006.12326

To reach near term quantum advantage, quantum applications have to be optimized to run on a specific quantum processor; this is why PASQAL offers a full-stack service

Pasqal product and service portfolio

Hardware

- Generation 1 100/200-Q
- Generation 2 512/1024-Q
- Generation 3 2k/5k/10k-Q
- ...
- Emulators 20/50/200-Q

Services

Access	• Cloud access • On-premise install • Manage ecosystem
Platform	• Coding platform • Graphical User Interface • Software integrations[1]
Solutions	• Turnkey solutions per problem and sector • Chemistry, CFD, Finance
Libraries	• Quantum (ready) algorithms per mathematical problem • PDE, optimization, ML, ...
Support	• R&D support • Tech support • Maintenance

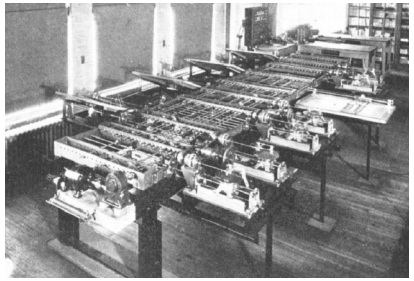
1: integrations with leading classical software packages (for instance the integration of our chemistry simulation platform with the software of schrodinger.com)

The analog mode of PASQAL's quantum computers will be the first to bring concrete computational advantages for important applications

Classical analog

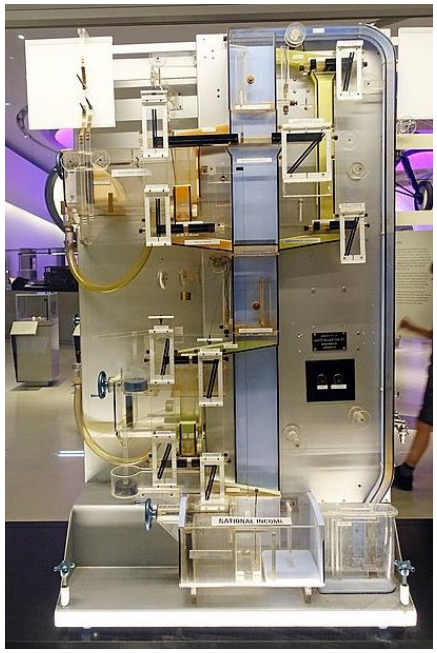
- In classical computing, analog was also first to bring concrete benefits: for instance analog solved differential equations already in 1836

Bush diff. analyser[2] (1931)



Deltar[3] (1960-1984)

Moniac[1] (1949)



Quantum analog

- **Digital**: algorithm implemented through sequence of **discrete** quantum gate operations
- **Analog**: user has control over small number of parameters and the quantum computer evolves towards an answer **continuously**[2]
- Digital is **universal**, but noise limits the use to **very short gate sequences**, which limits the near-term potential for quantum advantage
- Analog is perhaps **not fully universal**, but researchers are finding that it requires typically **10^4-10^5 less quantum operations**
- Analog quantum (or analog-digital) is therefore our **best option to showcase the first industry relevant quantum advantages**

1: https://en.wikipedia.org/wiki/MONIAC; 2: http://worrydream.com/refs/Bush%20-%20The%20Differential%20Analyzer.pdf
3: https://ub.fnwi.uva.nl/computermuseum/deltar.html; 4: note: the PASQAL analog mode is not equivalent to quantum annealing and has much broader applications than QUBO type optimization including quantum machine learning, simulation and solving differential equations
Note: more on analog QC: https://medium.com/pasqal-io/why-analog-neutral-atoms-quantum-computing-is-the-most-promising-direction-for-early-quantum-77b462cefee0

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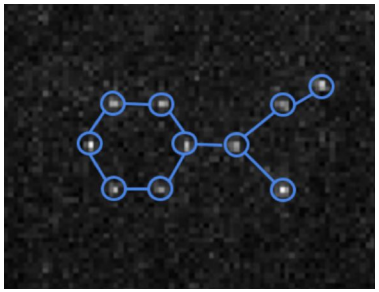
One promising application of the PASQAL analog mode is graph based machine learning; first example: determining graph similarity (e.g. for studying reaction pathways)

