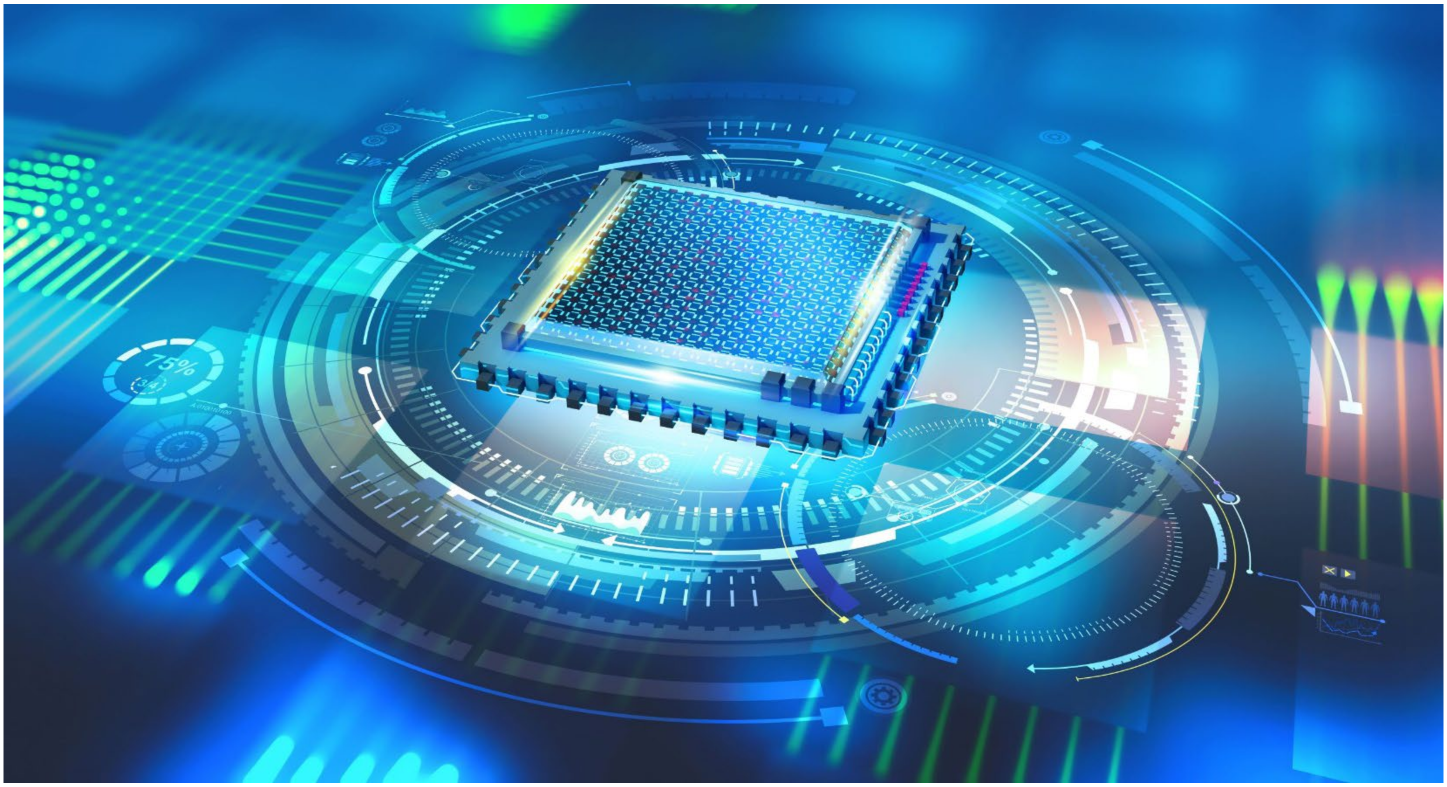
"Quantum Impact" — The Potential for Quantum Computing to Transform Everything



- There's a full-throttle race under way for the edge in developing and deploying computing based on quantum principles. Governments and industry leaders across tech and other key industries are investing heavily in research and development of both the core quantum technology and its potential applications.
- The transformative potential of quantum computing may take many years to fully realize. So why do these developments matter for investors now? Leaving aside the geopolitical implications, with China's planned investment outstripping that of the U.S., quantum computing will affect industries ranging from asset management to transportation. Leading companies are already investing significant sums to stake out their quantum strategies, with a focus on solving challenges that traditional computing power cannot.
- In this report, our contributors — Pathstone professionals and external industry experts — explore quantum computing, focusing in on its implications for sectors including asset management, cryptocurrencies, water technologies, chemicals, transportation, and healthcare. We also address the key question "Is quantum computing investable?"
- Importantly, across many of the governments and leading companies investing in quantum technology and its potential applications, there has been an emphasis on targeting the most pressing environmental and social challenges of our day, as framed by the 17 United Nations Sustainable Development Goals. If this current collective focus continues to inform the progress of quantum, it truly will have transformational impact.

