Cloud and infrastructure I Worldwide I 2019

Quantum computing state of the art

Part 2: Value chain and market players

SITSI I Market Analysis I InBrief Analysis

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PREFACE

"In less than ten years quantum computers will begin to outperform everyday computers, leading to breakthroughs in artificial intelligence, the discovery of new pharmaceuticals and beyond.

The very fast computing power given by quantum computers has the potential to disrupt traditional businesses and challenge our cyber-security. Businesses need to be ready for a quantum future because it's coming."

Jeremy O'Brian, Professorial Research Fellow in Physics and Electrical Engineering at the University of Bristol, and director of its Centre for Quantum Photonics in the UK

Objectives of this three-fold series of reports

Those reports have three main objectives, each one being assigned to a specific report:

- Part 1: explain quantum computing & describe the different quantum technologies
- Part 2: analyze the quantum computing value chain and position the different actors of quantum computing
- Part 3: evaluate quantum computing use cases and business models

Methodology and resources

To create this report, teknowlogy consulted senior IT decision-makers from a number of medium- and large-sized companies and from the public sector around the world, as well as key executives responsible for practices at large or specialist technology providers and key quantum computing researchers. teknowlogy has also used its standard market studies and surveys to enrich the analysis.

TABLE OF CONTENTS

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MANAGEMENT SUMMARY

After explaining quantum technologies in part one of this quantum series, this report will focus on the quantum value chain and how the different players in quantum computing are positioned along this value chain.

The quantum computing value chain is different from silicon-based computing as it is largely based on pure quantum physics engines. Quantum computing is an integrated high-end computing platform, which is quite closely related to High Performance Computing (HPC). The result is that the value chain is in fact composed of two connected value chains:

1. The core quantum value chain that integrates the quantum engine, its infrastructure and the quantum management platforms. This value chain is mostly composed of cutting-edge physics, materials and electronics systems, many of which are still not yet fully mastered. This is the critical part of quantum computing and where most investments are made. This value chain behaves very similarly to heavy hi-tech industry.
2. The non-core value chain, which is mostly based on IT technologies, to exploit, develop, distribute and use core quantum value chain capacities. This value chain behaves very similarly to a light industry such as the software industry.

Quantum computing players align themselves on those two value chains, with very few players being present on the two chains. The core value chain integrates many fundamental research laboratories, large hi-tech manufacturers, Internet giants and several start-ups. This chain includes many non-IT players around quantum physics and is largely based on the cooperation between state funded fundamental research, start-ups and large companies. The non-core chain players remain mostly IT players.

In the long term, the non-core value chain will be the most important in terms of revenues, but it cannot develop itself in the mid-term without the core value chain.

THE QUANTUM COMPUTING VALUE CHAIN

Characteristics

Quantum computing is like the hardware part of classical computing, very capital intensive, even if it is only the beginning of its industrialization. For the moment, the design and operations of the hardware part (in relation to software and services) are strongly predominant in the value chain. Let's compare "classical" and quantum computing on this point:

- In 2018, the hardware part of the "classical" computer market represents slightly more than 1/5 of the total computing market globally *(Source: SITSI Worldwide 2018, teknowlogy)*
- For quantum computing, this share is at least two-thirds for hardware - which will be referred to later as the value chain at the heart of quantum – with software representing the rest, and very little service.

Classical computing is strongly based on electronics, but quantum also requires expertise in strong physical engineering, with specificities depending on the type of technology, for example: superconductors, magnetics and cryogenics, photonics, lasers, microwaves, etc.

Therefore, the value chain of quantum computing involves not only electronics and programming specialists, and some mathematicians, but physicians and chemists as a large portion of the expertise in the physical and chemical sciences. This is critical as the quality of quantum computation depends essentially on this expertise.

The two different value chains of quantum computing

The value chain of quantum computing also includes traditional computing to analyze, complement and make quantum computing work. There are 2 distinct, but heavily coupled, value chains inside the global quantum computing value chain:

1. The "core value chain" of quantum computing, which remains very intensive in capital, is based on fundamental research with a long project lifecycle and is, therefore, very close to a traditional high-tech industry. It corresponds essentially to the hardware part of quantum computation. It consists of:
    - The quantum infrastructure: equipment and specific technology-related structures (cryogenics, vacuum generators, microwaves, photonics, etc.), energy, basic materials and consumables (nitrogen, helium 2 and 3, nanocarbon, diamonds, specific silicones, etc.)
    - The quantum hardware platform, where the calculation is made. It is basically a quantum engine, where quantum physics on the related architecture and technologies process quantum reactions that manage information.
    - This engine is backed by the quantum management platform (interconnections, metrology, computer control platform, etc.)
2. "The non-core chain" is much less capital-intensive, with a shorter project lifecycle, more agile and, therefore, much closer to the software and IT services market, or even strongly interconnected with the value chains of "classical" computing:

- Tools (development, test and simulation),
- Applications (algorithms and usages),
- Complementary systems (computers and networks),
- Services.

