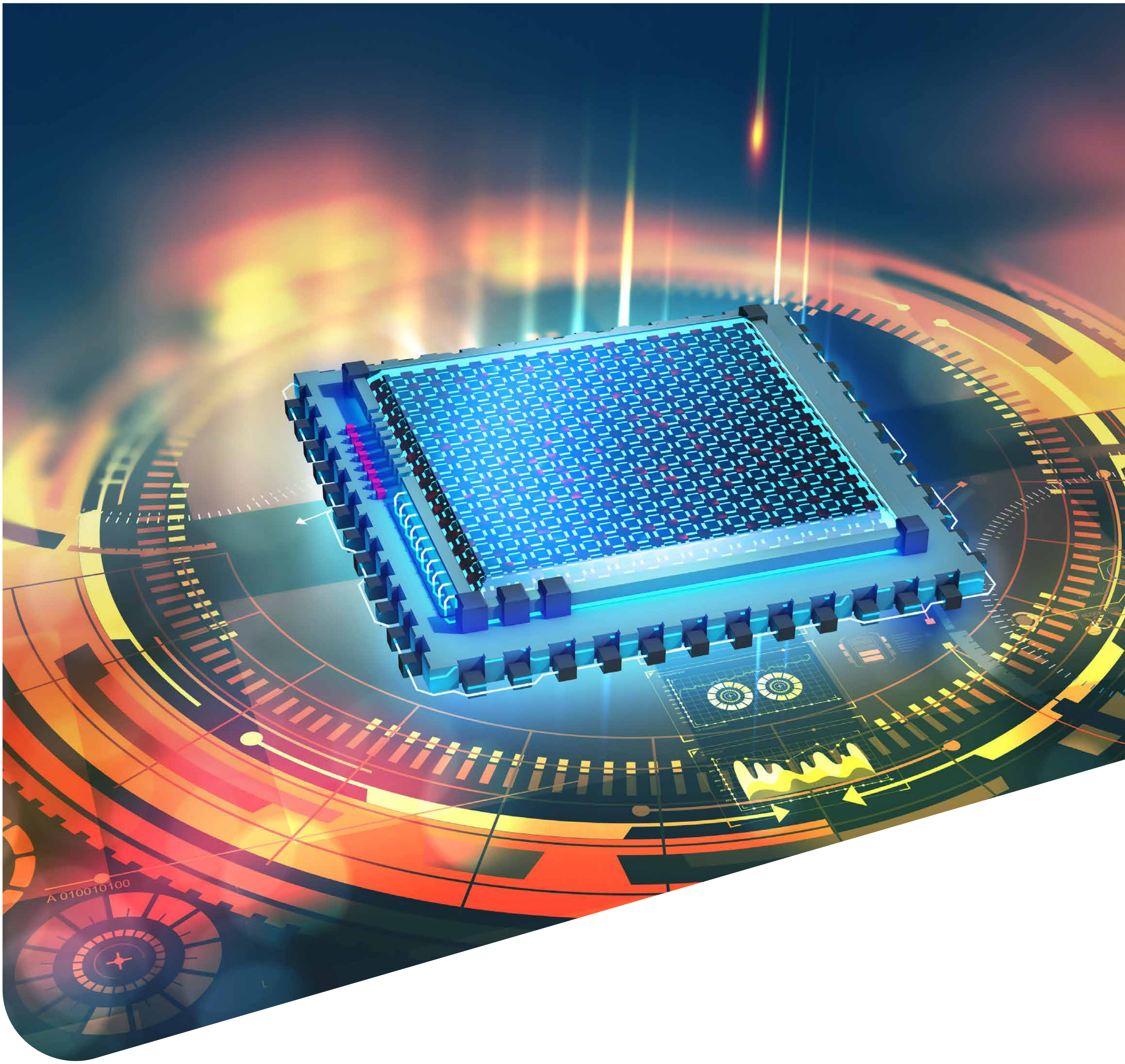

White Paper

QUANTUM COMPUTING

Technology with limitless possibilities looking for tough problems to solve!

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ADVANCING DISCOVERY

Quantum computing

Technology with limitless possibilities looking for tough problems to solve!