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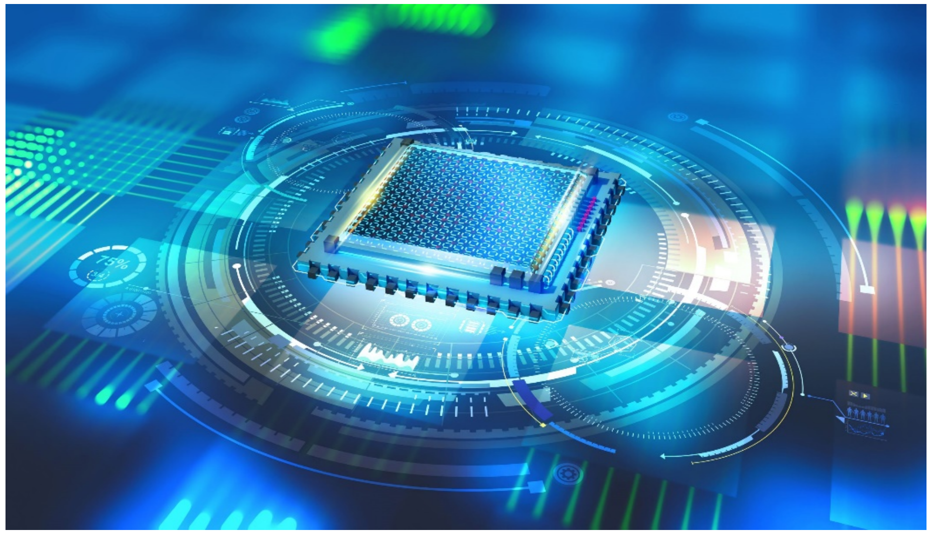
Quantum Impact: Why It Matters for Investors Now

Erika Karp, Pathstone



"Spooky action at a distance" is the concise, comprehensive, and accessible phrase used by Albert Einstein in the early twentieth century to describe entanglement, a key principle of quantum mechanics, where subatomic particles can interact in complex, bizarre, and random ways. And today, just 100 or so years later, the race for the edge in developing and deploying computing based on quantum principles is running full throttle.

This evolution beyond Newtonian classical mechanics is leading to the creation of arguably the most disruptive and transformative technology in history. In quantum mechanics, an object can exist in several states simultaneously; applying these principles to computing offers the potential to analyze a multitude of data points and scenarios simultaneously in order to solve complex challenges well beyond humankind's current capacity.

Why does this matter for investors?

How could it not? Quantum computing may literally shift the current world order. The E.U., the U.S., China, and Japan are the nations investing most heavily in quantum computing research and development, with China's stated commitment dwarfing the rest – with potentially meaningful implications for the balance of global power.

Looking beyond geopolitics, leading private sector enterprises are investing in demonstrations of "quantum supremacy" and creating roadmaps to practical use cases. The likes of IBM, Alphabet, Amazon, Goldman Sachs, Pfizer, Lockheed Martin, Mercedes-Benz and Microsoft, among others, are setting the stage to reimagine the competitive landscape. As we explore in this report, quantum computing will affect industries ranging from asset management to transportation as they seek to solve challenges that tend to fall into defined "problem types": encryption/decryption, optimization, machine learning, and simulation. A July 2021 report from Boston Consulting Group estimates the value creation potential from such developments in the many billions, as shown in the table that follows.

About This Report

Pathstone has created this collaborative research report to offer insight into the potential scope of quantum-driven transformation, how it may affect the future investment landscape from both the macro and sector perspectives, and its potential to do so in a way that sustains humankind and heals our planet as outlined in the UN Sustainable Development Goals (SDGs).

As an investment advisor, one of Pathstone's core services is to identify investment strategies that align with our clients' goals and needs. Integral to that effort is identifying asset managers who continually seek predictive insight, who can "look around the corner" and understand the whole system in which their industries and companies operate. The analysis we offer in this report is intended to challenge asset managers and investors to consider how a dramatically shifting technological landscape could affect geopolitics, the global investment landscape, and their portfolios as a new quantum world emerges.

