Quantum computers: industrial applications and actual players

Quantum technologies and industry

Kenneth MAUSSANG

Université de Montpellier

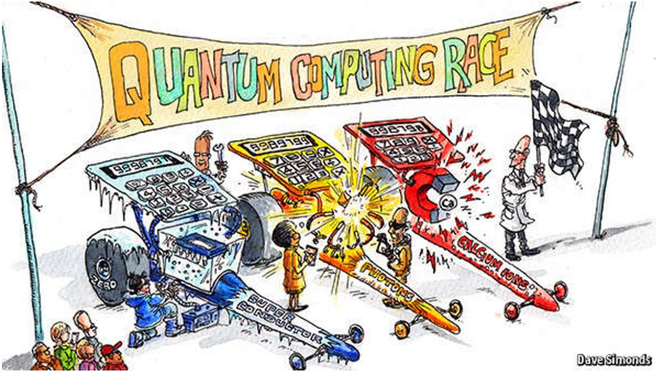
Ecole Centrale Casablanca

2020 – 2021

Quantum computers: industrial applications and actual players

Quantum computers: industrial applications and actual players

I.1. The quantum race



The quantum race for the most appropriate technology to develop a commercial quantum computer. Extracted from *A little bit, better*, The Economist, June 20th, 2015

`https://www.economist.com/science-and-technology/2015/06/20/a-little-bit-better`

Building a quantum computer relies on the ability to develop a chip on which are integrated qubits, or an equivalent system.

Hardware companies are pursuing a range of technologies with very different characteristics and properties.

As of now, it is unclear which will ultimately form the underlying architecture for quantum computers, but the field has narrowed to a handful of potential candidates.

Several systems might been proposed to achieve such a device:

- single photons (used in photonic computing);
- superconducting qubits (transmon's qubits);
- atoms (Rydberg atoms or neutral atoms);
- molecules (case of NRM quantum computing);
- ions (trapped with electrostatic potentials and manipulated with lasers);
- quantum dots;
- ...

Most of first industrial players which have developed industrial quantum computers have chosen a solution based on superconducting qubits. For instance, IBM, Google, Rigetti, D-waves have chosen such a technology.

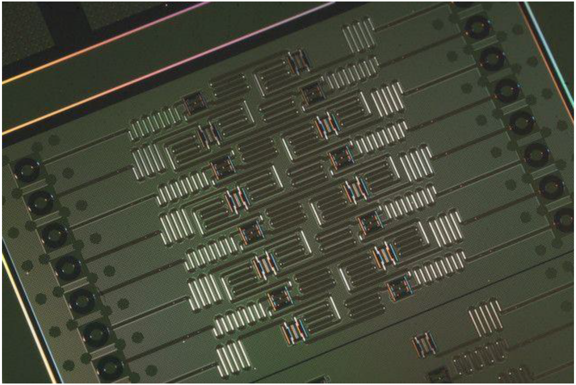


Photo of a chip with superconducting qubits (Picture credits: IBM research).

Beyond superconducting qubits, the research landscape is more open, with a few promising candidate technologies in the race, all of which are still immature. Each approach has its attractive aspects and its challenges.

Photons, for example, could have an advantage in terms of handling because they operate at room temperature and chip design can leverage known silicon technology.

The challenges for photons lie in developing single photon sources and detectors as well as controlling multiphoton interactions, which are critical for two-qubit gates.

- PsiQ, a Silicon Valley startup, wants to leapfrog the NISQ period with an ambition to develop a large-scale linear optical quantum computer.
- LOQC, based on photons as qubits, with 1 million qubits as its first go-to-market product within about five years (2025). This would be a major breakthrough if and when it becomes available.

Topological approach is an unprecedented low error rate of 1 part per million (and not excluding even 1 part per billion). This would constitute a game changer.

The underlying physical mechanism (the exotic Majorana quasiparticle) is now largely accepted, but the first topological qubit is still expected while it was initially announced by Microsoft to become reality in 2018.

Two-qubit gates, however, are an entirely different ballgame, and even a truly ambitious roadmap would not produce a workable quantum computer for at least five years.

I.1. Superconductive qubits

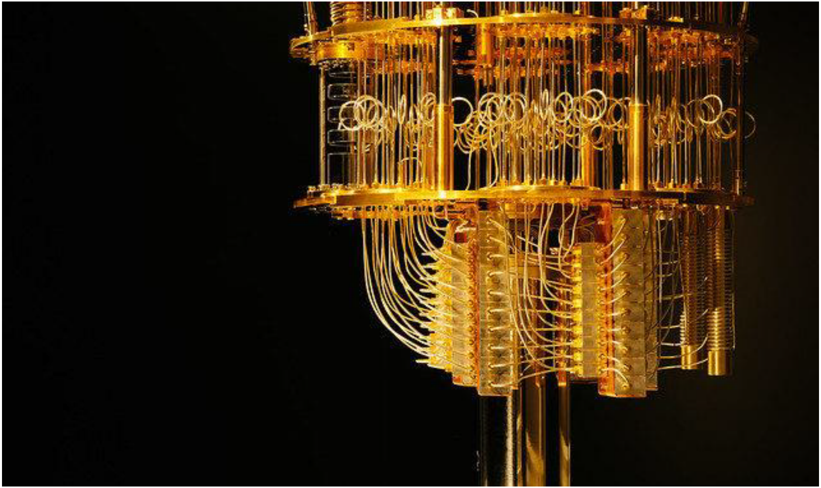


Photo of a IBM quantum computer with 53 cubits chip. (Picture credits: IBM research).

I.1. Superconductive qubits

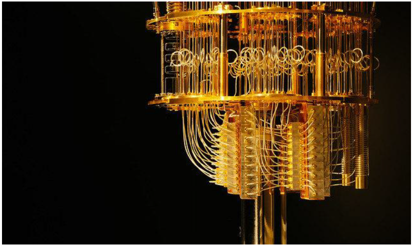


Photo of a IBM quantum computer with 53 cubits chip. (Picture credits: IBM research).

Advantages of superconducting qubits

- easily scalable;
- rather well-controlled clean room process well-adapted for on-chip integration;
- qubits might be probed and manipulated with electronic tools such as microwave and RF waves;
- short qubit manipulation time compared to coherence time.

I.1. Superconductive qubits

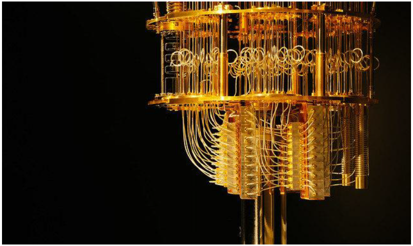


Photo of a IBM quantum computer with 53 cubits chip. (Picture credits: IBM research).

This technology is the most commonly used currently, adapted for first generation quantum computers with a rather small number of qubits manipulations.

Intel is also developing quantum chips based on superconducting qubits, but does not develop a quantum computer itself.

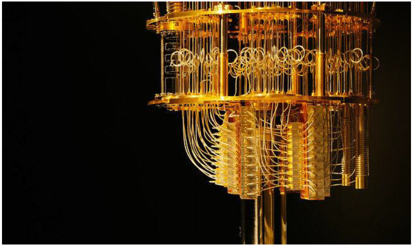
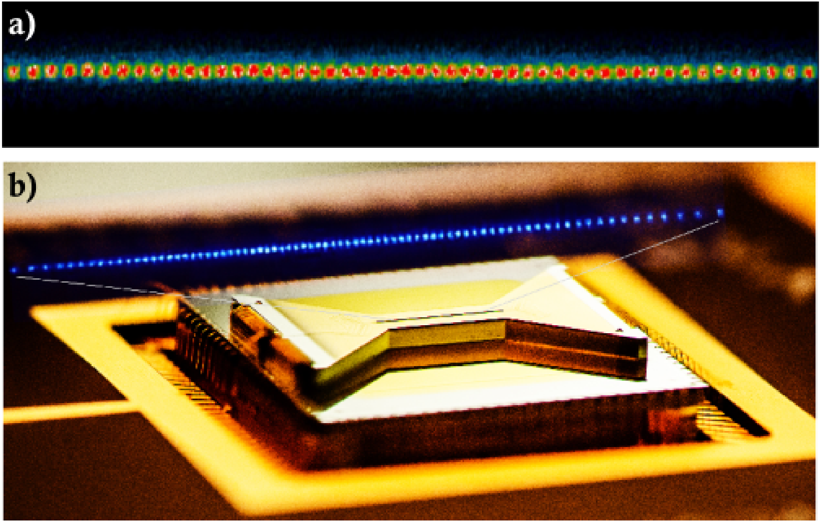


Photo of a IBM quantum computer with 53 cubits chip. (Picture credits: IBM research).

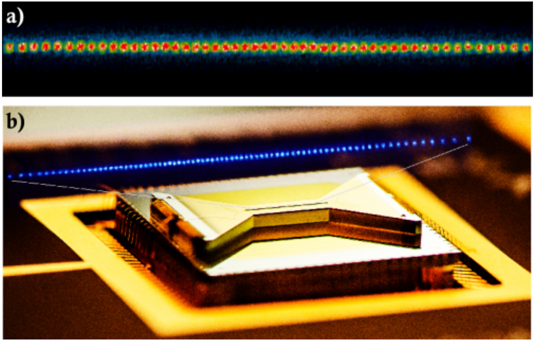
But (very) cold temperatures.

- Josephson junction circuit: a small insulating layer that couples two wavefunction of superconducting material.
- Quantum processor chips are kept at 15 mK typically (dilution refrigerators).
- The quantum computer is not really sold but the service is commercialised as a cloud quantum calculation which is most of provider business model currently.

I.1. Ions



I.1. Ions



a) Optical image of a chain of ion trapped. Each ion might be observed individually. Picture extracted from Prof. Christopher Monroe's group website (http://iontrap.umd.edu/). University of Maryland, Department of Physics, Joint Quantum Institute, and Center for Quantum Information and Computer Science.

b) Integration of a ion trap on a chip. K. Hudek & E. Edwards/Univ. of Maryland/IonQ, Inc./JQI.

