Roadmap on AI technologies & applications for the Media Industry

Section: "Quantum Computing"

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info@ai4media.eu www.ai4media.eu

Author	**Artur Garcia** (Barcelona Supercomputing Center)

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Quantum computing

Current status

With Moore's Law failing and anticipated to flatten by 2025[1], three different evolution paths have been predicted for post-exascale systems. One path considers the development of ever more specialised architectures and advanced packaging technologies that arrange existing building blocks in new ways (next 10 years after exascale); another path considers the development of CMOS-based devices that extend into the third, or vertical, dimension and on improving materials and transistors that will enhance performance by creating more efficient underlying logic devices (next 20 years); the third axis represents opportunities to develop new models of computation, such as neuro-inspired or quantum computing, which solve problems that are not well addressed by digital computing. Exploiting the microscopic properties of matter, as described by quantum mechanics, opens the door for a completely novel formulation of information processing tasks. ***Quantum computation***[2] emerges as a revolutionary technology, with the expectation to have deep impact on fundamental and applied aspects of computation, ranging from exponential speedups of complex computations, to a reduced cost and power consumption compared to major supercomputers.

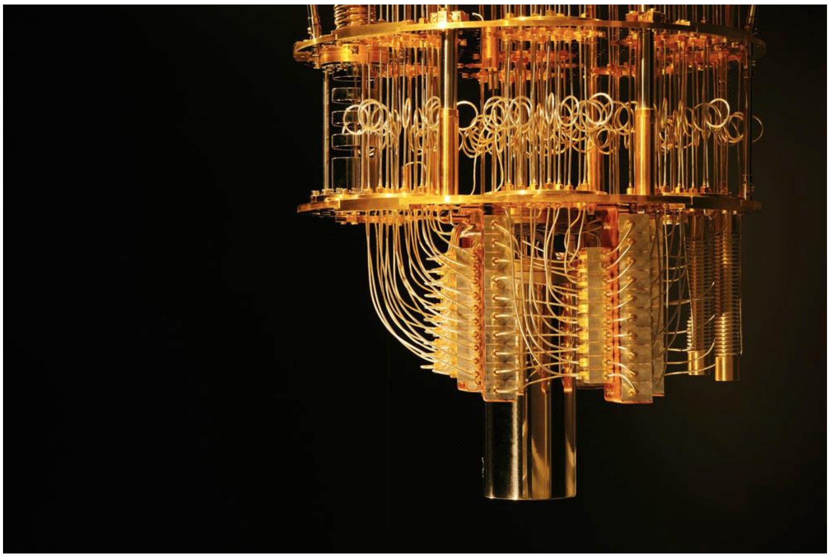

Figure 1: Quantum computer[3].

Since quantum computers are neither cheap nor easy to build, classical simulation is a valuable method for efficient simulation of quantum algorithms. For example, quantum devices are affected by noise which currently is a significant limitation to enhance their capabilities. Classical simulation tools are a must to understand noise sources and improve the performance of

[1] J. Shalf. "The future of computing beyond Moore's law." Philosophical Transactions of the Royal Society A 378, no. 2166 (2020): 20190061.
[2] M. Nielsen and I. Chuang, Quantum Computation and Quantum Information, Cambridge University Press (2000)
[3] Image source: IBM Newsroom - https://newsroom.ibm.com/media-center?keywords=quantum#gallery_gallery_0:21747

quantum algorithms. These tools overcome the fundamental limitation of measurement of quantum states, offering a deep insight into how a quantum computer works. Furthermore, classical quantum circuit simulation gives in-depth information about how future quantum machines will behave, reducing the cost to build and maintain them. Thus, improving classical simulation tools will help to better understand and to optimise quantum devices. Also, these simulations play a crucial role in the development of novel quantum algorithms.

However, these advantages come at a significant cost. The simulation of a quantum circuit is exponentially expensive with its size, thus requiring the power of **High-Performance Computing** (HPC) technologies even for small instances[4]. For example, one work[5] reports the usage of 196 TBytes (the whole available nodes' memory) for a 42 qubits circuit simulation while another[6] reports HPC simulations of 49-qubit hard random quantum circuits (RQC) on 4,600 out of 4,608 nodes of the Summit supercomputer, the second largest supercomputer in the world according to the Top500 list of June 2021[7]. Hard instances emerge as a combination of properties of the quantum circuit, more importantly its width (*N*, number of qubits) and depth (*D*), its simulation complexity depends on its product *N*x*D* and also on the resulting connections between qubits. While easy instances can be solved with current approaches, hard instances do not fit in current HPC systems making the simulation unfeasible. The use of HPC technologies is a crucial element in the design of new quantum devices, which will take a huge importance in the next few years to improve their quality.