At the turn of the 20th century German physicist Max Planck proposed that a 'perfect black body' emitted and absorbed electromagnetic waves as discrete bundles of energy referred to as 'quanta'. This was the birth of quantum mechanics that gave scientists unprecedented, and unique mathematical tools to understand our world on the atomic scale. Now, in the 21st century, the concept of quantum-mechanical states forms the basis of 'quantum computers' – a term coined by Richard Feynman in the early 1980s during his call for producing quantum mechanical computer systems [1]. Scientists agree that quantum computers are potentially exponentially faster and much cleverer in cracking codes deemed impossible for classical technology to accomplish.

The potential impact of quantum computing is highlighted by yearly increases in scientific publications in journals [Table 1 and Figs. 1 and 2], books [Table 2], in-depth review and articles news [2–5], and the launch of peer-reviewed journals such as NPJ *Quantum Information* [6].

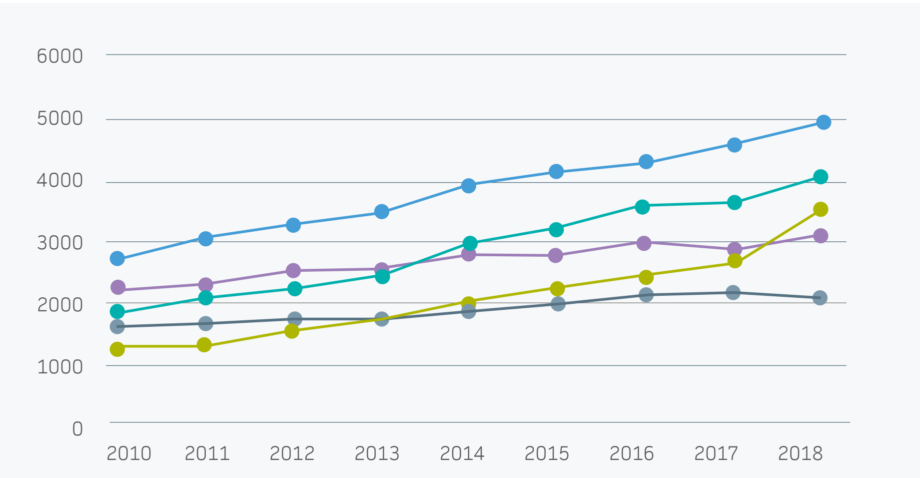

Figure 1.
Number of publications in peer reviewed publications from 2010 to 2018 in the categories shown. Criteria: text - "quantum computer" in full data
Source: https://sn-insights.dimensions.ai/

- Physical Chemistry (incl. Structural)
- Other Physical Sciences
- Materials Engineering
- Atomic, Molecular, Nuclear, Particle, and Plasma Physics
- Artificial Intellicence and Image Processing

Top 10 Journal/Books series

Name	Publications
Physical Review B	14,586
Physical Review D	11,386
Physical Review A	11,286
Lecture Notes in Computer Science (Book Series)	8,686
Journal of High Energy Physics	8,235
Physical Review Letters	6,111
Nuclear Physics B	4,176
Physical Chemistry Chemical Physics	3,527
Journal of Physics A: Mathematical and Theoretical	3,159
Chemical Physics Letters	2,918

Table 1.
Publications in peer reviewed international journals on quantum computing from 2010 to 2018

The two main properties of quantum computers that distinguish them from classical computation are first, in quantum computing computation values ‘quantum bits’ or ‘qubits’ exist as the superposition of 0’s and 1’s. This can be imagined as 0 and 1 corresponding to the horizontal and vertical directions of a physical quantity, such as the polarization of light, and in conventional computers bits are only oriented along the horizontal or vertical axes, whereas qubits can exist at any angle between these two directions. The second property is quantum entanglement. The bits of classical computers can only be manipulated independently of each other. In other words, a change in the state of one bit does not affect other bits. Quantum bits, however, can exist in so called entangled states where manipulation of one bit simultaneously affects the other bit(s). Strictly speaking, in an entangled state, it is not meaningful to talk about the state of one bit separately and any manipulation or quantum transformation of the system results in a new entangled state of the system. However, the notion of state of a bit is sometimes used in literature as a pedagogical aid. Quantum entanglement is a property unique to quantum systems and has no classical analogue.

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Scientists have exploited these two properties for the development of quantum algorithms, that is, series of quantum transformations – mathematically, unitary transformations on the quantum state – to perform computations that are potentially exponentially faster than classical systems. So, the ability of quantum computers to perform accurate and fast simulations of biological and chemical systems as well as to solve complex combinatorial optimization problems are expected to have a major industrial impact in applications including pharmaceuticals, finance, aerospace, big data and machine learning, and telecommunications.