Value creation potential for quantum computing at technology maturity (by problem type)

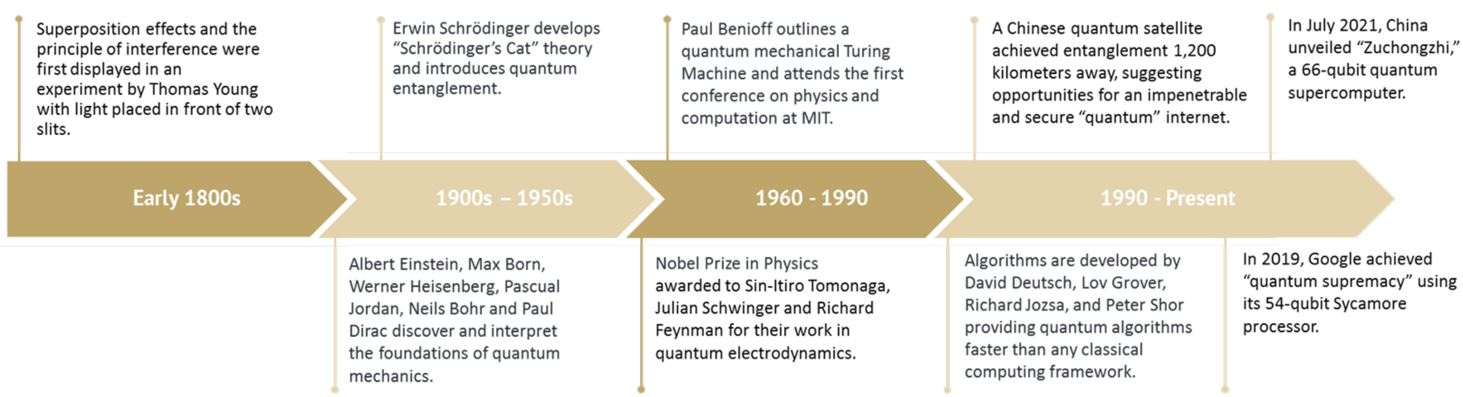
	Applications	Value Creation Potential ($B)	
		Low	High
Cryptography ($40 - $80B)	Encryption /decryption	$40	$80
Optimization ($110 - $210B)	Aerospace: Flight Optimization	$20	$50
	Finance: Portfolio Optimization	$20	$50
	Finance: Risk Management	$10	$20
	Logistics: Vehicle routing / network optimization	$50	$100
Machine Learning ($95 - $250B)	Automotive: Automated Vehicle, AI Algorithm	$0	$10
	Finance: Fraud and money-laundering prevention	$20	$30
	High tech: Search and ads optimization	$50	$100
	Other: Varied AI applications	$80+	$80+
Simulation ($175 - $330B)	Aerospace: Computational fluid dynamics	$10	$20
	Aerospace: Materials development	$10	$20
	Automotive: Computational fluid dynamics	$0	$10
	Automotive: Materials and structural design	$10	$15
	Chemistry: Catalyst and enzyme design	$20	$50
	Energy: Solar conversion	$10	$30
	Finance: Market simulation (e.g. derivatives pricing)	$20	$35
	High tech: Battery design	$20	$40
	Manufacturing: Materials design	$20	$30
	Pharma: Drug discovery and development	$40	$80

Source: Boston Consulting Group, based on academic research and industry interviews.

Quantum Computing Demystified (Not Really…)

Mark Peters, CFA, Pathstone

From quantum mechanics to quantum computing: key milestones



Source: Pathstone.

Quantum computing may soon deliver changes that are impossible to foresee, with ramifications that extend beyond our imagination. So what is this revolutionary and disruptive technology?

Quantum computing is founded on the work of Albert Einstein, Max Born, Werner Heisenberg, and Richard Feynman as they sought to understand "quantum mechanics," i.e., mathematics and physics within a universe described by the theory of relativity. Quantum mechanics is the foundation of modern physics, and yet conventional computers are still anchored in old Newtonian classical mechanics. It is increasingly likely that quantum computing will eclipse conventional computing in the foreseeable future for many complex calculations. Once we go beyond the tipping point, we should expect rapid advances in computing power within important areas of scientific research and development.

As described in the book Quantum Computing, Progress and Prospects, a quantum computer controls and manipulates a physical system of entangled "qubits" to evaluate an algorithm. The answer is revealed (with a high probability – nothing is ever 100% certain in quantum mechanics) by measuring the system's final state. To succeed, the quantum computer's environmental influences (their "Hamiltonian," in quantum lingo) must be controlled or buffered so that such influences do not result in noise and errors, which is described as "decoherence."

If you are puzzled, don't worry, you are not alone. Nobel prize winner Richard Feynman once said, "I think I can safely say that nobody understands quantum mechanics." To attempt to understand quantum mechanics, you need to leap from classical mechanics to a new intellectual paradigm, one in which the old "normal" rules of reality don't always apply.

Traditional computing vs. quantum

To better understand the inner workings of a quantum computer, let's examine the current conventional computing approach first. "Bits" are the building blocks for the binary logic structure in conventional computing. The logic is clean and simple, with the information conveyed through combinations of bits that are either a 0 or a 1. Conventional software and hardware were conceived and created around this simple logic. Large amounts of bits are orchestrated by your software and conducted through your semiconductor chips and other hardware to drive your computer games and display the text on your screen.