- Ions of rubidium or ytterbium, trapped in a vacuum chamber by time-varying electromagnetic fields.
- IonQ (`https://ionq.com/`), founded in 2016, has proposed a quantum computer architecture based on individual ions.
- Big advantage of ions: coherence time are very important (few tens of seconds).
- Scalability is more challenging than superconducting qubits.
- Qubits are manipulated with lasers rather than electronic means.
- Restricted to 1D topology.

I.1. Ions

To date, IonQ has run single-qubit gates on a 79 ion chain, and complex algorithms on chains of up to 11 ions.

While superconducting qubits permit a 2D topology to couple qubits, ion trap restrict topology to a linear chain.

But the performances of this technology are promising, such that Samsung and a sovereign wealth fund of the United Arab Emirates are leading a new $55 million funding round for IonQ.

I.1. Silicon based technologies

Experimental breakthroughs in silicon-based nanodevices have brought a third option to the fore, either from academics or industrial players as Hitatchi.

This option is to manufacture quantum processors in the same way as conventional microprocessors, by leveraging widely deployed industrial complementary metal-oxide-semiconductor (CMOS) technology.

This would provide a huge avantage for the architecture of the chip, with the benefice of all the technical knowhow of CMOS and silicon technologies and without the need of cryogenic temperatures.

The mean advantage of silicon-based quantum processors is that they use the same technology that the microchip industry has handled for decades. Manufacturers could still use previous multibillion-dollar infrastructure investments, and therefore reduce production costs.

Kane's quantum computer

Silicon-based CMOS technologies to build quantum computers was first proposed in 1998 by Bruce Kane, based on an arrays of individual phosphorus atoms in crystalline silicon.

Each individual phosphorus atom possesses a nuclear spin that might be seen as a qubit (just like NMR but localised specially in each phosphorus atoms). These spin qubits could be read and manipulated using nuclear magnetic resonance techniques.

Another reason for the focus on silicon stems from the properties of the material itself.

Noise is one of the great bugbears of quantum information processing, because it can make qubits change state leading to computational errors. Most interactions with the surrounding environment, such as charge instabilities and thermal fluctuations.

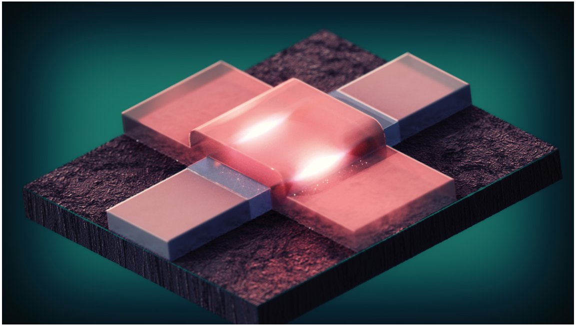
Each individual phosphorus atom possesses a nuclear spin that might be seen as a qubit (just like NMR but localised specially in each phosphorus atoms). These spin qubits could be read and manipulated using nuclear magnetic resonance techniques.

I.1. Silicon based technologies

The major source of unwanted quantum bit errors in silicon transistor-based qubits comes from the nuclear spins of ^{29}Si, the naturally dominant isotope, while otherwise silicon offers a relatively noise-free environment.

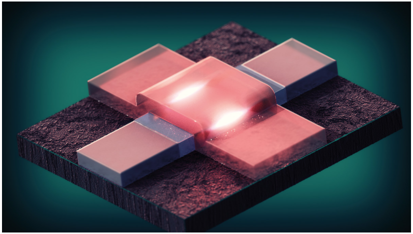
But ^{29}Si isotope is spin-free and offers long coherence times for phosphorus qubits in it. For this reason, electron spins in silicon are among the most robust solid-state qubits available, but requires highly purified ^{29}Si silicon wafer which is not a common material.

I.1. Silicon based technologies



Silicon nanowire based transistor for realization of a spin qubit with CMOS technologies. Two quantum dots are formed in the top corners of the nanowire and trap individual spins. Qubit control is achieved via electron spin resonance techniques with microwave pulsing. (Picture credits: Hitachi).

I.1. Silicon based technologies

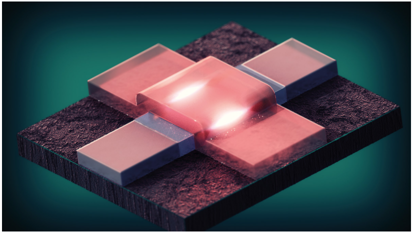


Silicon nanowire based transistor for realization of a spin qubit with CMOS technologies. (Picture credits: Hitachi).

CEA-LETI in France has proposed a qubit device based on an industry-standard fabrication process, based on a 300 nm silicon-on-insulator wafers.

The project has been developed as part of the European research consortium MOSQUITO (`http://www.mos-quito.eu`).

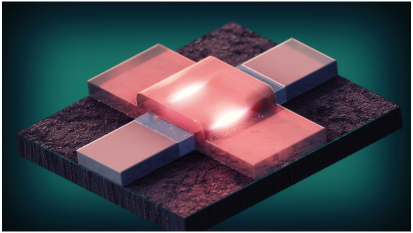
I.1. Silicon based technologies



Silicon nanowire based transistor for realization of a spin qubit with CMOS technologies. (Picture credits: Hitachi).

It consists in the development of a nanowire transistor with an undoped channel and wrap-around gate electrodes. At low temperatures, two QDs form in the upper corners of the nanowire in which individual spins can be trapped.

Under the effect of a magnetic field, the electron spins align parallel or antiparallel to the field direction, producing the necessary quantum binary states.



Silicon nanowire based transistor for realization of a spin qubit with CMOS technologies. (Picture credits: Hitachi).

The need for two QDs arises because one is used to host a qubit, while the other one is used as a sensor to readout the qubit state. If this technology has been demonstrated, it still requires cryogenics temperatures in milliKelvin range, while phosphorus nuclear spins in ^{29}Si have been demonstrated at room temperature.

I.1. The high-risk/high-gain way: topological qubits

Microsoft is supporting **fundamental research** on the development of a new kind of high-quality qubits, based on **topological insulators**.

Such qubits are very interesting since they are expected to be highly unsensitive to external noise, exhibiting low decoherence and consequently low error rates. They are so-called *topologically protected*.

They rely on the existence of a particle called *Majorana fermion*. But such a particle hasn't been observed yet!

That is a **highly risky strategy from Microsoft**.

But if they are successful, these qubits will be of high quality and very low error rates, resulting in huge gain for Microsoft, in term of performances and technological advance.

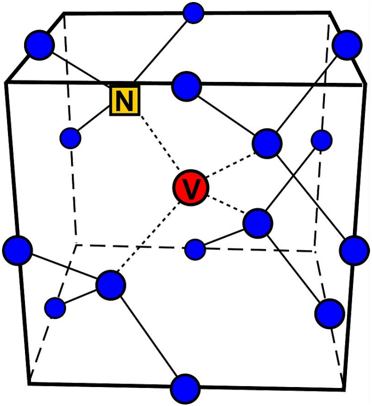
Recent technological progress have been reported toward the experimental observation of this particle, using indium phosphide nanowires in a hashtag shape, but it remains unobserved for the moment.

I.1. Other physical realizations

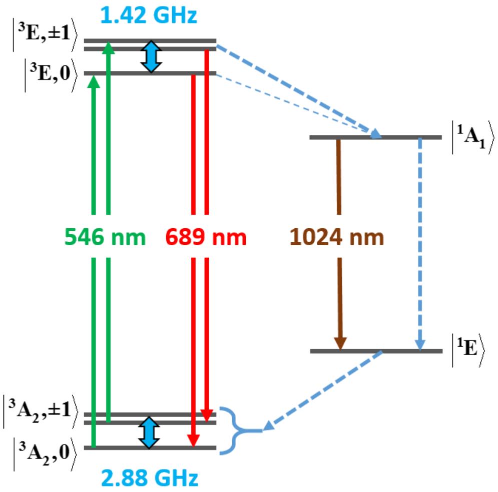
- **Optical lattices** qubit implemented by internal states of neutral atoms trapped in an optical lattice.
- **Quantum dot** spin-based (qubit given either by the spin states of trapped electrons or by electron position in double quantum dot.
- **Coupled Quantum Wire** qubit implemented by a pair of Quantum Wires coupled by a Quantum Point Contact.
- **Solid-state NMR Kane quantum computers** qubit realized by the nuclear spin state of phosphorus donors in silicon.
- **Electrons-on-helium quantum computers** qubit is the electron spin.

I.1. Other physical realizations

- **Cavity quantum electrodynamics (CQED)** qubit provided by the internal state of trapped atoms coupled to high-finesse cavities.
- **Molecular magnet** qubit given by spin states.
- **Linear optical quantum computer** qubits are realized by processing states of different modes of light through linear elements (mirrors, beam splitters and phase shifters).
- **Diamond-based quantum computer** qubit realized by the electronic or nuclear spin of nitrogen-vacancy centers in diamond.