Trends in quantum computing worldwide

USA

In the 1980s interest in quantum systems for computing focused on security and sharing information, including the BB84 quantum key distribution protocol. But the breakthrough in quantum computation came in 1994 when Peter Shor, then at Bell Laboratories, showed that quantum computers could be used to break encrypted information [7].

Since then, rapid and major advances in the theoretical aspects of quantum computing have led industries to experiment with implementing systems. Notably, IBM has led the way, recently announcing the world’s first commercial ‘universal approximate superconducting quantum computer’, the IBM Q System One, a 20-qbit quantum computer, where the hardware is based on superconducting devices [8].

Honeywell is leveraging its well-established expertise in science and engineering and has developed ‘trapped-ion quantum computers’ [9]. There are also startups including D-Wave that specializes in ‘quantum annealing’ to solve complex optimization problems much faster than classical computers [10]; and ‘the quantum-first cloud platform’ developed by Rigetti, that is a fusion of classical and quantum computing [11].

The US government has recently launched a $1.3 billion federal initiative to develop quantum computers [12] and NASA is collaborating with D-Wave on quantum computers for managing future missions [13].

Europe and Asia

The European Union (EU) launched 19 exploratory projects as part of a 10-year, €1 billion quantum computing flagship program with participation by industry and academia [14].

In **Japan,** information technology giants Fujitsu, NEC and NTT are developing their own 'quantum inspired' computers and the Japanese government funded 20 "Q-LEAP" projects starting Fall 2018 including a collaboration between RIKEN, NEC, Toshiba and NTT with the aim of launching a quantum computer-based cloud service in five years [15]. Notably, Fujitsu is focused on digital annealing for commercial use but is completely classical and solves the same types of problems as D-Wave [16].

In **China,** industry and the government are investing in quantum computing. Industrial giants like Alibaba [17] and Baidu [18] are already developing quantum computers and the government is planning the $10 billion National Laboratory for Quantum Information Sciences in Hefei, Anhui Province [19].

India has recently launched an 11-million-dollar Quantum-Enabled Science & Technology (QuEST) program with involvement of academia and its space agency, ISRO, to develop prototypes of quantum computing devices in the next three years [20].

Challenges and issues to resolve

There are three broad categories of challenges to realize the true potential of quantum computing. First, and perhaps most fundamental is the quest for the 'killer application' to demonstrate the advantages of quantum computers over conventional technology. As a result, there is intense interest in the development of quantum algorithms with emphasis on identifying problems where quantum computers conclusively outperform classical ones.

First, and perhaps most fundamental is the quest for the 'killer application' to demonstrate the advantages of quantum computers over conventional technology.

Another, perhaps more difficult challenge is design and engineering of devices and hardware. Specifically, thermal and vibrational noise disturbs the quantum entangled state of qubits and leads to erroneous computation. The term Noisy Intermediate Scale Quantum (NISQ) refers to the state of the art generation of quantum processors being used now. Ensuring high fidelity of qubit operations, especially with many qubits, is one of the most critical engineering challenges for the proliferation of quantum computers. Recently, Honeywell reported stabilizing qubits based on ion traps with a fidelity of 99.997% [21].

Finally, nurturing professionals to work with quantum computers is also a challenge. IBM, D-Wave, and Rigetti offer software libraries enabling users to learn how to program quantum computers without in-depth knowledge of the underlying quantum physics. In academia, MIT has launched a quantum computing course for helping professionals understand the benefits and challenges of quantum computing. In Japan, the IBM Q Network Hub @ Keio University – launched in May 2018 at the Yagami Campus in Yokohama – is the only Asian hub with access to the IBM Q quantum computer; Keio University now offers courses in programming and related topics [https://research-highlights.keio.ac.jp/2018/07/b.html].

Applications and future directions

The logistics industry would benefit if quantum computers could solve the ‘travelling salesman problem’ (TSP) to optimize routes to deliver packages on a global scale. The main problem is that as the number of destinations increases, so does the possible number of routes. Currently, TSP is analyzed using approximate methods that have no theoretical certainty of yielding optimal solutions. In contrast, quantum computing algorithms are expected to offer exponential increases in speed and efficiency for this application [22].

