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Hello Quantum! How Quantum Computing will Change the World.

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The world of information technology is buzzing around the possibilities that quantum computers might open up for organisations. But what are quantum computers and what could be their business potential, eventually?

Part of why quantum computers are steeped in mystery is because they rely on some very strange properties of the microcosm. From quantum interference to quantum entanglement, not to mention some of the underlying philosophical quantum implications like the possibilities for multiple universes and the foundations of quantum physics that revolve around peculiar mathematical formulations, quantum computers have been under development for decades, with IBM, D-Wave, and Google being amongst a handful of companies investing in this space.

But if you let all the esoteric constructs aside, a quantum computer is *just* a computer in that it processes data, and *quantum* in the sense that it relies on the principles of quantum physics. The latter does imply some special equipment and conditions, for example, cryogenics and super cool temperatures. The big difference when we compare it to classical computing, though, is that data is being processed fundamentally differently.

Classical computers rest on the theory of computation that has traditionally been close to physical processes. Classical computing (also referred to as Turing Computing) performs calculations using **binary bits** that travel through silicon chips, logical gates and so on. Because of their binary nature, each bit can be either be **0 or 1**. With two bits, four 'states' (read: combinations of zeros and ones) are possible (0-0, 0-1, 1-0, 1-1), eight with three bits (2^3), and so on. While computers have become smaller, faster, and cheaper, these basics have not changed since the first prototype binary computer was built by American physicist and inventor John Atanasoff in 1939.

Quantum computing is a concept first proposed in the 1980s by physicist Paul Benioff and further developed by physicists Richard Feynman and mathematician Yuri Manin. Instead of storing data as electrical signals, quantum computers can use a varied set of physical systems in order to store data, such as electrons and photons, which can be engineered to encode information in multiple states. To achieve this, quantum computing uses **quantum bits**, more commonly referred to as qubits. Unlike an ordinary bit, a qubit can be **both 0 and 1** in some linear combination of the two states (a phenomenon known as superposition). With quantum computing, this means that two qubits can be in the four states mentioned above (0-0, 0-1, 1-0, 1-1) but *at the same time.* This simultaneity is the key that unlocks the power of quantum computers and constitutes a rather radical difference (Rossi et al., 2019). The states that become possible in a quantum computer are represented by a 2^n expression. With three qubits, it's eight at the same time, and so forth. Google's Sycamore ran on 53 qubits (one failed as there were 54 on the chip) – yielding 2^{53} states simultaneously. This resembles more than 9 quadrillion states at once, or a 9 followed by 15 more digits. This notion of parallelism, physicists claim, allows a quantum computer to work on millions of computations at the same time, while a desktop pc, or even a powerful supercomputer, works on the principle of going through its computations one after the other.

The implications are hard to imagine, but the following example by Braga (2017) helps understand how this makes a fundamental difference to how data is processed. If we marked a page in a library book with an X, and asked a traditional computer to find it, it would scan each page of each book, one at a time, until it discovered the X. Across multiple libraries, this would of course take a very long time. Days, months, possibly much longer. Quantum computing, however, can scan all of the books, and all of the pages, at the same time, and find the X in seconds. However, this is not easy to achieve and subtle techniques are required even to achieve superposition, for example through lasers. And even when this superposition is actually achieved, it is difficult to maintain it as the qubits are in a really fragile state and require special treatment. The quantum activity, for instance, can only happen at extreme temperatures. The chip, although no larger than a usual chip, is housed and protected in a comparatively large, so-called supercool chamber that is physically kept at very close to 'absolute zero' (-273 Celsius) - the coldest sustained temperature achieved in the universe. Any slight disturbance means that the qubits lose their superposition and therefore their capacity to process data in this unique way.

With these conditions in mind, it is important that we stress that quantum computing changes the mode of computation completely. With quantum computing, “things” (e.g., algorithmic processes and the types of problems tackled) become radically different and therein lies the capacity of its immense computational power. It has already been showcased in 2019 that Google was able to achieve a phenomenon known as *quantum supremacy*; this is when quantum computers perform calculations that are beyond the reach of classical supercomputers. In this case, Google used a 54-qubit chip (the above mentioned Sycamore) to perform a calculation that would have taken a classical supercomputer 10,000 years to complete. It is precisely this incredible difference in the level of computation that has created the excitement about the future potential of quantum computers.

But beyond complex molecular simulations and mathematical calculations, what could be some of the real-world practical uses and business applications of quantum computing?