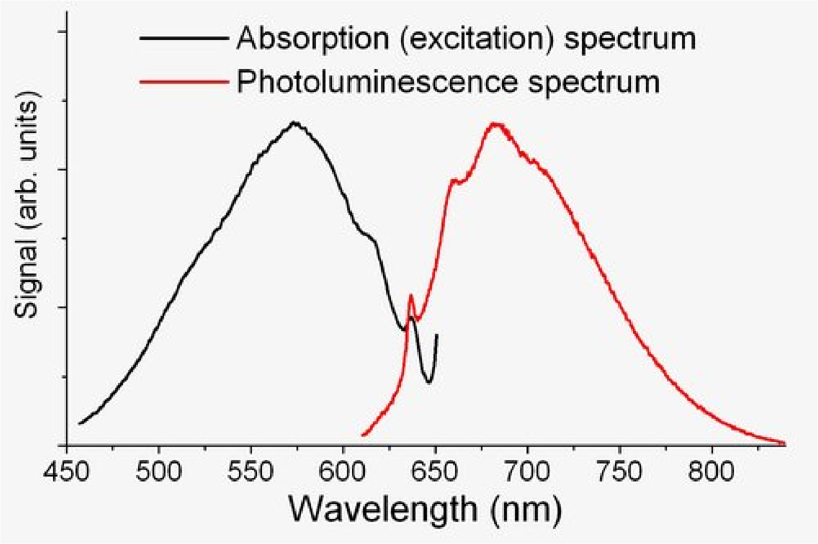


NV center https://fr.wikipedia.org/wiki/Centre_azote-lacune



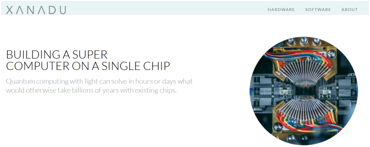
NV center level scheme

`https://fr.wikipedia.org/wiki/Centre_azote-lacune`



Absorbtion and emission spectrum of NV center

I.1. Other physical realizations



Photons as qubits (Xanadu). `https://www.xanadu.ai/`

I.1. Other physical realizations

EXHIBIT 6 | Assessment Criteria for Gate-Based Quantum Computers

CRITERIA	CURRENT RANGE	WHAT DOES IT MEAN?	WHY IS IT IMPORTANT?
Number of physical qubits	2–20	Number of physical quantum bits on a chip	Relevant for scaling and achievable operation complexity
Number of logical qubits	0	Number of error-corrected qubits used for fault-tolerant quantum computing	Determines scaling of sophisticated algorithms
Qubit lifetime	50 µs–50 s	Period of time information can be stored in a qubit	Determines how long qubits can store and process information
Gate fidelity	90–99.9 %	Accuracy for a two-qubit operation	Critical determinant for quality and overhead of quantum error correction
Gate operation time	1 ns–50 µs	Time for a two-qubit operation	Determines the clock speed for manipulating physical qubits
Connectivity	1:1–n:n	Connections between qubits	Determines how much information can be encoded in qubit group states
Scalability	low–high	Potential of the system to scale	Determines the ability to build a large-scale quantum computer
Maturity	TRL 1–5	Technology readiness level	Determines technological maturity on a scale from 1–9

Extracted from
Sources: BCG analysis; expert interviews.

https://www.bcg.com/fr-fr/publications/2018/next-decade-quantum-computing-how-play.aspx.

EXHIBIT 7 | Overview of Leading Quantum Computing Technologies During the NISQ Era

	Leading technologies in NISQ era[1]		Candidate technologies beyond NISQ		
Qubit type or technology	Superconducting[2]	Trapped ion	Photonic	Silicon-based[3]	Topological[8]
Description of qubit encoding	Two-level system of a superconducting circuit	Electron spin direction of ionized atoms in vacuum	Occupation of a waveguide pair of single photons	Nuclear or electron spin or charge of doped P atoms in Si	Majorana particles in a nanowire
Physical qubits[4,5]	IBM: 20, Rigetti: 19, Alibaba: 11, Google: 9	Lab environment: AQT[6]: 20, IonQ: 14	6×3[9]	2	target: 1 in 2018
Qubit lifetime	~50–100 µs	~50 s	~150 µs	~1–10 s	target ~100 s
Gate fidelity[7]	~99.4%	~99.9%	~98%	~90%	target ~99.9999%
Gate operation time	~10–50 ns	~3-50 µs	~1 ns	~1–10 ns	–
Connectivity	Nearest neighbors	All-to-all	To be demonstrated	Nearest neighbor	–
Scalability	No major road-blocks near-term	Scaling beyond one trap (>50 qb)	Single photon sources and detection	Novel technology potentially high scalability	?
Maturity or technology readiness level	TRL[10] 5	TRL 4	TRL 3	TRL 3	TRL 1
Key properties	Cryogenic operation Fast gating Silicon technology	Improves with cryogenic temperatures Long qubit lifetime Vacuum operation	Room temperature Fast gating Modular design	Cryogenic operation Fast gating Atomic-scale size	Estimated: Long lifetime High fidelities

Sources: BCG analysis; expert interviews.
[1]Noisy Intermediate-Scale Quantum devices era.
[2]Currently only technology with external cloud access; several forms (charge, flux, phase) of qubits exist but most pursue a less noise-sensitive

Quantum computers: industrial applications and actual players

1. Development of a commercial computer: a technological challenge!
   - Which technology is appropriated?
   - Open questions for the development of a commercial quantum computer
   - Growth of quantum technologies fundings
   - Scientific publishing
2. Applications of quantum computers
3. Quantum gold rush

I.2. Number of qubits and quantum volume

The number of qubit is not necessarily relevant to quantify the potentiality of a quantum computer. Performances are fundamentally related to coherence time and error rates of gates.

IBM as develop in 2017 the notion of *quantum volume* in order to have a metric of the performances of a quantum computer. Quantum volume is a heuristic measure somewhat may be seen as the number of qubits times the number of gate operations that can be reliably performed until an error occurs.

I.2. Number of qubits and quantum volume

Quantum volume should be seen as a tool that allowed them to systematically measure and understand how incremental technology, configuration and design changes affected a quantum computer's overall power and performance.

Scientists believe that computers with a few hundred physical qubits are within technological reach.

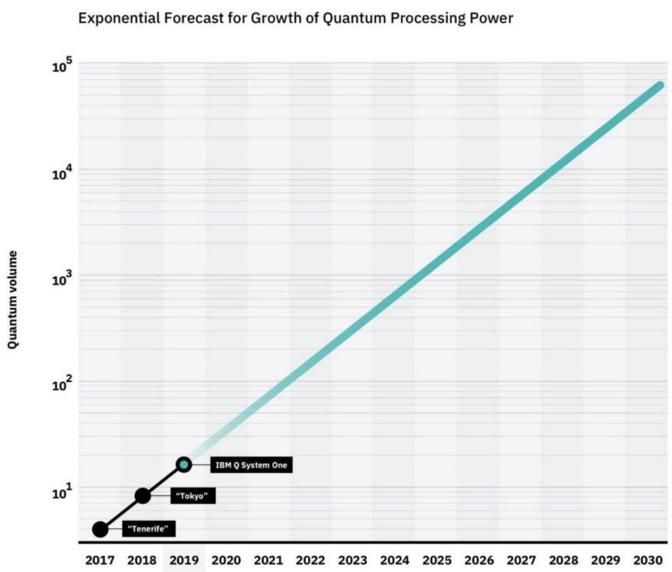
A better standard for size and capability in the future would be the number of fully error-corrected "logical qubits," but no one has yet developed a machine with logical qubits, so their number across all technologies is still zero (and will likely remain so for a while).

I.2. Number of qubits and quantum volume

Unfortunately, **the comparative performance of algorithms on different hardware technologies cannot be directly determined from these characteristics.**

The most common approach for performance assessments is a benchmarking on randomized algorithms by independent companies.

End-to-end software and specialist players are offering services at different levels of sophistication both to assess the performance of specific algorithms on the available hardware and to help with developing the best quantum algorithm based on these assessments.

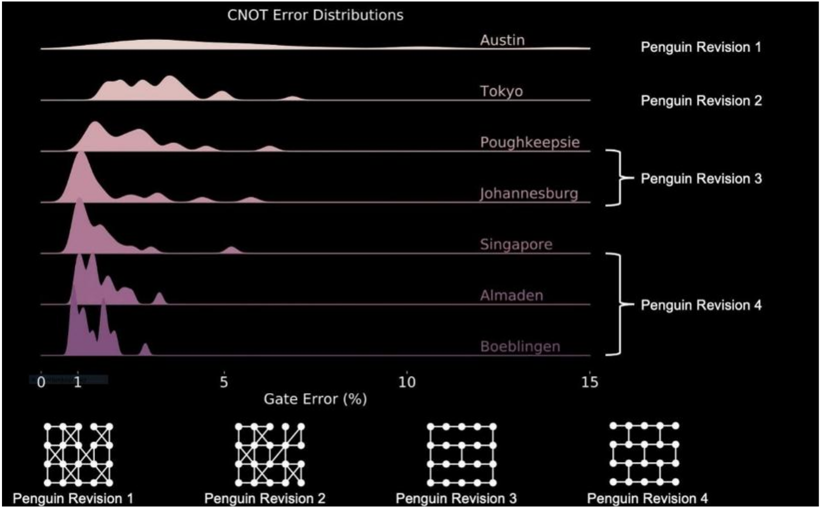


IBM Quantum Volume Growth Chart

The factors that determine a computer's calculating capability include a number of factors which are

- **Qubit lifetime** currently 50 μs to 50 s;
- **Operation accuracy** in particular the most sensitive two-qubit gate fidelity (currently 90% to 99.9%, with 99.9% minimally required for reasonably effective scaling with error correction);
- **Gate operation time** currently 1 ns to 50 μs;
- **Topology of the qubits connections** currently from the worst (one-to-one) to the best (all-to-all). This is important, because entanglement is a distinguishing factor of quantum computing and requires qubits to be connected to one another so they can interact.