The core value chain

Quantum infrastructure	Quantum hardware platform	Quantum management platform
• Nanostructures • Hi-tech metallurgy • Support technologies: vacuum, cryogenics, photonics, microwaves, etc… • Consumables	• Qubits engine according to the type of architecture and the selected quantum technologies • Quantum doors management electronic platform	• Quantum computing management computer • Nanotechnologies • Quantum embedded software

The most critical points - the ones that are the hardest to design, manufacture and operate - mostly concern the first two stages of the quantum core value chain. The quantum infrastructure is very specific, requiring very good engineering capabilities, which are mastered by very few manufacturers. They are also made in small volumes and, therefore, expensive. The other key issues are:

- The purity of materials at the atomic level is essential as those systems need accuracy at the atomic level.
- The use of rare earth ionized materials, such as ytterbium or erbium, whose production is essentially Chinese.
- Quantum computers operating at very low temperatures require liquid nitrogen, helium 4 (easy-to-find liquid), but also helium 3 (a much rarer and more expensive liquid). This currently comes from two plants in the USA and Canada. Former heavy-water reactors, increasingly rare, could also be sources of helium 3.

Qubit management systems are the most experimental, the most important, the most expensive and the least mastered part of the quantum value chain.

Quantum gate management electronics, which must be non-intrusive and operate under extreme conditions, is also critical.

The non-core value chain

Tools	Applications	Additional systems	Services
• Quantum software design, test, development and deployment tools • Integration software • Databases	• Quantum mathematics and algorithms • Data analytics • Models and applied use cases	• Quantum simulation on HPC • Cloud Computing • Cyber Security • Communications	• Education and training • Professional Services • Outsourcing and Cloud

The support chain is based on cutting edge IT technologies, but those technologies are already on the market (like HPC Quantum simulators) even if there is still a lot of development to come. In the long run, this part of the value chain will become the biggest part of the value chain.

Impacts on other value chains

HPC / Supercomputers

In the medium term, quantum computers will complement supercomputers, much like graphics chips have completed traditional chips, opening up new perspectives. This is also why some of the leading high-performance computing vendors, such as IBM, Huawei, Fujitsu and Atos, have embarked on quantum computing.

Cloud

Parallel computing is one of the major advantages of the cloud system, which approaches the concepts underpinned by the quantum computation. The perspectives of quantum computing on the Cloud are, therefore, of interest to some internet giants such as Google, Amazon, Alibaba, Baidu or Microsoft. This is the case for centralized cloud computing, but quantum computing can still not scale down to the growing cloud edge computing.

Cyber security

Theoretically, quantum computing capabilities can decode the encryption keys used today. This is a potentially huge threat to our current economic system. Most companies involved in cyber security are keeping a close eye on the developments in quantum computing.

Communication

Another facet of quantum is quantum communication, which has very strong links with quantum computing, regarding both technologies (photonics, for example) and use cases (security, for example). Using the **same** physical proprieties, quantum communication is the network version of quantum computing and as such it is increasingly important in our modern cloud-based digital system.

What are the implications of the two quantum computing value chains?

Quantum computing starts with the core quantum value chain. This chain is mostly applied quantum physics - a quite new field. The business model of this part of the chain is more related to heavy hi-tech industries such as nuclear than to the classical information technology value chain. This implies:

- High capital entry barriers (not to mention the even higher R&D entry barriers).
- Strong academic and research involvement.
- New players in the IT from the nuclear or military industry, such as CEA in France or Raytheon in the US.
- A very mixed-expertise talent pool, with physicists and IT people.
- That the market will structure itself around major leading companies.
- Until it reaches maturity it will rely heavily on public research programs and venture capital.

The complete value chain (core and non-core value chains) will progressively get closer to the HPC value chain, with more and more value on the non-core value chain, but where the fundamental capacities of the hardware are still at the heart of the model.

QUANTUM COMPUTING PLAYERS

Typologies of actors

The different types of technology actors classified by business models are:

- IT giants such as IBM, Intel, Google or Atos
- Start-ups, most often from university laboratories, such as D-Wave, 1Qbit or Rigetti
- University research centers, such as CEA or the University of Waterloo in Canada.

There are also important related actors from the hi-tech manufacturing segment that are specialized in:

- Cryogenics, supra-conductors, vacuum, microwaves and photonics according the selected quantum technologies,
- Specialists in quantum physics systems,
- Specialists in extreme electronics.

The specific technological characteristics explain the positioning of the various actors. For example: Intel or IBM do not develop certain types of quantum computers because they do not have enough control of photonics. As we do not know yet which technology/technologies will prevail, we do not know which actors will pull out of the game.

We can also classify the actors by their involvement in the R&D process, divided into those who are fundamental in research and development and those who are catalysts for development, although these two segments of actors tend to mix:

Firstly, the players with their roots in fundamental research:

- The big manufacturers and IT and Internet leaders who also have powerful research centers, especially in the United States,
- Start-ups, indispensable elements of innovation, which are often entities from universities,
- Public research and academics, who collaborate with other actors and are crucial elements of fundamental research, which is so important in quantum computing. Country level investments in fundamental research are a very important jump starter for quantum computing.