In the world of quantum computing, "qubits" (short for quantum bits) are the building blocks for quantum computing's logic structure. Qubits encode information, like conventional bits, but have unique characteristics that can be observed and manipulated at the atomic and subatomic levels under carefully controlled environmental conditions. These characteristics increase their usefulness for processing information and open the door for quantum computing to solve problems in unique ways when compared with conventional computing.

Why is quantum computing hard to understand?

The universe is much more complex than the simple picture drawn by classical mechanics. You might consider classical mechanics as a convenient wrapper. This wrapper projects an unwavering image with great certainty at the macro level. Meanwhile, at the micro level, subatomic particles are rapidly interacting in complex, bizarre, and random ways.

IBM provides a good introduction to quantum computing, which describes two counterintuitive principles of quantum physics:

1) A physical system in a definite state can still behave randomly.
2) Two systems that are too far apart to influence each other can nevertheless behave in ways that, though individually random, are somehow strongly correlated.

Superposition's superpowers

Radio waves, microwaves, and light all show **"**superposition**"** effects. Superposition is used in classical mechanics to describe how waves impact one another, amplifying magnitude with constructive interference or reducing magnitude with destructive interference. Within quantum mechanics, quantum superposition notes that two states, such as a 0 and a 1, can be added together, or "superposed", to get another valid quantum state. Qubits can utilize not only the "basis states" of 0 and 1 but also something other than 0 and 1, a valid state resulting from the combination.

Consider flipping a coin, where 0 is heads, 1 is tails, and "Superposed" is the spinning of the coin itself, with the possibility of being either heads or tails when it lands. In this case, when you flip the coin, it frequently lands on "Superposed," which can be in several states *at the same time*. However, when you look down at the coin, its quantum state is disrupted, and the wave (or spinning) nature of the coin collapses into one observable state of either heads or tails.

Another nonintuitive aspect of quantum computing is that light is a wave and a particle at the same time. Thinking of light as its particle form, a photon, it is difficult for many of us to understand how it can have superposition effects that are happening at the same time as a wave. Again, in my understanding, it collapses to a photon particle in one state when observed. Observe it directly, it is a particle. Look away, it is a wave.

Entanglement – the intimate, long-distance relationships of qubits

Qubits can be **"**entangled**"** so that their states are in alignment, such as a superimposed state. Amazingly, a change made to one qubit that is entangled correlates with what you will observe in the other. Using another coin analogy, if you entangle two coins and flip one to heads, the other is observed to be heads as well.

Entanglement is a unique aspect of quantum physics, one which Einstein famously described as "spooky action at a distance." Once entangled and sent to different places, the entanglement does not disappear, since location is not relevant. One experiment has shown that entangled relationships exist even when qubits are 1,200 kilometers apart.

What advantages do quantum computers have compared with conventional computers?

Superposition allows a qubit to hold substantially more information than a conventional binary bit since it can be in a combination of those two other possible states. When many of these qubits are combined, the information capacity grows exponentially.

The ability to handle more information in a different way provides an edge to quantum computing for solutions that require many iterative calculations. The approach should shine for problems that require tremendous processing power and can be approached in a non-sequential manner. From the software end, the programming presents a large set of potential paths to a solution at the outset, which will then be solved nearly instantaneously by the hardware through superposition, rather than walking through a sequential trial and error process that evaluates each path individually. Using a mouse in a maze analogy, you might think of one "conventional" mouse that must try each path in the maze separately to find the cheese, while another "superposed" mouse looks down from above and quickly scans them all for the best solution.

What challenges must researchers overcome to build better quantum computers?

To hold and process information, superposed and entangled qubits need to be organized and manipulated in an extremely cold, quiet, and still environment (i.e., maintain the Hamiltonian). Movements, sounds, atmospheric pressure changes, temperature changes, and even cosmic rays that impact the system can be thought of as unwanted "observations" that collapse parts of the system, causing it to lose its coherence, with an increase in noise and a decrease in signal. Calculation errors in the form of "bit flips" are caused by this destabilizing decoherence.

To minimize decoherence, scientists often conduct their research at temperatures close to absolute zero (the lowest possible temperature) and within a vacuum. They control the qubits with extremely precise lasers and optical devices. To construct more effective quantum computers, researchers will continue to seek to control this sensitive environment ever more effectively, even as they strive to correct errors or "peer through noise."