I.2. Complexity of accurate calculations

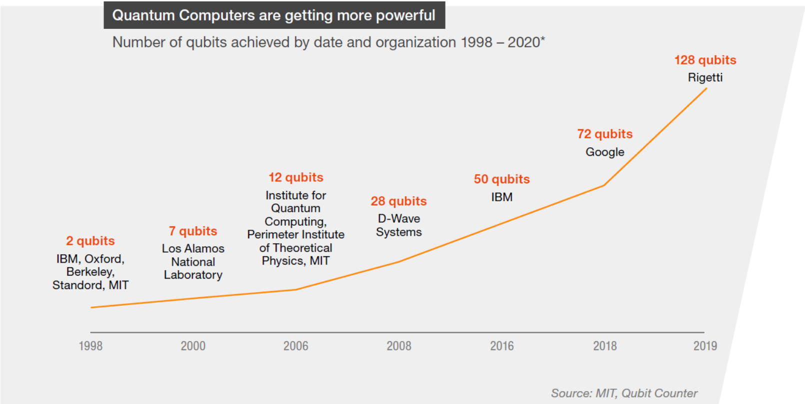


CNOT Error Distributions for different version of IBM's 20-qubits systems.

I.2. Remaining technological challenges

There are a number of technical challenges in building a large-scale quantum computer, David DiVincenzo listed the following requirements for a practical quantum computer:

- scalable physically to increase the number of qubits;
- qubits that can be initialized to arbitrary values;
- quantum gates that are faster than decoherence time;
- universal gate set;
- qubits that can be read easily.



Quantum computing: a technology of the futur already present (PWC).

I.2. Remaining technological challenges

One of the greatest challenges is **controlling or removing quantum decoherence**.

Decoherence times for candidate systems in particular, the transverse relaxation time T_2 (the dephasing time), typically range between nanoseconds and seconds at low temperature.

Currently, quantum computers based on superconductive qubits require the quantum chip to be cooled to 15 millikelvins in order to prevent significant decoherence. To achieve such temperature, dilution helium fridge cooling systems are necessary. Such cooling systems are based on the use of ^{3}He, which is a nuclear research byproduct, very expensive with important price fluctuations (from $500 to $2000 per litre).

Then a good qubit should be isolated from the environment for long coherence time.

But on the other hand, a good qubit should be able to interaction strongly with other qubits to perform mulitqubits gates within a short timescale.

That's the main technological paradox to solve.

I.2. Remaining technological challenges

Due to decoherence, time-consuming tasks may render some quantum algorithms inoperable, as maintaining the state of qubits for a long enough duration will eventually corrupt the superpositions.

If the error rate is small enough, it is thought to be possible to use quantum error correction to suppress errors and decoherence (if the error correction scheme can correct errors faster than decoherence introduces them).

But numerical studies estimate that, assuming a depolarizing error probability of $p < 10^{-3}$ per elementary gate, **a logical qubit needs to consist of between 1,000 and 10,000 physical qubits**. Building a large logical qubit with such a low error rate could be a second rest stop along the road to robust quantum computing.

I.2. Remaining technological challenges

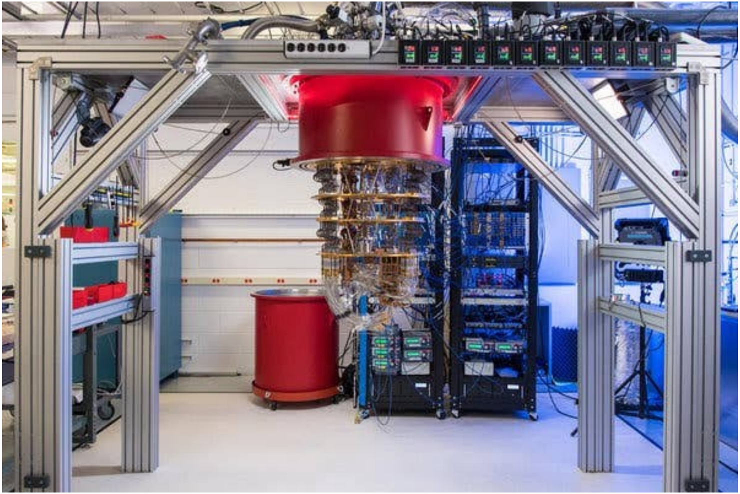
If error correction has been implemented, there is a price on clock speed that all gate-based technologies will have to pay for fault-tolerant quantum computing.

Measurement times, required in known error-correction schemes, are in the range of μs. Thus, an upper limit on clock speed of about 1 MHz emerges for future fault-tolerant quantum computers. This in turn will be a hurdle for the execution speed-up potential of quantum algorithms.

The use of helium fridge for the development of quantum computers has been pointed out as a difficulty for mass production of such systems.

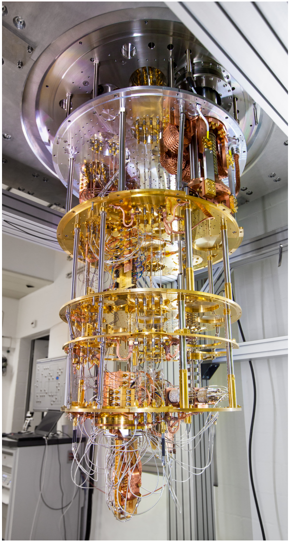
Dilution fridge, which can cost between $500,000 and $1 million each, are custom-made usually, by only a few companies like BlueFors in Finland and Oxford Instruments in the UK, are producing high-quality ones. Such a fridge might requires up to $40,000 of ^{3}He.

I.2. Remaining technological challenges



Quantum Computer.

I.2. Remaining technological challenges



Quantum Computer (ETH Zurich).

In addition to the use of ^{3}He, it requires the use of superconducting cables to control and measure qubits. These are specially designed to conduct very little heat so that they don't affects qubits states. Only one main manufacturer supplies them, a Japanese company called Coax Co. Sourcing parts for quantum computers has been stressed out as a difficulty for their mass production deployment.

Dilution fridge, which can cost between $500,000 and $1 million each, are custom-made usually, by only a few companies like BlueFors in Finland and Oxford Instruments in the UK, are producing high-quality ones. Such a fridge might requires up to $40,000 of ^{3}He.

I.2. Remaining technological challenges

In fact, superconducting qubits scaling challenge may seem somewhat mundane: electric cabling and control electronics.

The current way of addressing a qubit with two to four cables, while also maintaining cryogenic temperatures, triggers severe engineering challenges when the number of qubits runs into the hundreds.

That being said, even superconducting qubit architectures have achieved only about 50 to 128 reliable qubits so far (IBM: 50qubits; Google: 72 qubits; Rigetti: 128 qubits; Intel: 49 qubits), compared with 10^{10} bits on a chip for classical computing, so there is still some ways to go.

The roadmaps of all these players extend to about 1 million qubits! They have a strong grip on what needs to be resolved consecutively along the journey, even if they do not yet have workable solutions for them.

The two biggest questions facing the emerging quantum computing industry are

- **When will we have a large, reliable quantum computer**?
- **What will be its architecture?**

The main remaining question is **the utility of quantum computing, even if one may achieve a perfect qubit with no errors.**

Is a universal quantum computer sufficient to efficiently simulate an arbitrary physical system ? that is still an open question.

Even quantum supremacy, regardless usefulness of the algorithm, is still not demonstration until now.

However, quantum supramcy demonstration is deemed imminent, and Rigetti recently offered a $1 million prize to the first group that proves quantum advantage.

Several companies are proposing *quantum challenges*, to investigate, in a open innovation scheme, to potential benefits of such technologies.

- Airbus: `https://www.airbus.com/innovation/tech-challenges-and-competitions/airbus-quantum-computing-challenge.html`
- Zeiss: `https://www.zeiss.com/corporate/int/careers/events/zeiss-quantum-challenge.html`

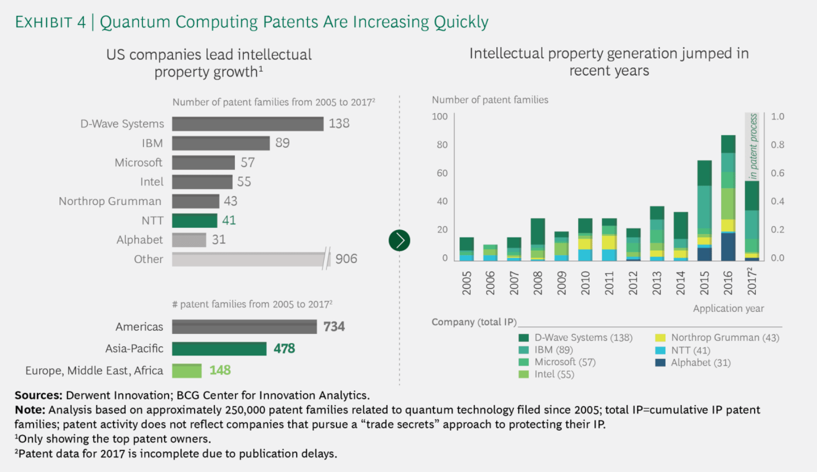
Quantum computers: industrial applications and actual players

1. Development of a commercial computer: a technological challenge!
   - Which technology is appropriated?
   - Open questions for the development of a commercial quantum computer
   - Growth of quantum technologies fundings
   - Scientific publishing
2. Applications of quantum computers
3. Quantum gold rush

I.3. Public fundings

- China: \$10 billion quantum program spanning the next five years, of which \$3 billion is reserved for quantum computing.
- EU: €1 billion investment for a large-scale EU-wide quantum technologies flagship in 2016.
- Germany: €650 million for quantum technology R&D.
- UK: \$381 million in the UK National Quantum Technologies Programm.
- USA: National Quantum Initiative Act, a law that allocates \$1.2 billion for quantum information science research (2019).
- Many other countries, notably Australia, Canada, and Israel are also very active.

I.3. Private companies race for Quantum Computing Supremacy



Extracted from

`https://www.bcg.com/fr-fr/publications/2018/next-decade-quantum-computing-how-play.aspx`.

I.3. Private companies race for Quantum Computing Supremacy

With more than 60 separate investments totaling more than **$700 million since 2012**, quantum computing has come to the attention of venture investors, even if is still dwarfed by more mature and market-ready technologies such as

- blockchain (1,500 deals, $12 billion, not including cryptocurrencies)
- AI (9,800 deals, $110 billion).