Quantum Problems and Solutions

There are multiple arenas where quantum computing will be employed, and we could not possibly envision or list all of them today. We can, however, speculate about a) various “problem types” quantum will approach differently, b) think about “humanitarian use-cases” - too wicked for traditional computing to solve - that quantum computers will be able to attack, and c) envision “organizational use-cases” that traditional computing has been unable to crack. We illustrate the advancements through their impact on the energy sector (companies in the business related to the production and supply of energy) in order to provide more tangible examples and to showcase how quantum computing will become useful. In Table 1, we outline further examples.

Quantum Optimization

While the meaning of “optimization” in IT discussions is rarely defined, there seems to be consensus on what it actually means. When authors talk about business process optimization or optimization algorithms (Hu et al., 2019) or about the optimization or redesign of existing services (Harmon et al., 2016), they all broadly refer to finding the “most appropriate ways of meeting the technological and informational needs of an organization, with the main objective of assisting it in the generation of value in a sustainable way" (Heflo, 2021).

While this perspective positions IT optimization as an organizational practice that extends beyond issues of a technological nature, technology itself remains the key enabler. Optimization algorithms, for instance, are used to deal with scientific and mathematical optimization problems (e.g., solving "satisfiability" problems in computer science, or finding the equilibrium (folded) configuration of proteins in biology; Young, 2016). Some problems are complicated, but clever algorithms, although throttled by hardware constraints, can solve them. Others, though, are so complex that traditional computers are not effective (or efficient) at optimizing and solving them, and where quantum will make a real difference. The library problem above, despite being largely unrealistic, is one such example. Yet, one can consider current computational approaches that are stretched to their limits and where quantum computing might help us push new frontiers. For example, researchers are pushing the agenda of computational prediction of clinical drug combinations against cancer. The aim is to "develop computational methods that can identify promising drug combinations before experimentally testing them" (Ling and Huang, 2020). But with so many drugs available, the permutations allow several thousands of combinations to be tested. This is a remarkable approach to a persistent health problem wherein quantum computers might one day give us a significant advantage.

In the *energy sector*, one utility optimization scenario is that of prevention and timely resolution of utility service outages. In a traditional computing setting this is currently held back by limitations to the ability to process data in a sufficiently quick and timely manner. Quantum computing contributes to solving the problem by providing a mode of computation that can turn outage management from a reactive exercise (detect and fix outages) to a more proactive exercise. It enhances the ability to prevent outages by processing information about the quality and state of the grid and key risk factors thereby aiding in making recommendations for how to maintain and service the grid. These key risk factors may range from external and impossible to control (such as weather, supply chain of key maintenance material) to maintenance issues (such as material exhaustion and age of utility poles). The result of this would include ensuring both a better customer experience (customer risk is reduced, as outages can be truly detrimental to core services such as some in-home medical devices), increased crew safety and assurance of revenue (since utility services can more reliably be provided to – and thereby billed - to the customer).

Quantum AI/ML

Artificial intelligence and machine learning have certainly come a long way in the recent past, but these advances will pale in comparison to quantum-enhanced machine learning. Quantum artificial intelligence (QAI) will improve computational tasks within artificial intelligence, including sub-fields like machine learning. While today's machine learning algorithms are used to compute immense quantities of data, these complicated processes take time (Schuld et al., 2015). Quantum machine learning will improve computational speed and data storage, and help tackle computationally difficult subroutines done by algorithms in a program. Such Quantum AI/ML approaches will be much more efficient than classical AI algorithms, for instance those used in computer vision, natural language, and robotics (Sgarbas, 2007).

The *energy sector* offers both humanitarian and organizational use-cases. There is potential to offer global air quality benefits by using AI and ML to effectively transition to renewable energy sources. Not only would this mean improved demand forecasting and asset management, but also improved understanding of the renewable energy sources. For example, forecasting what is available from renewable energy sources such as wind turbines and solar panels requires producing long-term weather predictions and knowledge of how that weather will interact with the installed equipment. Additionally, by conducting so called energy balancing an energy utility can quantify and account for how much and where energy is drawn by mapping (including rendering and re-rendering usage on energy infrastructure maps) and analyzing all known nodes in a dynamic utility network. By conducting this computing and analysis – and for example comparing it to expected (and billed for) energy consumption – different types of energy 'leakages' or 'black holes' can be identified. These 'holes' in a grid may have a wide range of root causes, such as undetected malfunctioning equipment or even as malicious as energy theft. By continuously learning what energy usage is expected on the grid, any suspicious (unidentified) energy draw can be closer investigated.

This aids in both improving safety, providing revenue assurance, optimizing the grid for inefficiencies, taking a sustainable approach to it and, by extension, making it possible to keep utility rates lower by lowering cost.