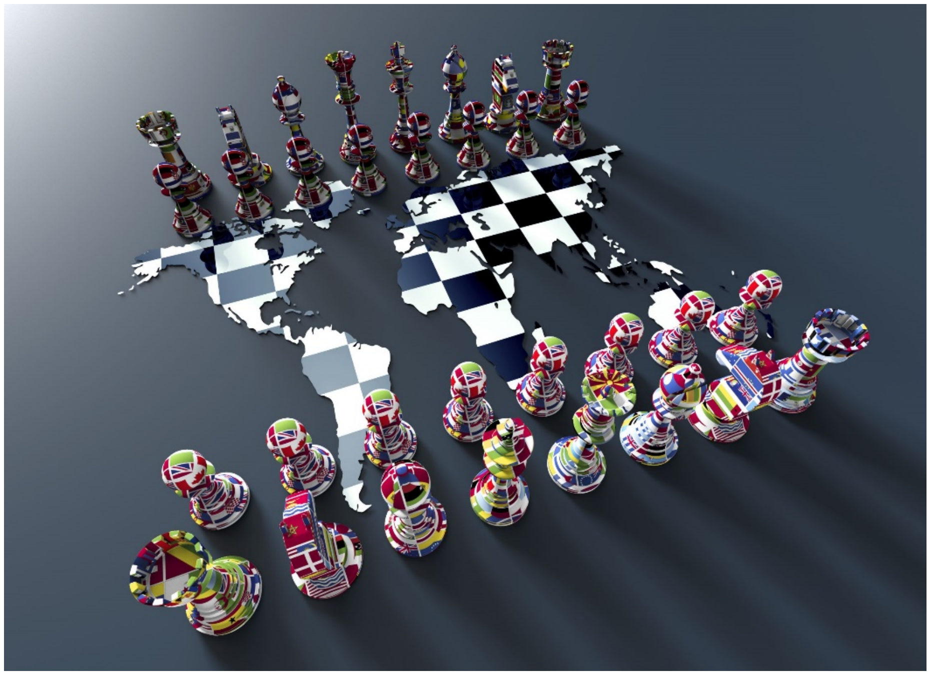
For an example of a quantum system operating now, look to nature

To get an idea of what is possible with quantum computing, just look outside at a tree. Feynman once said, "Nature isn't classical, dammit, and if you want to make a simulation of Nature, you'd better make it quantum mechanical."

Our sophisticated computer systems pale in comparison to the myriad complex computations that are being executed at the cellular level within living organisms. With respect to computing power, humans' abilities are far outdone each day by the computations within Earth's ecosystem. In his 2011 book Wetware: A Computer in Every Living Cell, Dennis Bray describes how organisms' cells perform constant computations as they adapt to the environment in an intelligent manner. They are naturally computing a response in each instance, with logic flowing through circuits, their systems refined through evolution. As smart as we are, we are not yet able to create a seed that can absorb water, minerals, nutrients, and carbon dioxide, and flourish into a tree that thrives amidst complex environmental adversity.

Computing Power and the New World Order

John Workman, Pathstone



When it comes to conquering new frontiers, competition for geopolitical advantage will be fierce and the consequences far reaching. Quantum computing primacy may change the old paradigm, potentially reshuffling the world order in more dramatic fashion than we have previously witnessed.

Although this is a new chapter in the story of world order, history serves to inform us how new discoveries can impact the economic and political power of sovereign nations. The power of the world's greatest empires — the Roman, Ottoman, Yuan Dynasty, Macedonian, Tang, Han, Qing Dynasty, Mongol, and British, to name a few — stemmed from access to natural resources, military might, exploration prowess, innovation, control of information, and a trustworthy currency. These factors were all critical to establishing an empire, while culture and a universal ideology were also necessary to sustain the empire.

The current hierarchy of world power is led by U.S., with China the closest rival following the fall of the Soviet Union in 1991. The European Union remains an important bloc that has historically been allied with the U.S., though this relationship has suffered bumps in recent years. Russia under Vladimir Putin is still a powerful economic and military force but wields limited political influence with other countries. And while there are several regimes that can saber-rattle with the best of them (e.g, North Korea, Iran), they are mostly relegated to rogue nation status. In sum, China seems to be the only nation that can come close to rivaling the U.S. in terms of potential economic and military.

Will quantum computing power be the game changer in terms of which of these two horses takes the lead, or might it be just the thing to jumpstart another nation, or group of nations, to become the unexpected winner? How might current alliances shift in response to developments in quantum computing expertise?

We can imagine both positive and more sinister ways in which quantum computing could change geopolitical dynamics. The race to develop quantum capabilities will cost an exorbitant amount, perhaps giving the wealthiest nations an insurmountable head start. Advances in the development of energy resources, healthcare, military technology, security, and space exploration could have far-reaching impacts on economic and political power globally. While that would suggest the world order is not likely to change too drastically from the current state of the U.S. and China battling for number one, alternatives should be considered.

We cannot rule out that a less developed nation, perhaps one where a dictator usurps basic resources and redirects them to quantum computing development, could level the playing field. The concern of the more dominant economic and political powers would be the threat this could create. As the world continues to move increasingly "online" with everything, cybersecurity will have to remain a top priority, as espionage and hacking could prove immensely costly and damaging. It would be difficult for a nation without significant economic strength and political clout to take over a leadership role in the world order, but it may well cause alliances to shift.