I.3. Private companies race for Quantum Computing Supremacy

For instance, several private quantum computing companies have risen important funds in recent years (total risen amount)

- D-Wave (since 2012), $205 millions;
- Rigetti, $119 millions;
- PsiQ, $65 millions;
- Silicon Quantum Computing, $50 millions;
- 1QBit, $35 millions;
- IonQ, $22 millions;
- Quantum Circuits, $18 millions.

I.3. Private companies race for Quantum Computing Supremacy

STARTUPS

Quantum Shop Rigetti Computing Has Raised Over $71M In New Funding, Per SEC Filing

Jason D. Rowley March 2, 2020

Extracted from https://news.crunchbase.com/news/quantum-shop-rigetti-computing-has-raised-over-71m-in-new-funding-per-sec-filing.

I.3. Private companies race for Quantum Computing Supremacy

The money has been accompanied by a flurry of patents and publishing.

- North America and East Asia are clearly in the lead; these are also the regions with the most active commercial technology activity.
- Europe is a distant third (a number of leading European quantum experts joining US-based companies in recent years).
- Australia, a hotspot for quantum technologies for many years, is striking given its much smaller population.

I.3. Private companies race for Quantum Computing Supremacy

EXHIBIT 3 | Funding for Startups Has Increased in Recent Years

Startup	Total [US$ millions]	Most recent funding	
D-Wave Systems	205	June 1, 2018	US$10.15 million of grant funding in a deal led by the Canadian Government
Rigetti Computing	119	March 28, 2017	Announced further US$40 million in its series B round of funding
PsiQ	65	Undisclosed	Undisclosed
Silicon Quantum Computing	60	August 2017	AU$83 million venture funded by: New South Wales Government (AU$9 million), University of New South Wales (AU$25 million), Commonwealth Bank of Australia (AU$14 million), Telstra (AU$10 million over two years), and the Australian Government (AU$25 million over five years)
Cambridge Quantum Computing	50	August 26, 2015	US$50 million of development capital
1QBit	35	November 28, 2017	CA$45 million of development capital in Series B funding
IonQ	22	February 24, 2017	US$20 million of Series B venture funding
Quantum Circuits	18	November 13, 2017	US$18 million of Series A venture funding
Alpine Quantum Computing	12	February 8, 2018	€10 million of grant funding
QC Ware	8	July 5, 2018	US$7 million of Series A venture funding
Optalysys	8	September 21, 2017	£3 million of seed funding from undisclosed investors
Nextremer	5	August 8, 2017	JP¥500 million of venture funding
Oxford Quantum Circuits	3	September 8, 2017	£2 million of venture funding

Sources: Crunchbase; Pitchbook; BCG analysis.

Quantum computers: industrial applications and actual players

1. Development of a commercial computer: a technological challenge!
   - Which technology is appropriated?
   - Open questions for the development of a commercial quantum computer
   - Growth of quantum technologies fundings
   - Scientific publishing
2. Applications of quantum computers
3. Quantum gold rush

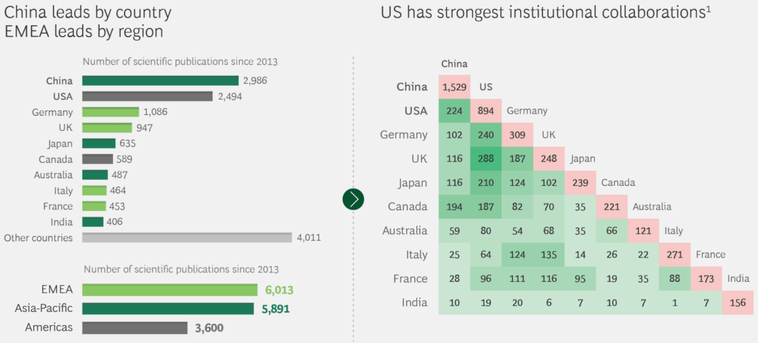
I.4. Scientific publishing

Two things are noteworthy about the volume of scientific publishing regarding quantum computing since 2013

- the rise of China, which has surpassed the US to become the leader in quantity of scientific articles published;
- the high degree of international collaboration (in which the US remains the primary hub).

The cooperation shows that quantum computing is not dominated by national security interests yet, owing in large part to consensus around the view that cryptographic applications are still further in the future and that effective remedies for such applications are in the making.

EXHIBIT 5 | China Leads in Publications on Quantum Computing, But the US Is More Integrated Internationally



Sources: Web of Science; BCG Center for Innovation Analytics.
Note: Analysis based on approximately 10,000 scientific publications related to quantum computing submitted from 2013 to mid-2018; EMEA=Europe, Middle East, Africa
[1]Where two or more universities from the same country were affiliated with the same publication, they were counted as one internal collaboration.

Extracted from

https://www.bcg.com/fr-fr/publications/2018/next-decade-quantum-computing-how-play.aspx.

Quantum computers: industrial applications and actual players

1. Development of a commercial computer: a technological challenge!

2. Applications of quantum computers
   - Boosting big data and AI
   - Quantum computers and chemistry: killer apps?
   - Quantum computing is a marathon not a sprint

3. Quantum gold rush

II.1. Boosting big data and AI

Supercomputer calculation power relies on the ability to process huge batches of data simultaneously and exchanging data between them quickly. Thus they are not based on a very powerful processor but rather on a architecture of many processors running in parallel. But there is still a number of problems that bring these supercomputers to their limits.

Quantum computers fully exploits quantum parallelism: they can prepare quantum registers in a way that explores a lot of inputs at the same time – all within a single processor, no need for many copies.

II.1. Boosting big data and AI

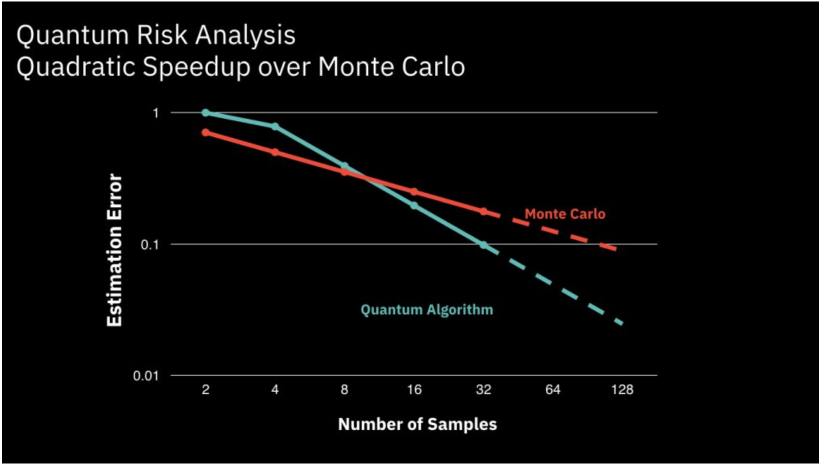
Several problems have been demonstrated to be adapted to quantum computers

- signals processing;
- unsorted databases search;
- molecular simulations;
- salesman problem,...

But many of these algorithms are what drives the services we get from big data and artificial intelligence.

The business model proposed relies on a cloud accessible service. A good example is GPS navigation for cars. The optimum trajectory relies on artificial intelligence learning what traffic patterns predict – learning from these big data can be made faster by the parallel computing of a quantum computers (to retrieve the fastest way for example).

II.1. Boosting big data and AI



Quantum Risk Analysis.

`https://www.nature.com/articles/s41534-019-0130-6`

II.1. Boosting big data and AI

Quantum computational finance: Monte Carlo pricing of financial derivatives

Patrick Rebentrost,[1,*] Brajesh Gupt,[1,†] and Thomas R. Bromley[1,‡]
[1] *Xanadu, 372 Richmond St W, Toronto, M5V 2L7, Canada*
(Dated: August 23, 2018)

This work presents a quantum algorithm for the Monte Carlo pricing of financial derivatives. We show how the relevant probability distributions can be prepared in quantum superposition, the payoff functions can be implemented via quantum circuits, and the price of financial derivatives can be extracted via quantum measurements. We show how the amplitude estimation algorithm can be applied to achieve a quadratic quantum speedup in the number of steps required to obtain an estimate for the price with high confidence. This work provides a starting point for further research at the interface of quantum computing and finance.

`https://arxiv.org/abs/1805.00109`

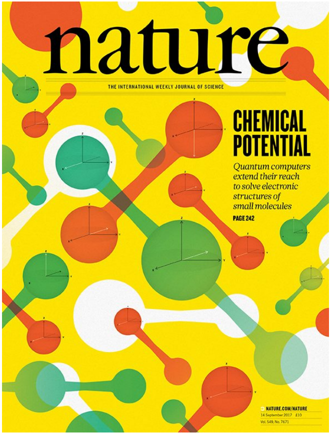
Quantum computers: industrial applications and actual players

II.2. Impact on the materials and pharmaceutical industries

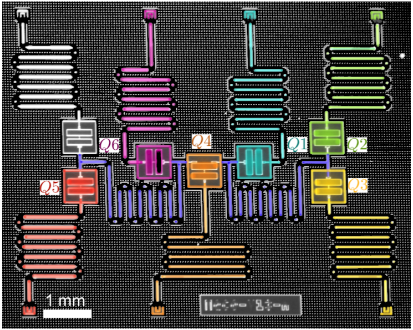
Computational chemistry aims at simulating molecules and chemical reactions. But chemical bond, which is the key element of molecule stability, conformation and configuration, is inherently of quantum nature.

To simulate it completely, one needs to store the complete quantum state in a computer memory, which often leads to memory problems. This memory issue is inextricable when molecule size is getting important (pharmaceutical components, proteins,...).

But a quantum computer is well suited to simulate quantum systems, especially molecules. And since the quantum state is stored in a quantum qubits, memory is no longer a limitation in such systems. This has been performed on small molecules with the first generation of quantum computers. One of the most anticipated uses for quantum computers is as a tool for developing new drugs, catalysts, and materials.