Quantum Simulation

Computer simulations rely on mathematical modelling to predict the behaviour of or the outcome of actual or potential real-world systems or scenarios (e.g., in climatology, biology, manufacturing, health care). Simulations can be used to explore and to estimate the performance of systems too complex for analytical solutions (Strogatz, 2007).

Importantly, quantum simulators are not the same as simulations with quantum computers. The former simulates a quantum effect and quantum dynamics, whereas the latter deploy quantum computers to solving a wider range of simulation problems. For instance, current computational chemistry methods rely heavily on approximation, since the exact equations cannot be solved by classical computers. Quantum computing, though, will be able to model and simulate molecules over longer timescales, which will hopefully lead to life-saving drug discoveries and faster development of pharmaceuticals (Gil et al., 2018).

In the *energy sector*, contributions can be made toward slowing climate change by reducing greenhouse gas emissions through facilitating the transition to electric vehicles. This transition requires not only understanding of the technology and infrastructure required to provide the energy, but simulations to aid in understanding local and distributed population density, travel patterns and dynamically account for an ever evolving technology of EVs (including how far you can drive on a charge) to appropriately plan for and install charging stations. Further, utility demand-side management entail planning, implementing, and monitoring activities meant to encourage consumers to modify the amount of energy they use and the pattern of usage (for example slightly shifting timing of private energy use, such as the 'TV pickup' – the significant energy draws that happen during television commercial breaks). Demand-side management can be greatly aided by running advanced simulations, analyzing and predicting outcomes of different scenarios where effective demand management can be conducted. By balancing out the demand over the day, and the days of the week, cost can be kept down since utilities do not have to buy peak demand power boosts from other jurisdictions (this holds true even if the total amount used stays the same over a comparable length of time, and only the timing of when it is used is shifted).

Table 1: Quantum Problems and Use-Cases

Problem Type	**Humanitarian Use-Case**	**Organizational Use-Case**
Optimization *Traditional computing:* Currently held back by data processing abilities. *Quantum computing:* Will solve problem by providing a mode of computing that allows for sufficiently fast processing.	Utilities: Resolve energy-poverty for 1.2 billion people in the world who have little or no access to electricity.	Utilities: Prevent and resolve utility service outages. Improve service reliability and increase customer and crew safety.
	Logistics: Reduce greenhouse gas emissions by improving traffic and vehicle routing.	Logistics: Enhance production and distribution supply chains.
	Life Sciences: Expand drug combinatory discoveries, speed up drug fabrication and supply (e.g., COVID).	Chemical: Improve refining process.
AI/ML *Traditional computing:* Currently held back by ability to learn from sufficiently large and varied, often unstructured data set(s). *Quantum computing:* Will solve problems by providing the ability to run AI/ML computing and providing the increased processing power required to solve complex, multi-facetted issues.	Utilities: Improve air quality by transitioning to renewable energy sources.	Utilities: Solve energy loss issues, assure revenue, safety, and utility rate consistency.
	Health: Predict and prevent famine	Financial Services: Detect money laundering and (cyber-enabled) fraud.
	Life Science: Advance cancer research, develop personalised medicine through full genome sequencing and drug-combinatorial pursuit.	Pharmaceutics: Enhance clinical trials.
Simulation *Traditional computing:* Currently held back by the inability to run many complex, simultaneous simulations to land on (dynamic) recommendations within a reasonable time.	Utilities: Contribute toward slowing climate change through facilitating the transition to electric vehicles.	Utilities: Simulate energy demand to reduce the load on the system and minimize the need for expensive peak usage.
	Life Science: improve drug discovery and accelerate safety and efficacy verification	Manufacturing: Advance materials discovery, improve manufacturing processes

Quantum computing: Will solve problem by overcoming both the complexity and the time challenge associated with traditional computing.	Simulate and improve disaster readiness, recovery and management (e.g., earthquake, flooding, pollution).	Financial Services: Improve derivatives pricing

Conclusion

Quantum computing is seen as a silver bullet for many humanitarian and organization problems, particularly those require significant advancements in IT optimization, AI/ML and simulation. Despite significant quantum improvements in recent years, though, quantum computing is still in its infancy. Among other needed improvements are qubits themselves, which need to be much more reliable for wider applications.

However, recent advancements suggest that the future is bright for quantum computers. Google's recent proof-of-concept of quantum supremacy solved a mathematic equation in just under 3.5 seconds. Supercomputers, Google claimed, could not complete in under 10,000 years. Hartmut Neven, founder and manager of the Quantum Artificial Intelligence lab, a joint initiative of NASA, Universities Space Research Association, and Google, likens Google's breakthrough to a Sputnik moment, and Google CEO Sundar Pichai compared it to the first airplane flight of the Wright brothers in 1903. The plan did not fly far or for a long time, but the fact that it went airborne was proof that flying a plane was really possible. The realization of air-travel, much like the widespread use of quantum computing will be years before it can fulfill its potential.