While quantum computing will require significant investment to develop, it could be the great equalizer. It is no longer a guarantee that the wealthiest country with the strongest military will win the next "war." Quantum computing capabilities, in the end, will matter most in the race between China and the U.S. to determine who will enjoy supremacy in the next chapter of world order. And while quantum computing will enable wonderful innovations, the initial focus is going to have to be around upgrading passwords, encryption, and cyber defenses, particularly for nation states that have a lot to lose should they become easy targets for hackers that gain access to new computing power.

Key Government Funding Initiatives

As of January 2021, 17 countries and the European Union had announced some form of national strategy around the research, development, and commercialization of quantum computing. The E.U., U.S., Japan, and China are investing the most heavily in the necessary research and development. Below we highlight spending across key global players.

United States: National Quantum Initiative. In 2018, the U.S. Congress passed the National Quantum Initiative Act, intended to accelerate quantum research and development in key institutions such as the National Institute of Standards and Technology, the National Science Foundation and the U.S. Department of Energy. The Act includes funding for plans and alliances that are intended to strengthen Quantum Information Science. To date the U.S. has committed approximately $1.2 billion to quantum computing research. https://www.quantum.gov/

China: Chinese Academy of Sciences Center for Excellence in Quantum Information and Quantum Physics. Quantum computer research and development was included in the government's Fourteenth China Economic and Social Development Plan and "Made in China 2025" manufacturing strategic objective. China's quantum initiative aims at fulfilling the Chinese government's objective to become a global technological superpower through its Digital Silk Road initiatives, an essential part of its Belt and Road Initiatives. China has made a commitment of US$10 billion to build a National Laboratory for Quantum Information Science.
https://english.cas.cn/Special_Reports/Pioneer_Initiative/

Canada: National Quantum Strategy. The government agency Innovation, Science and Economic Development Canada (ISED) is tasked with helping the Canadian government to develop a national strategy on quantum. The strategy is aimed at putting Canada at the forefront of quantum research, deployment, and commercialization. So far, the Canadian government's Budget 2021 economic recovery package has committed approximately C$360 million over the next seven years for investments in quantum initiatives.
https://www.ic.gc.ca/eic/site/154.nsf/eng/00001.html

Australia: Sydney Quantum Academy. The Australian government has made considerable contributions towards the research and development of quantum technology. The Australian Research Council's Centre of Excellence for Quantum Computation and Communication Technology, which is one of four centers under the agency, was funded by the Australian government to support and advance the research, deployment, and commercialization of quantum technology. In its 2021/22 Federal Budget, Canberra designated A$1.2 billion towards Australia's digital future through its Digital Economy Strategy. Approximately A$22.6 million is to be used to improve the skills of Australians in emerging technological fields such as artificial intelligence, robotics, and quantum computing.
https://www.sydneyquantum.org/

European Union: Quantum Technologies Flagship Program. The Quantum Technologies Flagship Program was established in 2018 as one of the largest and most ambitious research programs in the European Union. This flagship project, with a budget of at least €1 billion over a 10-year timeline, is designed to bring together research institutions, academia, industry, business, and policymakers in an unprecedented collaboration. https://qt.eu/

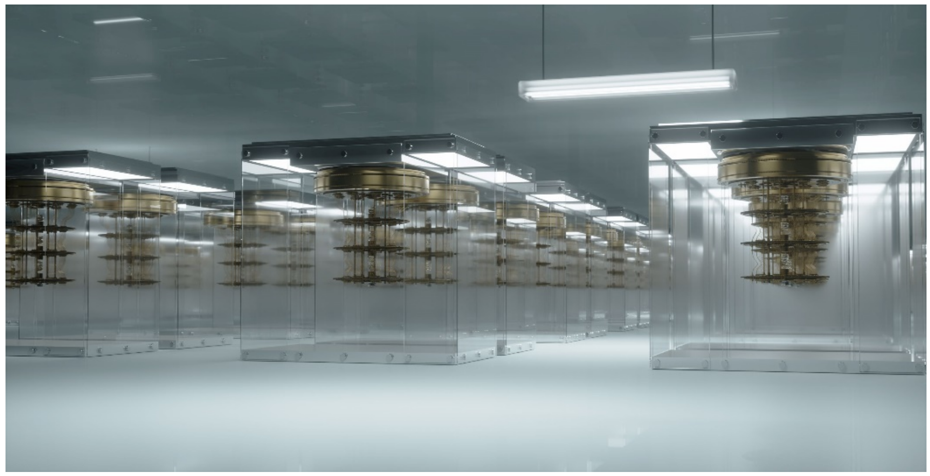
United Kingdom: U.K. National Quantum Technologies Programme. The Government of United Kingdom National Quantum Technologies Programme was established to advance and create a cohesive partnership between government, the private sector, and academia. The program is designed to place Britain at the global forefront in the pursuit of new quantum offers the promise of adding value within some of Britain's most important industries.