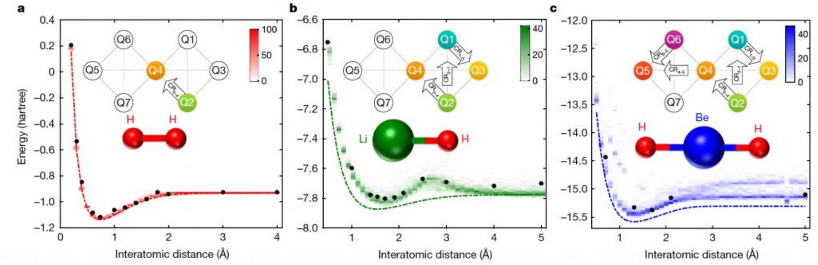


Hardware-efficient Variational Quantum Eigensolver for Small Molecules and Quantum Magnets. doi:10.1038/nature23879



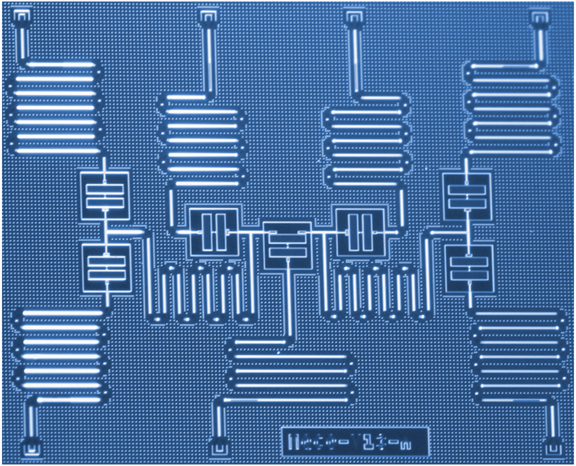
Photography of the chip used in IBM's quantum computer used for BeH_2 quantum chemistry simulation.

In 2017, IBM has demonstrated the calculation of the ground state of small molecules, up to three atoms with the molecule BeH_2 simulated. Those simulations have been realized with a 6 qubits quantum computer (variational quantum eigen-solver), also computing potential energy surface and demonstrating the possibility for magnetic properties prediction.



Hardware-efficient Variational Quantum Eigensolver for Small Molecules and Quantum Magnets. doi:10.1038/nature23879

II.2. First realizations



Hardware-efficient Variational Quantum Eigensolver for Small Molecules and Quantum Magnets. `doi:10.1038/nature23879`

II.2. First realizations

- *Chemical and engineering news* journal has published an article entitled *Chemistry is quantum computing's killer app*.
- Computational chemistry methods such as density functional theory (DFT) work well for many problems (in organic chemistry in particular).
- DFT is less efficient when applied to inorganic systems, which are nevertheless of importance in term of applications.

Indeed, computational chemistry requires approximations regarding the electronic structure, in order to simplify calculation so they might be handle by a classical computer. But it neglects important details of the electronic structure, which affects properties predictions.

II.2. First realizations

The more electrons there are in a system, the harder it is to describe on a classical computer with DFT.

the strategy to simplify calculation consists in neglecting the behavior of some electrons. Today's computational chemistry modeling algorithms can provide usually good enough, but inexact, predictions.

For example, metal are poorly described with such algorithms. On the contrary, the advantage of a quantum computer simulation is that no approximation would be introduced; so the exact solution would be provided and consequently reliable prediction on molecule or material properties.

"*If you have 125 orbitals and you want to store all possible configurations, then you need more memory in your classical computer than there are atoms in the universe*," says Matthias Troyer (Microsoft Research, Zurich), but a quantum computer could model such a system with just 250 qubits!

Quantum computers could help in explaining the electronic structure of molecules but also **their reactivity**: it would be possible to compute all the possible transitional structures that a molecule could present during each phase of a chemical reaction and the associated energy. Once all these informations are obtained, it is possible to predict exactly what could happen, *i.e.* the reactivity of the molecules and the products obtained after chemical reaction.

II.2. Expectations

Researchers at Microsoft and ETH Zurich have decided in 2014 to explore that possibility without waiting for a real quantum computer with enough qubits to exists: they decided to simulate classically the quantum simulation of a quantum computer!

Several industrial players have the same strategy (Total, Atos,...).

It consists in developing appropriate quantum algorithms with classical supercomputers in order to test, to optimise then and explore their possibilities prior to the existence of a quantum computer with enough qubits to implement it. It also permits to evaluate the effect of noise and decoherence on the quantum calculation, and to estimate which qubits performances are required (error rate, number of qubits, topology of the chip.

II.2. Expectations

In term of innovation strategy, it is a way of exploring the potentiality of the technology and its impact on the market for companies.

It is also a method to established a specification chart of what is required for a given application in target and consequently guide potential investments in hardware.

Companies want to know how many qubits with which error rate the quantum computer would need for their applications and whether it would truly solve a real, important problem in a reasonable amount of time.

In 2017, Google released an open-source software package called OpenFermion to help scientists translate existing quantum chemistry software into algorithms compatible with quantum hardware.

Several start-up companies have emerged (like Zapata Computing), oriented toward the development of software for chemistry applications on quantum computers.

OpenFermion

OpenFermion is an open source library for compiling and analyzing quantum algorithms to simulate fermionic systems, including quantum chemistry. Among other functionalities, this version features data structures and tools for obtaining and manipulating representations of fermionic and qubit Hamiltonians. For more information, see our release paper.

build passing | docs passing | pypi package 0.10.0

python 2.7, 3.4, 3.5, 3.6

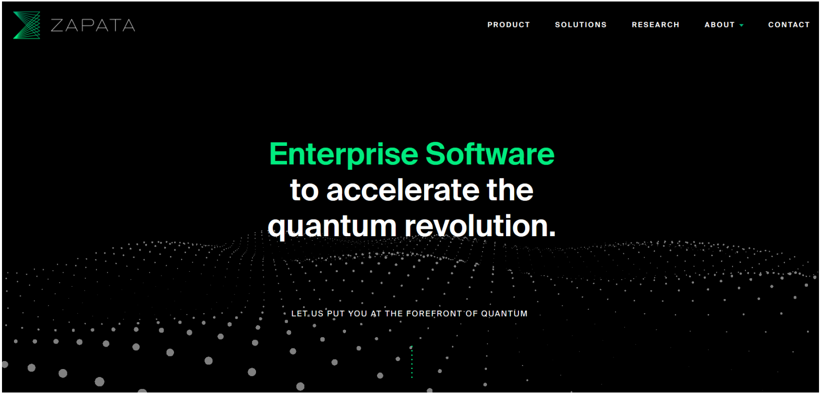
Run the interactive Jupyter Notebooks on MyBinder:

launch binder

OpenFermion. https://github.com/quantumlib/OpenFermion

https://arxiv.org/abs/1710.07629

II.2. Expectations



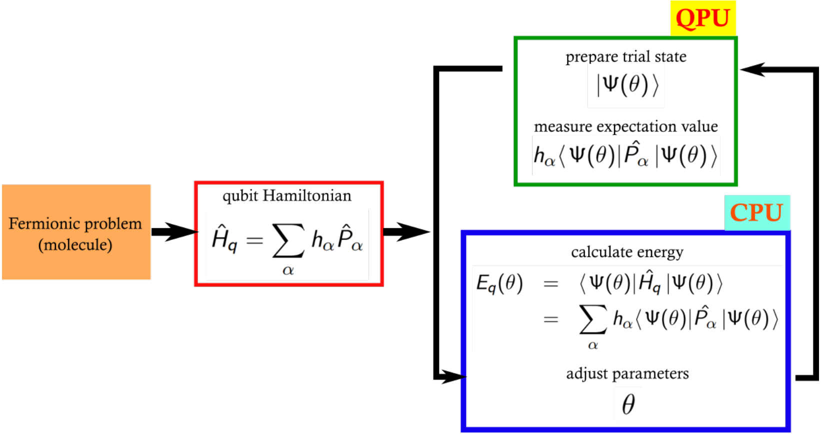
Zapata. https://www.zapatacomputing.com/

II.2. Expectations

Quantastica: software tools and quantum simulations.

`https://quantastica.com/`

II.2. Top targets for industrial applications



II.2. Top targets for industrial applications

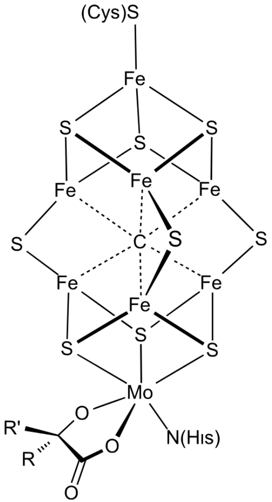
Number of (qu)bits required to represent energy states of molecules.

Molecule	Formula	Bits needed	Qubits needed
Water	H_20	10^4	14
Ethanol	C_2H_6O	10^{12}	42
Caffeine	$C_8H_{10}N_4O_2$	10^{48}	160
Sucrose	$C_{12}H_{22}O_{11}$	10^{82}	274
Penicillin	$C_{16}H_{18}N_2NaO_4S$	10^{86}	286

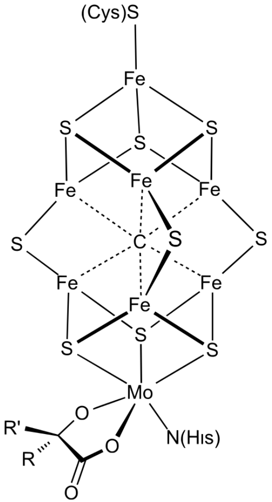
Nitrogenase:

Nitrogenase is an enzyme which is used by bacteria to make ammonia from atmospheric nitrogen in ambient conditions. The mechanism by which nitrogenase performs that conversion is still unknown. Industrial actors would like to understand how nitrogenase performs this reaction in order to design industrial processes for synthesizing nitrogen-based fertilizers with less energy consumption.