Materials science and specifically, materials informatics is also expected to benefit from quantum computing, in this case for the design of new materials with tailored structural and chemical properties. Another area is predicting local weather, where for example, the UK’s Met Office is looking at the combinatorial optimization provided by D-Wave systems for more accurate weather forecasting [23].

In the long term, one of the most important roles of quantum computing is accelerating the industrial applications of artificial intelligence (AI). Implementation of Internet of Things (IoT) is leading to an ever-increasingly connected world that is generating unprecedented amounts of data that AI systems must analyze to “learn” and pick up pertinent trends and correlations. In this context, ‘quantum machine learning’ has the potential to analyze vast amounts of data that currently overpowers classical computers. Quantum machine learning [24] could fundamentally transform a wide range of industries including financial trading, digital marketing, and quantum cryptography equipment. Notably, the financial sector is taking a keen interest in quantum computing to provide new products for their customers. To this end, major banks in Japan have joined the IBM Q network at Keio University. As NISQ devices mature and qubits increase, industries reliant on combinatorial optimization problems will benefit from quantum computation. Examples include chemicals, pharmaceuticals, and materials design industries.

In the long term, one of the most important roles of quantum computing is accelerating the industrial applications of artificial intelligence (AI).

Looking beyond the next decade, quantum gate computers are expected to be integrated with classic computers to form so-called quantum accelerators-computers designed to solve a specific set of problems, such as AI engines found in smartphones today that perform pre-defined tasks such as facial recognition in real time.

Ultimately, the fusion of quantum computers, machine learning, and AI will lead to a new era of applications for quantum mechanics that Max Planck could not have envisaged in the 1900s. The ‘quantum computational supremacy’ of quantum computing will be determined by whether these computers can solve problems that are beyond the power of conventional computers. We are at a stage where quantum computing is a technology with limitless possibilities that is looking for tough problems to solve!

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What the experts say

Senior manager at one of Japan's leading computer companies:

The killer applications of quantum computing will be

- *Decryption*
- *Quantum computing annealing application are for calculations in quantum chemistry and materials informatics*
- *Quantum computing in general for combinatorial optimization problems for logistics, finance, chemistry*

Hurdles and challenges

- *Quantum gate computers: The biggest challenge is expanding the scale. Even the size of NISQ is still very small and insufficient for practical applications*
- *Quantum annealing computer: The biggest challenge is expanding the scale. Next comes the number of bonds between qbits.*

Quantum computers are considered to be candidates for replacing or for solving problems that cannot be handled by conventional computers. However, from the industrial perspective, this is not practical yet. In terms of current applications, you should perhaps think about hybrid of a conventional computer and a quantum computer.

Franco Nori, Chief Scientist, Theoretical Quantum Physics Laboratory, RIKEN, Saitama, Japan:

Full scale quantum computing is not likely to have important applications either this or next year. This is a promising area of research, but it will take considerable time. Patience is important to explore challenging new frontiers. Moreover, precise predictions about the future are often inaccurate.

But there are already successful examples of quantum technologies to control quantum coherent effects, in natural and more so in artificial atoms, including quantum sensors using nitrogen vacancy centers in diamond for magnetometry. Quantum detectors and quantum sensors are an important but often overlooked spin off of research on quantum computing.

Also, quantum simulations of micrometer-scale artificial atoms are currently being conducted and will grow in the future.

Finally, the number of qubits is growing annually. But this popular fixation on this number is misleading because the quality of the qubits is improving at a much slower pace. Thus, significant patience is needed to develop the technology for these new and challenging frontiers. Too much hype on any new development does not help any new endeavor. Thus, less hype and more patience will eventually pay off.

Future application

"I think the main applications will be

- *Monte-Carlo calculations for example for financial derivatives*
- *Chemical dynamics*
- *Machine learning, for example for, classification*

But I am not sure which is the most useful application; I think nobody knows. Regarding future challenges, I think hardware is really important. The devices used currently cannot deal with the above applications at any practical level."

Naoaki Yamamoto, Chair of the Keio Quantum Computing Center, Kanagawa, Japan

What kinds of applications will quantum computing be most useful for?

"At this moment, I would say quantum chemistry computations."

What issues/hurdles must be over-come to realize these applications?

"Integrating and packaging the qubits and related classical control circuits."

Jaw-Shen Tsai, Professor, Tokyo University of Science and Senior Scien-tist at the Center for Emergent Matter Science, RIKEN, Saitama, Japan

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