In anticipation, many of the use-cases envisioned today are perhaps "low-hanging fruit"; however, not in the usual metaphoric sense that they are obvious and easy to solve. On the contrary, they are among the most obvious, hardest, and most important problems that today's supercomputers just cannot solve. They are the ones we should pick first.

That having been said, the quantum race is a dangerous one, as not all use-cases will contribute positively to solving big problems. As with all emerging technologies (Baccarella et al., 2018, 2020), there is a dark side to quantum computing, too. In the wrong hands, some warn, the sheer power of quantum can cause equally big problems as it can solve, for instance brute force attacks that will break any code and defeat the encryption keys that protect our data. Some even fear that quantum power could render communications and e-commerce as insecure as if they weren't encoded at all (Denning, 2019).

As one would expect, achieving all this requires multi-million-dollar investments that only a few promising companies have been able to attract. Expecting any significant desktop-based leap for a commercially available quantum computer at a reasonable price is a scenario for an unknown number of years. But, as Roy Amara, the late American researcher, scientist, and futurist reminds us, people tend to overestimate the effect of a technology in the short run and underestimate the effect in the long run. It is with this perspective in mind that we should all be excited about a quantum future in which the quality of life for people around the world will be dramatically improved – eventually.

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References:

Baccarella, C. V., Wagner, T. F., Kietzmann, J. H., & McCarthy, I. P. (2020). “Averting the rise of the dark side of social media: The role of sensitization and regulation.” European Marketing Journal 38(1), 3-6.

Baccarella, C. V., Wagner, T. F., Kietzmann, J. H., & McCarthy, I. P. (2018). Social media? It's serious! Understanding the dark side of social media. *European Management Journal*, *36*(4), 431-438.

Braga, M. (2017) “New Canadian quantum computer called twice as powerful as last one, but what does that mean?” Canadian Broadcasting Centre, https://www.cbc.ca/news/technology/dwave-new-quantum-computer-twice-as-fast-so-what-1.3949886, January 25, last visited January 31, 2021.

Denning, D.E. (2019) “Is Quantum Computing a Cybersecurity Threat?” American Scientist 107(2), 83, https://www.americanscientist.org/article/is-quantum-computing-a-cybersecurity-threat, last visited January 31, 2021.

Gil, D., Mantas, J., Sutor, R., Kesterson-Townes, L., Flöther, F., & Schnabel, C. (2018). “Coming soon to your business: Quantum Computing. *IBM Institute for business value.” IBM Research Insights, https://www.ibm.com/downloads/cas/OV1V0NLX.[dl: 29.07. 2020]*, last visited January 31, 2021.

Harmon, R. R., Bin G., and Lee, M.R. (2016) "Guest editors' introduction: IT in Smart Cities." *IT Professional* 18(4), 14-17.

Heflo (2021) “IT process optimization.” https://www.heflo.com/blog/itil/it-process-optimization/, last visited January 31, 2021.

Hu, W., Zhipeng, F., and Ye, G. (2019) "Research on smart contract optimization method on blockchain." *IT Professional* 21(5), 33-38.

Ling, A., Huang, R.S. (2020) “Computationally predicting clinical drug combination efficacy with cancer cell line screens and independent drug action.” *Nature Communications* 11**,** 5848. https://doi.org/10.1038/s41467-020-19563-6

Rossi, A. and Gonzalez-Zalba, F. (2019) “We Need to Replace Moore's Law to Make Way For Quantum Computers, But What's Next?”, The Conversation, 29 July, https://www.sciencealert.com/why-it-might-be-too-soon-for-a-moore-s-law-for-quantum-computers, last visited January 31, 2021.

Sgarbas, K. N. (2007) “The road to quantum artificial intelligence.” *arXiv preprint arXiv:0705.3360*.

Schuld, M., Sinayskiy, I., & Petruccione, F. (2015) “An introduction to quantum machine learning.” *Contemporary Physics*, *56*(2), 172-185.

Strogatz, Steven (2007). "The End of Insight". In Brockman, John (ed.). *What is your dangerous idea?*. HarperCollins. ISBN 9780061214950.

Young, P. (2016) “Can a quantum computer solve optimization problems more efficiently than a classical computer?“, Colloquium at Ludwig Maximilians University, https://young.physics.ucsc.edu/talks/oldenburg.pdf, , last visited January 31, 2021.