Research challenges

Recent efforts to establish the computational power of quantum computers relate their capabilities to classical computers using computational complexity, where one classifies a given problem based on the efficiency with which we are able to solve it. There exist quantum algorithms for classical problems that are much better than any known classical algorithm[8,9], even if they are too complex for the current quantum devices. Recently, proposed Noisy Intermediate-Scale Quantum (NISQ) devices have approached the breaking point of quantum advantage[10,11], where they perform simulations that cannot be done efficiently on a classical computer. In general, finding the problems that offer such an advantage on quantum computers and why is at the core of theoretical research in the field. These quantum devices have been implemented using different quantum technologies, and quantum advantage has been shown for superconducting circuits and photonic devices.

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[4] Y. Zhou, M. Stoudenmire, and X. Waintal. "What limits the simulation of quantum computers?." Physical Review X 10, no. 4 (2020): 041038
[5] G.G. Guerreschi, J. Hogaboam, F. Baruffa, and N. Sawaya. "Intel Quantum Simulator: A cloud-ready high-performance simulator of quantum circuits." Quantum Science and Technology 5, no. 3 (2020): 034007
[6] Villalonga et al. "Establishing the quantum supremacy frontier with a 281 pflop/s simulation." Quantum Science and Technology 5, no. 3 (2020): 034003
[7] TOP500 The list (2021): https://www.top500.org/lists/top500/2021/06/
[8] L. Grover. "A fast quantum mechanical algorithm for database search". In:STOC '96.1996.
[9] P. Shor. "Polynomial-Time Algorithms for Prime Factorization and Discrete Logarithms on a Quantum Computer". In:SIAM Journal on Computing 26.5 (Oct. 1997), pp. 1484–1509. issn: 1095-7111.doi:10.1137/
[10] Han-Sen Zhong et al. "Quantum computational advantage using photons". Science 370.6523(2020), pp. 1460–1463
[11] F. Arute et al. "Quantum supremacy using a programmable superconducting processor." Nature 574, no. 7779 (2019): 505-510

Simulation of quantum circuits has been recently leveraged to support the claims of supremacy of quantum computations over their classical counterparts. Afterwards, these claims have been revisited, showing the need of a general effort to establish the full potential of HPC systems to simulate quantum circuits. The use of tensor networks for quantum computing simulation is relatively new, however already identified as the leading approach. Igor L. Markov and Yaoyun Shi first acknowledged the power of tensor networks for quantum computing simulation and the tensor contraction the more common and complex operation[12]. While there are implementations of software simulation of quantum circuits using tensor networks, there is a general lack of methodologies to use HPC systems to simulate very large tensor networks.

A major research challenge is to define in a solid way the computing capabilities of quantum computers against current technologies in practical problems. These problems have to be selected to be of practical interest, yet needing a large computational power. Among these applications, one identifies machine learning related operations as those interesting to boost with advanced technologies such as quantum computing. However, finding a quantum algorithm suitable for these tasks is just a first step in a series of technological challenges. The final one, namely constructing an operational quantum computer in the lab, is a major challenge in our current manipulation of systems in the microscale.

Societal and media industry drivers

Vignette: Analysing gigantic image datasets with the help of quantum computing

Lisa is a researcher in a small AI startup analysing an enormous dataset of images for object recognition to build an AI model for a public service media organisation that wishes to exploit their vast audiovisual archives. Unfortunately, the available computing resources are running out of free space. However, a subroutine of her pipeline has been improved with a quantum version. This variant allows a large speedup assuming data can be loaded efficiently to a quantum device. Fortunately, Lisa has access to a cloud account for a nearby research institute where classical and quantum machines run together in hybrid systems. She uploads the data to the hybrid cloud device and runs the pipeline. The novel quantum algorithm performs very well and the boost is significant, despite the overhead loading and unloading the data to the quantum device. More tests will be required to assess the scope of this speedup in the following datasets, as these keep growing in size. Fortunately, due to low energy requirements and short duration of the quantum computations, the dataserver runs on green energy and is not raising prices since last year.

Future trends for the media sector

A major resource in data manipulation using AI is computational power. Dataset size is a major indicator of the complexity, but also the intrinsic hardness of a particular problem can be a major hurdle to reach a good solution. Reaching to alternative computing technologies is becoming a popular study for fields reaching a saturation of their available resources.

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[12] I.Markov and Y. Shi. “Simulating quantum computation by contracting tensor networks”, SIAM Journal on Computing, 38(3):963-981, 2008

For providing better solutions with quantum devices performing AI tasks, with processing capabilities for large datasets of text, images, and media in general, one needs to develop novel quantum algorithms, i.e. algorithms intended to run on a quantum device. These novel algorithms are hard to formulate, and the community has been only able to produce a few. However, with more implementations of real quantum computers, one expects an increasing interest of researchers for the possibilities of these novel formulations.