Graph Similarity

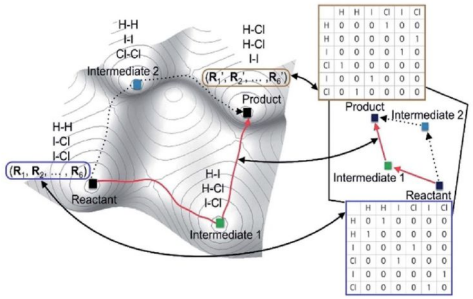
- PASQAL has developed a unique (and fully analog) quantum kernel method which can be used to study graph similarity[1,2]

- Graph structure directly implemented on QPU
- Time evolution under Hamiltonian with strong correlation to input graph structure
- Output (energy histogram) corresponds strongly to graph structure: similarity analysis reduced to comparing 2 histograms

Molecular graph implemented in PASQAL qubit array

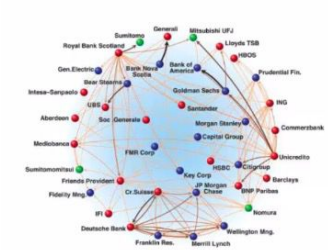


Application: study reaction pathways

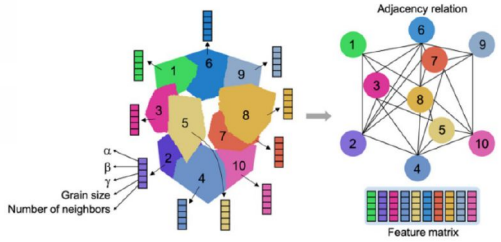


Graph Machine Learning

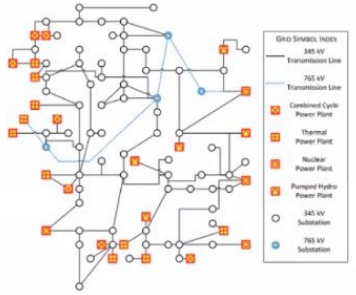
Economic networks



Materials-science



Power grids



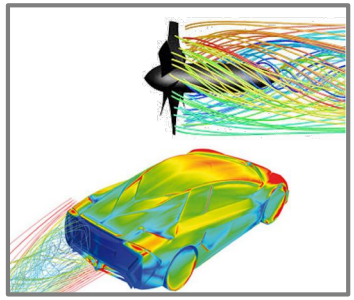
Social networks

1: Quantum evolution kernel, Henry et al. (DOI:10.1103/PhysRevA.104.032416)
2: https://pasqal.io/2022/04/11/towards-quantum-advantage-with-efficient-graph-implementations/
Note: PASQAL filed a patent on the QEK method, please contact us if you are interested in a research license

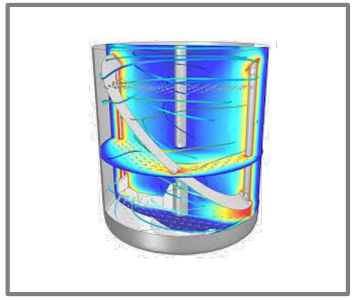
Combining analog with digital (single qubit gates) allows us to solve complex sets of differential equations with near-term quantum processors