The current process used to produce nitrogen-based fertilizers from atmosphere nitrogen is the Haber-Bosch process, realized at high pressures and high temperatures. It consumes then a lot of energy and produces an important quantity of greenhouse gases. As a result, the carbon footprint of a loaf of bread - from growing and harvesting the wheat to the baking - is about 590 g.
Nitrogen-based fertilizer for wheat growth represent 40% of the total emission of CO_2.



At nitrogenase's heart is on iron-molybdenum cofactor called FeMoco. Traditional supercomputers can't model the nitrogen fixation on FeMoco. Quantum computers are expected to provide information on that mechanism. In 2017, researchers from ETH Zurich have demonstrated that quantum computers with 100 qubits working perfectly could solve the FeMoco mechanism within days or months.



The calculation is based on phase estimation algorithm, parallelised over 100 quantum computers in their estimation. The required space and time resources for simulating FeMoco using the 54-orbital basis and nesting are comparable to that of Shor's factoring algorithm for 4,096-bit numbers.

II.2. Top targets for industrial applications

Iron sulfide clusters (Fe-S) simulations in Molybdenum nitrogenase (Total).

4 Fe - 4 S

$$4 \times 26 + 4 \times 16 = 168 \text{ electrons.}$$

10^{50} permutations
192 qubits

Photosystem II:

It is an enzymatic complex that has an important role in the firsts steps of photosynthesis, the mechanism occurring in vegetable such that absorbed light permits to oxidize water and harvest electrons (cellular breathing). Water oxidation occurs at a location of the macromolecule called *the manganese center*.

Quantum computers should help to model the behavior of this manganese center during the photosynthesis process. A better understand of the reactivity of Photosystem II could enable chemists to design catalysts for artificial photosynthesis as a path toward renewable process for hydrogen or hydrocarbon fuel production.

<u>High-T_c supraconductors:</u>
These material are not yet understood dispite their discovery decades ago. Quantum computers could help in understanding the microscopic process at the origin of supraconductivity in such materials.

II.2. Top targets for industrial applications

Solar-cell materials:
A current challenge in these materials consists in understanding the charge carriers dynamics from their photogeneration to their capture by electrodes as free-carriers for generation of electrical current.

Better understanding of this dynamics would permit to predict and design new solar-cell materials with better performances or additional properties such as low cost or flexibility.

Quantum computers are good candidates for simulation of carriers dynamics in solar-cells materials.

II.2. Computers for drugs discovery

A 2018 report by the Boston Consulting Group suggested that a massive $20-billion quantum pharmaceutical industry could emerge by 2030.

Pharmaceutical drugs are typically small molecules of 50 to 80 atoms. But to be effective, drugs must interact with biological molecules such as proteins, which can contain thousands of atoms, far beyond what any quantum computer will be able to handle in the near future.

Nowadays, such molecules are simulated with molecular dynamics and DFT methods. The number of atoms involved is high and the gap is important for quantum computers to be competitive.

Lower number of atoms were considered previously, focusing on a given active center of a large molecule, which is not the case of a drug activity on proteins. But the potential market is so huge that it remains of interest.

II.2. Hybrid approach

The noisy quantum processors of the near future need not tackle an entire protein to have an impact. A classical method like DFT might be used to treat most of the system and then treat just the most quantum part of it, the calculation might be delegated to a quantum computer.

It is an **hybrid approach**: a classical computer is combined to a quantum computer and only particular tasks are treated by the quantum computer where quantum algorithms offers performances benefits compared to classical ones.

IBM proposes a cloud access to its quantum computers, accessible with an API or a python script, particularly well adapted to such hybrid architecture. In the case of drug activity calculation on a protein, the quantum calculation would concerns the electrons involved in forming or breaking a bond between the protein and ligand. Other electrons dynamics could be calculated classically.

II.2. Software and quantum algorithm optimisation

Quantum computers are still far from performances required for useful applications. But another side of quantum computing has been developed recently and rapidly: quantum software development. Software optimization of the quantum algorithm could help to deal with noisy quantum computers.

Microsoft researchers, for example, used algorithm improvements to reduce by a factor of ten million the number of quantum logic operations needed to exactly solve FeMoco.

Such software may help to reduce the number of quantum gates used for a calculation. And the lower the number of gates are, the higher will be the tolerance on the error rate of each gate.

Moreover, this software step is necessary to implement a given algorithm on a chip with a given topology of qubits which is a properties of the hardware. This step is called "transpilation" in the case of IBM Q experience's quantum computers.

Besides topology, the implementation of the quantum algorithm (compilation) is also optimized, taking into account the calibration of qubits (measured error rates) on the hardware used.

Quantum computers: industrial applications and actual players

II.3. Quantum computing is a marathon not a sprint

Christopher Monroe is Professor of Physics at the University of Maryland and co-founder and CEO of IonQ, a quantum computing startup. In a recent article on-line on `venturebeat.com`, he warned

that quantum computing is a marathon not a sprint, and too much hype risks disillusionment that may slow the progress.

He predicted that 5 to 10 years of additional research and development will be needed before quantum computers start solving useful problems.

Quantum computers: industrial applications and actual players

III.1. "The quantum computing era is here"

In Forbes, Matt Hunter has listed several applications of quantum computing

- hyper-accurate long term weather forecasting;
- drugs discovery through deep study of the behavior of complex molecules;
- new synthetic carbon capturing materials;
- stable, long lasting batteries.

III.1. "The quantum computing era is here"

Matt Hunter: *"One analyst predicted* **quantum will be as world altering in the 2020s as the smartphone was in the decade just ended"**

E. Gibney has analyze the development of start-ups and spin-off in quantum technologies.
"Robert Schoelkopf spent more than 15 years studying the building blocks of quantum computers, until, in 2015, he decided it was time to start constructing one (Quantum Circuits Inc.)*. Within 2 years, the team had secured* **US $ 18 million from venture capitalists**".

III.1. "The quantum computing era is here"

"Hundreds of firms are rushing to invest in the field, by names such as IBM, Google, Alibaba, Hewlett-Packard, Tencent, Baidu and Huawei all doing their own research. From the perspective of investors, the cash pumped into the field annually represents a small outlay so far - on a par with VC (venture capital) investments in artificial intelligence (AI) firms before 2010, for instance."

III.1. "The quantum computing era is here"

Computing isn't the only quantum technology attracting funds. For example, the swiss startup Qnami in Basel has reveived $130,000 in 2018 to develop a quantum magnetic microscope using NV centers. The hottest quantum technologies field is quantum communication and quantum cryptography.

There are solid reasons to think that quantum technologies will create game changing advances. "*It is a question of the timeline, rather than if that will happen*" says Celia Merzbacher, Director of the Quantum Economic Development Consortium Associate.

Quantum computers: industrial applications and actual players

III.2. End-to-end providers

End-to-end providers are mainly big tech companies and well-funded startups.

IBM has been the pioneer in quantum computing and continues at the forefront of the field.

More recently: Google and Alibaba have drawn a lot of attention. Microsoft is active but has get to unveil achievements toward actual hardware. Honeywell has just emerged as a new player. Rigetti is the most advanced among the startups.

III.2. End-to-end providers

Each company offers its own cloud-based open-source software and varying levels of access to hardware, simulators, and partnerships.

In 2016, IBM launched Q Experience, arguably still the most extensive platform to date.

It has been followed in 2018 by Rigetti's Forest, Google's Cirq and Alibaba's Aliyun, which has launched a quantum cloud computing service in cooperation with the Chinese Academy of Sciences. Microsoft provides access to a quantum simulator on Azure using its Quantum Development kit. Finally, D-wave Systems, the first company ever to sell quantum computers, its own real-time cloud access to its quantum annealer hard-ware, in October 2018.

III.2. Hardware and Systems Players

Other entities are focused on developing hardware only (since this is the core bottleneck today).

Again, these include both technology giants (such as Intel) but also startups (IonQ, Quantum Circuits, QuTech).

Quantum Circuits is a spinoff from Yale university (R. Schoelkopf). It intends to build a robust quantum computer based on a unique modular architecture.

III.2. Software and Services Players

Another group of companies work on potential applications: translating real world problems into the quantum world. It consists in algorithmic and software development.

Actual players are Zapata Computing, QC ware, QxBranch, Cambridge Quantum Computing,... which provide software and services to users.

Such companies see themselves as an important interface between emerging users of quantum computing and the hardware stack. All are partners of one or more of the end-to-end or hardware players within their mini-ecosystems.

III.2. Specialists

Theses are mainly startups, often spinoffs from research institutions, that provide focused solutions to other quantum computing players or to enterprise users.

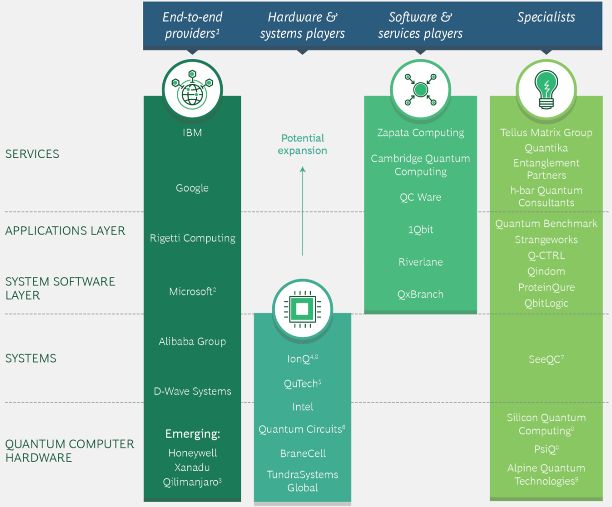
For example

- Q-CTRL works on solutions to provide better systems control and gate operation.
- Quantum Benchmark asses and predicts errors of hardware and specific algorithms.

Both serve hardware companies and users.