In 2013, The U.K. government committee allocated approximately £385M towards the Programme's first phase. It has since attracted more funds; recently, in partnership with IBM, the U.K. government announced it "will invest £172 million over 5 years through U.K. Research and Innovation, with an additional £38 million being invested by IBM. £28 million of the government's investment will be in the first year." *https://uknqt.ukri.org.*

Jude Erondu, Pathstone

"Quantum-Interested": Potential Use Cases Across Sectors

Eric Hsueh, CAIA, Pathstone



There has been an acceleration in interest from potential corporate users of quantum computing in the past few years, driven by three main factors:

1) **Technical advancements.** Since 2019, there have been two highly publicized demonstrations of "quantum supremacy" – the threshold where a quantum computer can perform a calculation that is practically impossible with classical computing. Google and University of Science and Technology of China are the two institutions that have achieved this technical milestone.

2) **Increased timeline clarity.** Major quantum computing technology providers have released roadmaps laying out critical milestones over the next decade.

3) **Practical use case scenarios.** The first two factors above have spurred businesses to begin identifying ways quantum computing could help their businesses and budgeting for related investment. According to Gartner, only 1% of companies actively budgeted for quantum computing in 2018; this number is expected to rise to 20% by 2023.

Aside from the full-stack large-cap companies (IBM, Microsoft, Google, Alibaba, et al.,) and startups dedicated to quantum, there is a diverse set of "quantum-interested" parties that foresee a future where quantum computing is transformational to their businesses. A representative, though not exhaustive, list includes the industries and companies below:

- **Aerospace:** Airbus, Lockheed Martin
- **Automotive:** Daimler, Toyota
- **Chemicals:** Dow Chemical, JSR Corporation
- **Consulting:** Accenture, Deloitte
- **Finance:** Citi, Goldman Sachs, J.P. Morgan
- **Pharmaceuticals:** Merck, Pfizer

Currently, quantum computing research is focused on a select number of use cases that can be categorized as follows:

- **Simulations**, particularly those with complex relationships that cannot be practically handled by classical computers. Examples include processes that occur in nature (e.g., determining how molecules might interact with other molecules) or finance (e.g., how market participants interact with one other). Simulations have enormous implications for advancements in pharmaceuticals (drug discovery), aerospace (computational fluid dynamics), chemicals (materials design), and finance (derivative and option pricing).

- **Optimization**, or identifying the best solution among a set of feasible options. The use of quantum computing for optimization would have broad application in industries from finance (portfolio and risk optimizations, risk management) and logistics (network optimization), to aerospace (route optimization) and e-commerce (placement of robots on the warehouse floor).

- **Machine learning** to identify patterns for training algorithms. Applications include advancements in the automotive industry (automated vehicles), finance (anti-fraud, anti-money laundering), and technology (search ad optimization).

- **Cryptography** is a major usage case as governments and corporations will look to quantum to bolster encryption and decryption standards.

"Quantum-interested" activity

Companies are gearing up for a future where the power of quantum computing can be harnessed for practical application. For example, Goldman Sachs has a dedicated quantum research group tasked with figuring out high-value use cases. To stay on the vanguard of developments, this group partners broadly with startups, full-stack tech providers, and academic institutions on research, making their findings public (e.g., in late 2020, Goldman Sachs and IBM published their research on pricing financial derivatives using quantum computers).

Willis Towers Watson is another example of a financial institution partnering with leaders in quantum. The firm is working with Microsoft to explore ways that quantum computing might assist with its work in the areas of insurance, financial services, and investing.

Pharmaceutical companies like Pfizer, Novartis, and others are also exploring in-house efforts to assess quantum. In the meantime, Pfizer has partnered with XtalPi, a Chinese tech startup, to develop and model small-molecule drugs as part of its discovery and development efforts.

Given the potentially transformative impact of quantum computing, businesses should be closely monitoring developments. Those who want to be at the forefront of their industries need to invest the time and resources to position their firms to take advantage when the time comes.

Which Public Companies Are Leading the Way?

Setting the stage in 2016, **IBM** was the first company to provide the world with the opportunity to access a quantum computer by putting it on the cloud. From 2019 through 2020, registered users have grown over 42%, from more than 200,000 to more than 285,000 users. IBM introduced a 53-qubit computer in 2019 and by 2023 plans to produce a quantum processor with more than 1,000 qubits.[1]

Mercedes-Benz has been using quantum computing to design better lithium batteries to create a more sustainable energy future. The development is intended to boost charge capacity, increase battery life, diminish energy loss from heat, and dramatically lower costs.