Examples of industry relevant problems governed by differential equations

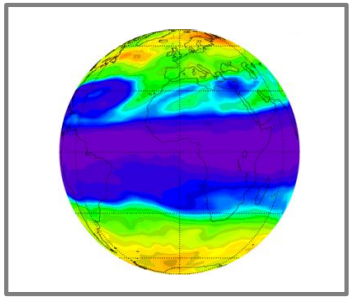
Mechanical Engineering



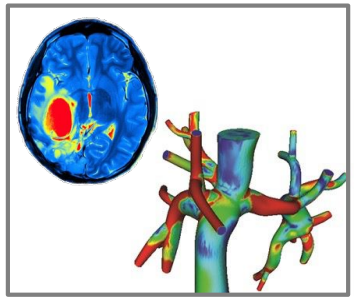
Chemical engineering



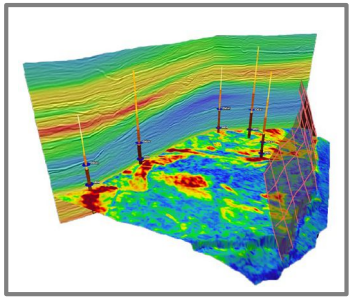
Metrology & Climate



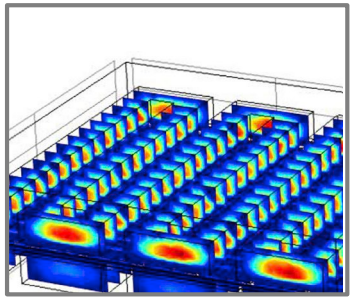
Biomedical



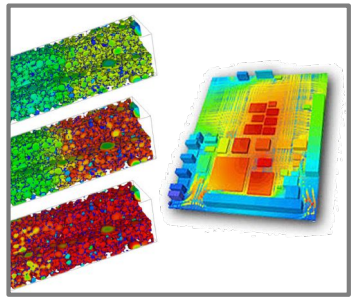
CO_2 storage & Seismic



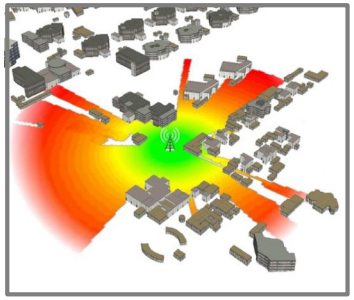
Fuel cell design



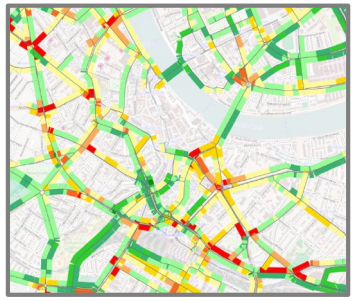
Batteries & Electronics