Fundamental research in quantum computing and clusters are essential in the creation of start-ups and in the involvement of industry. This highlights the importance of public policies and investments.

However, the development catalysts are a critical part of quantum computing and should not be neglected, as they are one of the main reasons for Canada's in quantum computing:

- The users, who collaborate with research, finance not only experimental projects but also start-ups.
- Venture capital, which remains notoriously low in Europe compared to North America, with 73.5 MUSD already invested in Europe compared with 367 MUSD in North America.

The ecosystem of quantum computing will continue to grow strongly due to the low maturity of the concept with two value chains that are rich in technologies, but without any technology predominating. Nevertheless, many actors will disappear.

The positioning of the players in the quantum computing value chain

Quantum players are quite different, and ecosystems evolve according to the two quantum value chains. The two constituent value chains of quantum computing are based on two different hi-tech business models:

- The core of the quantum value chain (the equipment part), which is heavy industry and very capital intensive. This chain will focus around a few major manufacturers. This chain also includes manufacturers of electronic engineering, cryogenics and advanced mechanics.
- The non-core chain of quantum is similar to that of computing (light industry and services) and should evolve in a similar manner.

Some large actors cover the whole chain of quantum computation, and these are the biggest manufacturers in the digital sector.

We can classify the actors according to these two chains.

The quantum computing core value chain players

Being a heavy industry, the barriers to entry in this market are high, even higher given the technological level required, and almost impossible to overcome without public education and academic ties for fundamental research.

Dozens of major players are present throughout the value chain, but most of the players have specialized in some areas. No player can achieve quantum computing on his own. Start-ups are numerous but may be limited by their size in this very capital-intensive quantum core chain. However, because of their links to basic research, they are essential to the development of the value chain.

Here are some of the most interesting private players:

Support platform	Hardware platform	System management platform

The quantum computing non-core value chain players

Barriers to entry to this value chain are lower than for the core quantum computing value chain in terms of investments, time and research, which will allow many more players to take a position in the future, as quantum computing validates its use cases. Nevertheless, the non-core value chain needs the core value chain (and its players) to develop.

Here too, only a handful of manufacturers are present in all segments, but in the mid-term many companies will join and emerge from this part of the quantum computing ecosystem.

Here are some of the most interesting private players:

Tools	Applications	Complementary and related systems	Services

Other ways of positioning quantum computing players

By type of quantum computing

It seems that from the point of view of investment and the support of large companies, the vast majority of actors bet on the universal calculators that promise quantum supremacy or at least a large performance gap when compared with traditional computing.

D-Wave took a substantial lead with its adiabatic approach and other companies that are building calculators prefer to bet on universal calculators, which is more promising than trying to catch up with D-Wave. The Hamiltonian calculators do not seem to have taken off because few major investments are visible, and it seems that their delta of performance between Hamiltonian calculators, the adiabatic calculators and the universal quantum computers are not consequential enough. Nevertheless, the Japanese have quite a strong position in these technologies. However, the competition remains strong and undecided between the various technologies used to operate universal calculators.

The most important private players by type of quantum computing are:

Hamiltonian	Adiabatic	Universal
NEC, Northrop Grumman	D-Wave The Quantum Computing Company	IBM, intel, NTT, Google, rigetti, IONQ

By type of quantum computing technologies

Here are the main private players classified according to the main quantum technologies they are working on.

Supra-conductors	Diamonds cavities	Linear optics	Topological	CMOS silicium	Trapped ions
IBM, NEC, intel, Google, QuTech, rigetti, qci, UCSB, cea, Oxford Quantum, Raytheon, Northrop Grumman	QDTI, cea, Universität Stuttgart, TU Delft, Fraunhofer, Thales	Xanadu, hp, University of Oxford, Tundra Systems Global Ltd, PsiQuantum, Sapienza, University of Bristol, universität wien	Microsoft, QuTech, Nokia, TU Delft **Quantum recruit** D-Wave The Quantum Computing Company, University of Waterloo	intel, cea, Yale University, NTT, Nokia	IONQ, MIT, University of Maryland, Sandia National Laboratories, Harvard University, JG|U, IQI, IQST, universität innsbruck, Honeywell, Atos

Main trends

The fundamentals of quantum, and its low level of maturity mean that public research and university actors are very present.

The specificities of quantum computing and its level of maturity push the different types of actors to work collaboratively if they want to succeed, hence the importance of clusters / competitive clusters: Waterloo, Oxford, Innsbruck, Grenoble, etc. This involves all actors and demonstrates the importance of public policies to develop a quantum industry, which brings together public and academic research, start-ups, industry and venture capital.

Compared to "classical" computing, the evolution of quantum computing actors will be different depending on their positioning in the two quantum value chains:

- Core quantum value chain: an ecosystem that will focus around heavy industry, although there will always be young shoots. This is a riskier chain for financial investors.
- Non-core quantum chain: an ecosystem that will become increasingly important, more abundant with many new entrants as the market matures, with more and more young shoots but also industrialists.

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