III.2. Tech companies

EXHIBIT 1 | Companies Assume Four Roles Across Layers of the Stack in the Quantum Computing Ecosystem



Sources: Quantum Computing Report (quantumcomputingreport.com); BCG analysis.
[1] Based on player's ambition with varying levels of maturity and service activities.
[2] Multiple technologies in the labs with focus on topological qubits.

III.2. Tech companies

EXHIBIT 2 | Multiple Potential Use Cases for Quantum Computing Exist Across Sectors

INDUSTRIES	SELECTION OF USE-CASES	ENTERPRISES (EXAMPLES)
High-tech	• Machine learning and artificial intelligence, such as neural networks • Search • Bidding strategies for advertisements • Cybersecurity • Online and product marketing • Software verification and validation	IBM, Telstra, Alibaba, Baidu, Google, Samsung, Microsoft
Industrial goods	• Logistics: scheduling, planning, product distribution, routing • Automotive: traffic simulation, e-charging station and parking search, autonomous driving • Semiconductors: manufacturing, such as chip layout optimization • Aerospace: R&D and manufacturing, such as fault-analysis, stronger polymers for airplanes • Material science: effective catalytic converters for cars, battery cell research, more-efficient materials for solar cells, and property engineering uses such as OLEDS	Airbus, BMW, NASA, Volkswagen, Northrop Grumman, Lockheed Martin, Daimler, Honeywell, Raytheon, Bosch
Chemistry and Pharma	• Catalyst and enzyme design, such as nitrogenase • Pharmaceuticals R&D, such as faster drug discovery • Bioinformatics, such as genomics • Patient diagnostics for health care, such as improved diagnostic capability for MRI	BASF, JSR, Biogen, DuPont, Dow Chemical, Amgen
Finance	• Trading strategies • Portfolio optimization • Asset pricing • Risk analysis • Fraud detection • Market simulation	J.P. Morgan, Barclays, Commonwealth Bank, Goldman Sachs
Energy	• Network design • Energy distribution • Oil well optimization	Dubai Electricity & Water Authority, BP

Quantum computers: industrial applications and actual players

III.3. Simplifying the quantum algorithm zoo

The US National Institute for Standards and Technology (NIST) maintains a webpage entitled Quantum Algorithm Zoo that contains descriptions of more than 60 types of quantum algorithms.

Two of their attributes are especially important in the near term:

- **Speed-Up** How much faster can a quantum computer running the algorithm solve a particular class of problem than the best-known classical computing counterpart?
- **Robustness** How resilient is the algorithm to the random "noise," or other errors, in quantum computing?

III.3. Simplifying the quantum algorithm zoo

There are two classes of algorithm today, named *purebreds* and *workhorses* by BCG in their analysis.

- purebreds are built for speed in noiseless or error-corrected environments.
- workhorses are very sturdy algorithms, but they have a somewhat uncertain speed-up over classical algorithms.

III.3. Simplifying the quantum algorithm zoo

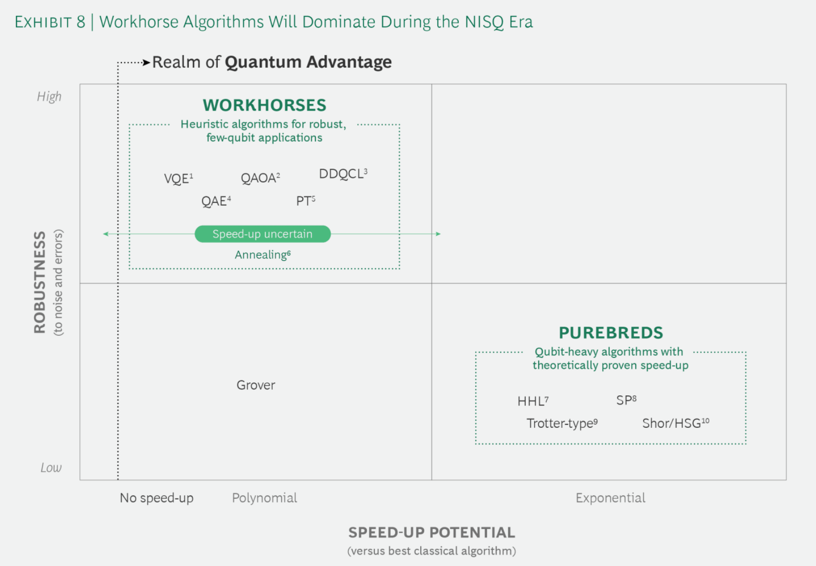
Purebreds have theoretically proven exponential speed-up over conventional computers for specific problems, but require a long sequence of flawless execution, which in turn necessitate very low noise operations and error correction.

Workhorses are designed to be robust in the face of noise and errors. They might have built-in error mitigation, and the number of gate operations is kept low. Most of them are then integrated with classical algorithms. The workhorses should be able to run on anticipated machines in the 100 qubits range. But very little can be proven about their speed-up performance with respect to classical algorithms until they are put to experimental testing.

III.3. Simplifying the quantum algorithm zoo

But remember that deep learning, which today dominates the fast-growing field of AI, was also once a purely experimental success. Indeed, almost nothing had been proven theoretically about the performance of deep neural networks by 2012 when they started to win every AI and ML competition. The real experiments in quantum computing of the coming years will be truly interesting.

Quantum computing companies are currently betting on the workhorses, which are likely to be the useful algorithms during the error-prone NISQ period of the next decade.



Sources: BCG analysis; expert interviews.
[1]Variational quantum eigensolver.

Quantum computers: industrial applications and actual players

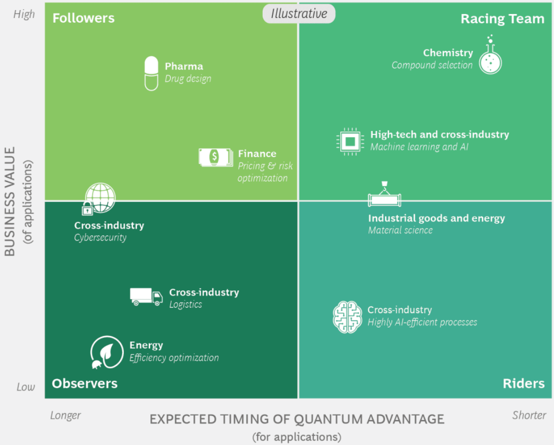
Industries and potential applications can be clustered on the basis of two factors:

- the expected timing of quantum advantage;
- the value of this advantage to business.

BCG's has grouped them into four categories of engagement: racing team members, riders, followers, and observers.

- **Racing team members** They are at the forefront of immediate business benefits. Their expected time frame to quantum advantage is shortest and the potential business benefit is high. It consists mainly of companies experimenting with quantum chemistry, followed by AI, ML, or both.
- **Riders** they will profit from similar developments, but for less critical value drivers, and are therefore less likely to fund core investments.
- **Followers** They see high potential in the quantum computing technology but are aware of the long development time frames to quantum advantage. For observers, both a clear path to benefits and the development time are still unclear.
- **Observers** Observers are looking at his technology but both a clear path to benefits and the development time are still unclear.

EXHIBIT 9 | The Determinants of a Quantum Play for Business



HOW TO PLAY

Racing Team
Build superior QC network
Launch new offerings

Riders
Engage with QC ecosystem
Lead own effort

Followers
Participate in QC networks
Gain experience

Observers
Monitor QC ecosystem
Analyze business potential

Sources: BCG analysis.

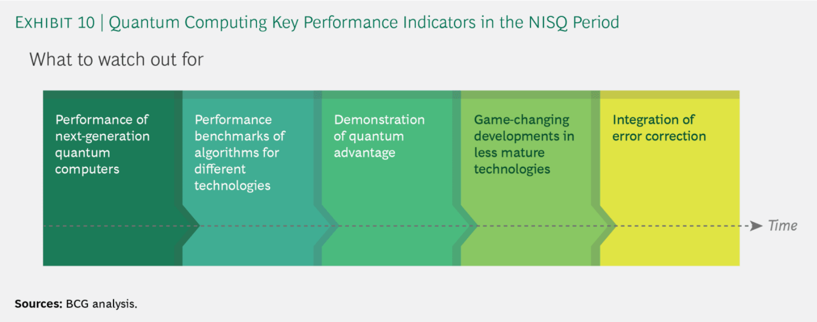
III.4. Within next five years

A few companies with a significant interest in the technology (Northrop Grumman, Lockheed Martin, or Honeywell), already own or are building their own quantum computing systems.

Several partnerships are emerging between quantum computing players and other industries

- JP Morgan, Barclays, and Samsung are working with IBM;
- Volkswagen Group and Daimler are working with Google;
- Airbus, Goldman Sachs, and BMW prefer to work with software and services intermediaries;
- Commonwealth Bank and Telstra have co-invested in Sydney's Silicon Quantum Computing startup (spinoff of University of New South Wales);
- Intel and Microsoft have set up strong collaborations with QuTech;
- OTI Lumionics (startup specialized in customized OLEDs) has started integrating quantum algorithms to discover new materials, in collaboration with D-Wave, Rigetti, and others.

III.4. Within next five years



1 Development of a commercial computer: a technological challenge!

2 Applications of quantum computers

3 Quantum gold rush

- "The quantum computing era is here"
- Tech companies
- Simplifying the quantum algorithm zoo
- Within next five years
- A potential quantum winter

III.5. A potential quantum winter

Quantum computing has already been through cycles of excitement and disappointment.

While the NISQ period undoubtedly has demonstrated few surprises and breakthroughs, the pathway toward a fault-tolerant quantum computer may well turn out to be the key to unearthing the full potential of quantum computing applications.

Some experts thus warn of a potential "quantum winter", as a consequence of too much excitement which tends tend to overestimate the technology potential.

III.5. A potential quantum winter

As Christopher Monroe warned, **quantum computing is a marathon not a sprint**, and too much hype risks disillusionment that may slow the progress.