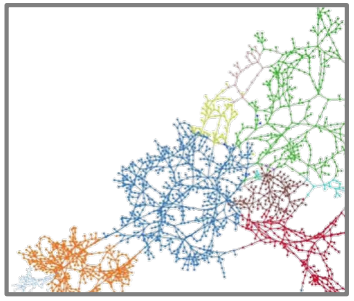
Wireless networks



Traffic flows

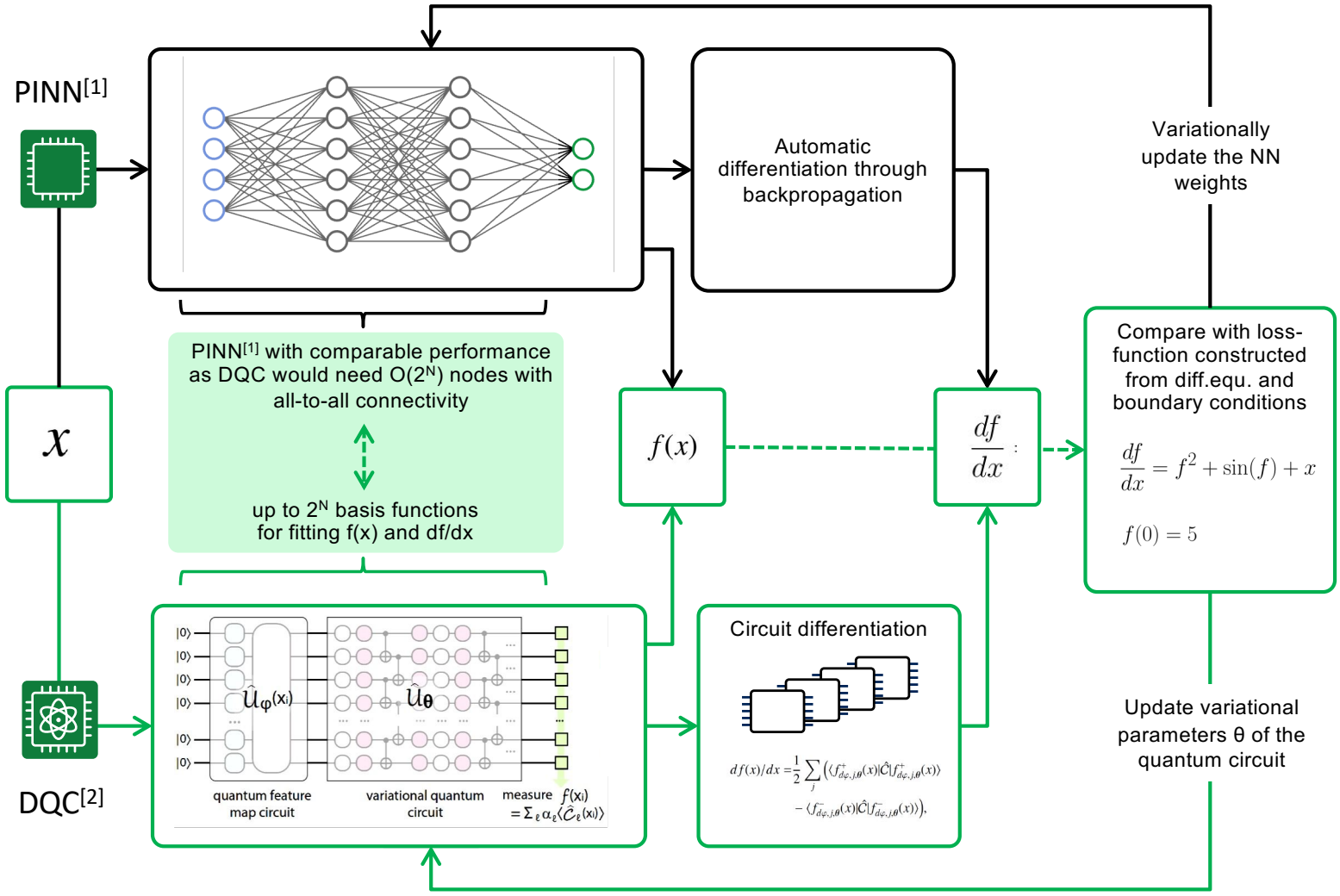


Power grid management



1: DQC = differentiable quantum circuit (https://arxiv.org/abs/2011.10395)
Note: PASQAL filed a patent on the DQC family of algorithms, please contact us if you are interested in a research license

Inspired by classical neural network solvers[1] for differential equations we proposed a unique quantum neural network method[2] which promises higher expressivity