Among other interesting avenues of research, quantum formulation of classical algorithms allows an alternative approach to well-known numerical methods. However, this novel point of view has provided important insight, and even improvements, over these methods[13]. With these quantum inspired algorithms, with clear applications to data science, one may benefit from the power of the quantum formulation of an algorithm, without the need to execute them on a real quantum algorithm.

Following results of benchmarking classical and quantum computations for well-known problems, we can establish a direct comparison between these technologies from the perspective of the resources used. These include running time, memory, but also energy consumption and fabrication costs. The expected consumption of novel supercomputers exceeds by orders of magnitude those of quantum computers. This opens a new opportunity of cheap computing power in some specific tasks (e.g. NLP), which may be relevant even in conditions on which classical computers offer an advantage in computing power, but a large disadvantage in any other consumed resources.

Goals for next 10 or 20 years

The major goal of the field of quantum computation, and a necessary condition in order to provide real quantum solutions, is the production of functional quantum computers providing a large number of qubits. This requirement allows the execution of error correction over the quantum system which is plagued with experimental errors. With this quantum computer, one is then able to further develop, test and execute novel quantum algorithms.

Quantum computing development in the next years is expected to be a hot topic and we expect many novel advancements. IBM among others (such as Google, Rigetti or IonQ) is one of the main actors developing quantum hardware and their predictions for the next years include devices with 1000+ of Qubits starting at 2023 (Figure 2). Similar projections by other actors suggest the availability of 1M+ of Qubits in the mid-term. With these resources one expects to offer fully capable quantum computers.

[13] E. Tang, Quantum principal component analysis only achieves an exponential speedup because of its state preparation assumptions, Phys. Rev. Lett. 127, 060503 (2021)

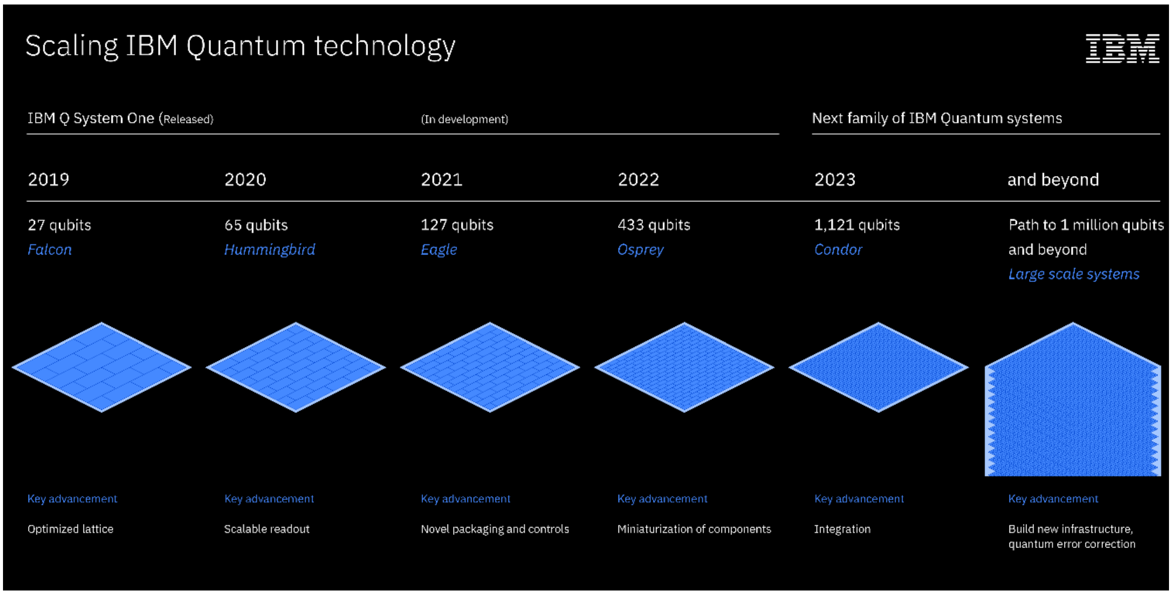

Figure 2: Infographic - IBM's Roadmap for Scaling Quantum Technology [14].

Having a working quantum algorithm is a starting point for major advances in computational applications. However, a careful benchmark of a new computational device has to be performed to assess its utility in different tasks. The field of benchmarks for quantum devices will have to provide answers to which tasks will benefit from the development of real quantum computers.

Finally, while we are still far from having full powered quantum computers in the lab, hybrid architectures can be built from the integration of classical and quantum technologies. The integration of a noisy quantum device with classical computers (even in HPC environments) may take advantage of a limited selection of quantum features under the robust setup of an established classical methodology.

[14] Image source: IBM Newsroom - https://newsroom.ibm.com/media-center?keywords=quantum#gallery_gallery_0:21737

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