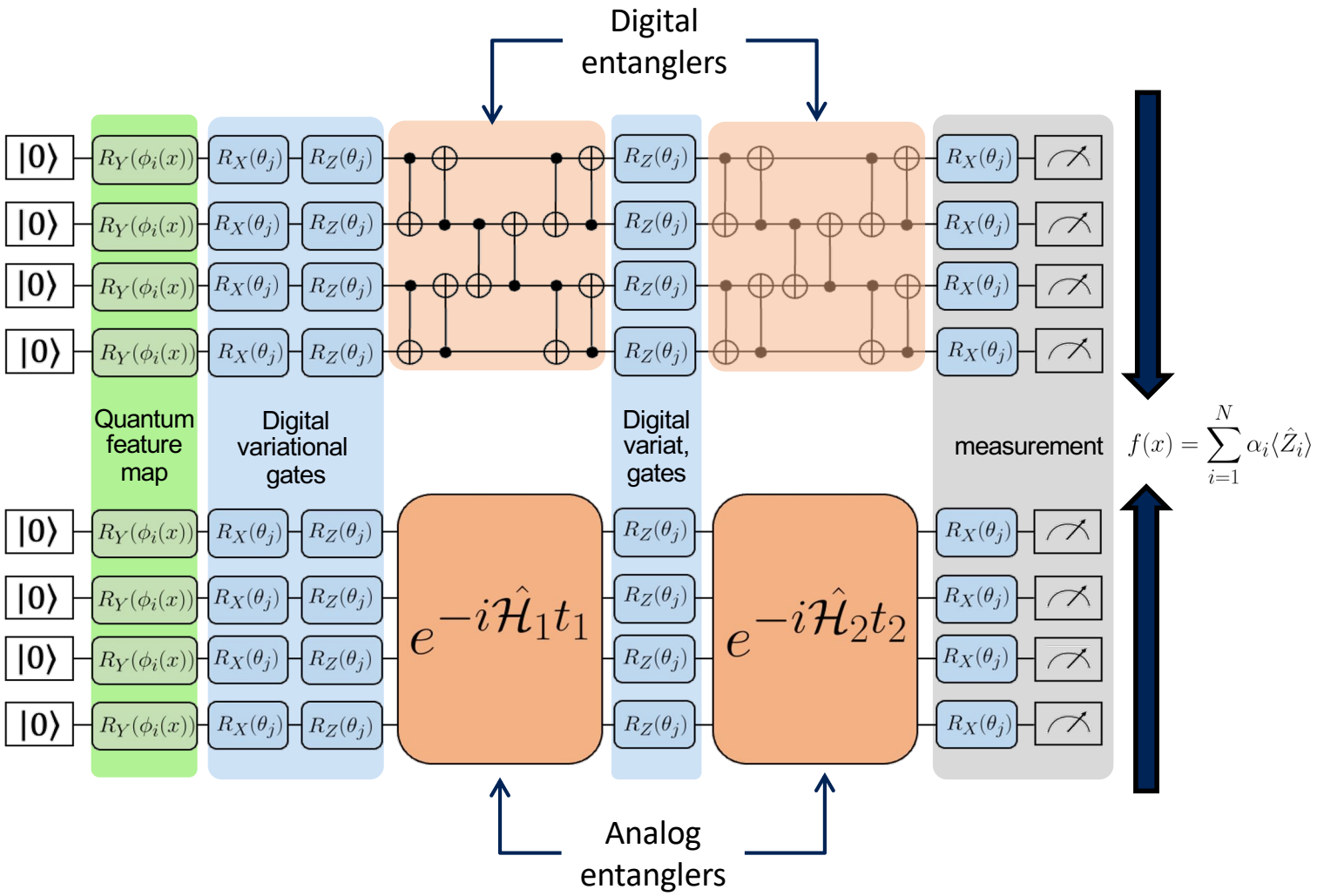


1: PINN = Physics Informed Neural Network; 2: DOI:10.1103/PhysRevA.103.052416
Note: PASQAL filed a patent on the DQC family of algorithms, please contact us if you are interested in a research license

Our differential equation solver can be implemented digitally, but by instead employing analog entanglers we have made it an early candidate for quantum advantage

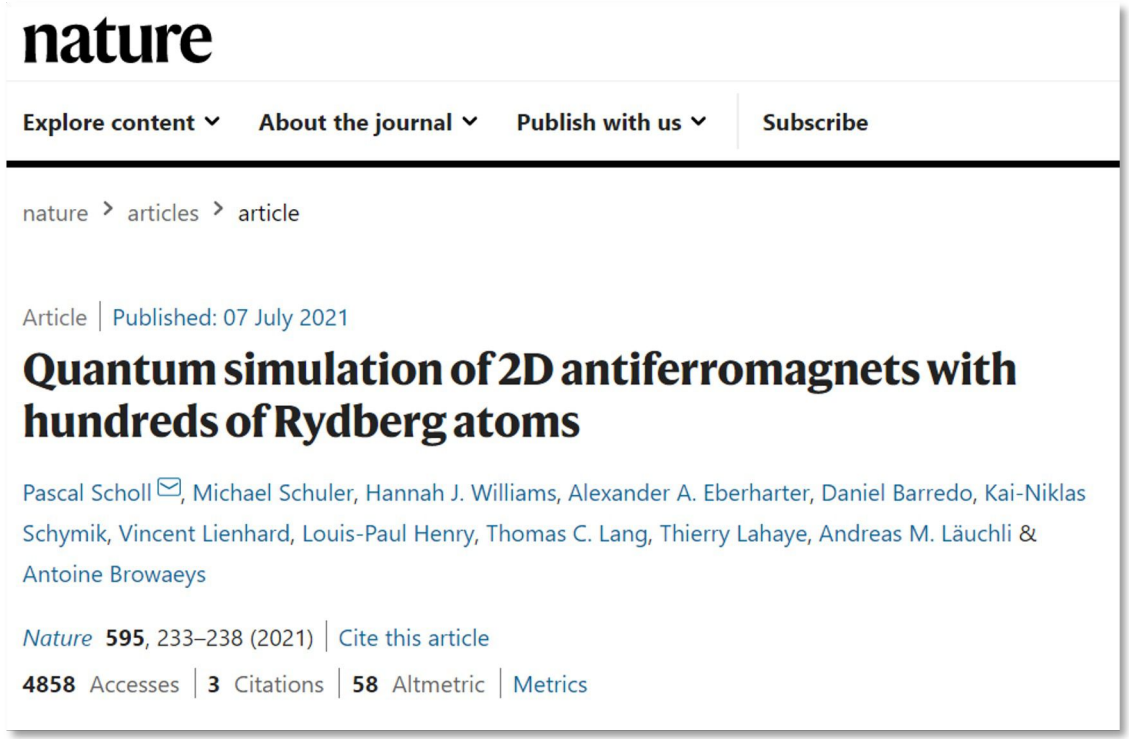
Fully digital DQC[1] circuit

Optimized analog-digital DQC[1] circuit



1: DQC = Differentiable Quantum Circuits method (DOI:10.1103/PhysRevA.103.052416)
Note: PASQAL has filed a patent on the DQC method and on its analog-digital equivalent, please contact us if you are interested in obtaining a research license on one of these approaches

And in the field of analog quantum simulation (quantum material-science), our co-founder Antoine Browaeys has already shown results which go beyond what is classically feasible



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Article | Published: 07 July 2021

Quantum simulation of 2D antiferromagnets with hundreds of Rydberg atoms

Pascal Scholl, Michael Schuler, Hannah J. Williams, Alexander A. Eberharter, Daniel Barredo, Kai-Niklas Schymik, Vincent Lienhard, Louis-Paul Henry, Thomas C. Lang, Thierry Lahaye, Andreas M. Läuchli & Antoine Browaeys

Nature **595**, 233–238 (2021) | Cite this article

4858 Accesses | **3** Citations | **58** Altmetric | Metrics

- "We have probed the quantum dynamics of Ising magnets in square and triangular geometries, **beyond situations which can be exactly simulated classically**"
- "We have **validated** the experimental results with comprehensive numerical simulations up to computationally feasible sizes"
- "We have shown a **high degree of coherence and control, over a large number of atoms**"
- "Combined, this demonstrates that our platform is now able to study quantum spin models in regimes **beyond those accessible via numerical investigations**"

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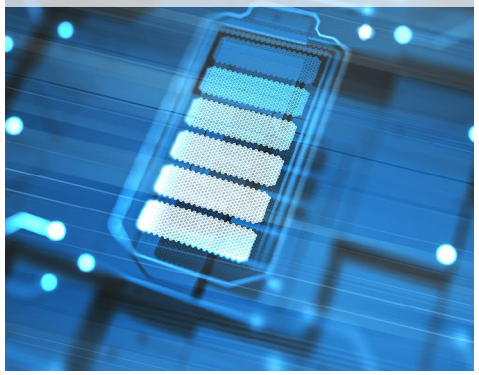
Coming back to the examples of early quantum applications: the analog and analog-digital quantum methods I mentioned are applicable to all of these applications

Some examples of products and services which will be impacted by quantum computing

Battery Development



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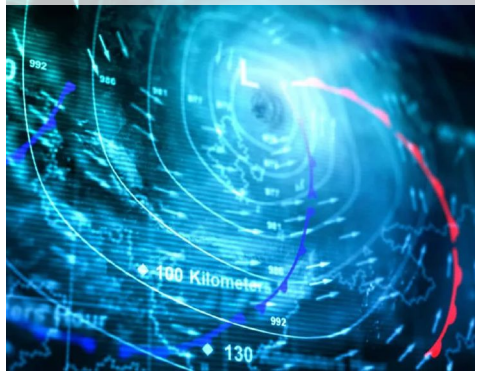

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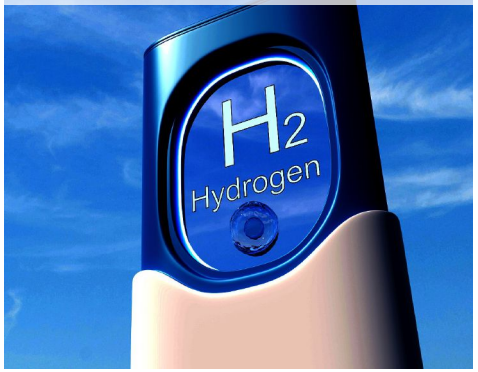

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Conclusions

- Future HPC workflows will likely combine multiple types of specialized compute resources; each of them best positioned to solve a specific mathematical challenge
- Quantum Computing is real; two weeks ago, HPCQS announced that two 100 qubit quantum processors developed by PASQAL will be installed at GENCI and FZJ
- The analog mode of PASQAL's quantum computers will be the first to bring concrete computational advantages for important applications
- PASQAL is working towards early quantum advantage for analog and analog-digital applications in sectors like energy, mobility, healthcare and finance
- Get started now:
  - Download our open-source SDK called Pulser (whitepaper: arXiv:2104.15044)
  - Contact me (benno.broer@pasqal.com) to start your journey towards quantum advantage