In the aerospace industry, **Lockheed Martin** utilizes the D-Wave Two, a 512-qubit quantum computer, to verify and validate solutions. D-Wave Two is one of several quantum computing systems developed by D-Wave Systems, a Canadian quantum computing company. Within milliseconds, D-Wave Two can review all potential trajectories a spacecraft might take and determine the most efficient path.[2]

Alibaba formed a quantum lab called the DAMO Academy with the intention of using cutting-edge technology to integrate science and industry. The goal is to accelerate the speed with which information is shared between the two disciplines. The DAMO Academy has applied the technology to computed tomography (CT) imaging analytics to understand the differences between COVID-19 pneumonia, common pneumonia, and other conditions. As early as March 2020 the academy had reviewed over 240,000 CT images, the equivalent of 13,000 results per day.[3]

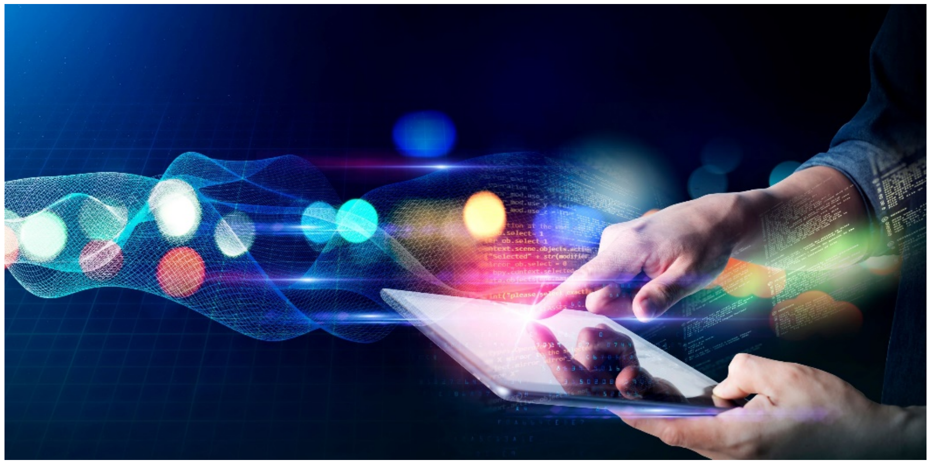
During **Tesla**'s Artificial Intelligence (AI) event, held in August 2021, the company unveiled the Dojo A1 chip and its first functional computing tile. These developments are significant for the Tesla Dojo, the company's version of a supercomputer. With these components Tesla anticipates the Dojo will be fully operational by 2022. The Tesla Dojo seeks to achieve best-in-class AI training performance and create larger and more complex neural net models, while being power-efficient and cost-effective to run. Although this is not a quantum computer, there is no denying the value such computing power and speed offers to tackle today's complex issues.

Heng Yang, Pathstone

[1] https://www.ibm.com/annualreport/assets/downloads/IBM_Annual_Report_2020.pdf
[2] https://www.lockheedmartin.com/en-us/news/features/2017/quantum-computing-spot-checking-millions-lines-code.html
[3] https://www.alibabacloud.com/blog/speeding-up-ct-scans-to-detect-covid-19_596124

Quantum Computing, AI, and Asset Management

Garvin Jabusch, Green Alpha Advisors



Quantum computing capabilities represent a step change for the global economy. In October 2019, Google represented that their quantum processor had worked out a classical computer test problem in an amazingly short time, by running calculations at more than 3 million times faster than the world's most advanced supercomputers. If and as this technology becomes commercially available, the number of operations per second that humans — as a civilization — will become capable of will increase by orders of magnitude. Orders, plural, likely many.

We already have examples of the impressive scale of exponentially increasing processing power using pre-quantum processers. Consider SpaceX and the reusable booster. When Elon Musk started SpaceX, he was derided by some veterans in the space industry for even suggesting a booster could be recovered and reused, much less gently landed on a drone ship. As we now know, SpaceX prevailed in their attempt to create the technology. Why was this? Why now? Primarily, because the computing power Musk and his team were able to bring to bear on the problem was greater than ever before realized in the history of that problem. (That and the maverick, outsider-naiveté-based rejection of the conventional wisdom that claimed it wouldn't be possible meant that it could be.) After all, a booster reenters the atmosphere at something greater than Mach 25, and old hands who had been practicing rocketry for decades knew that the precise firing of thrusters and boosters at just the right times in just the right synchronicities and combinations was impossible, and that a soft touchdown couldn't therefore be realized. And yet, here we are.

SpaceX did this with classical – albeit very advanced – computing capabilities.

So, the first key realization as we enter the quantum era is that there are innumerable unforeseeable emerging applications, technologies, and capabilities that will result. Insolvable problems will be cracked.

Case Study: Green Alpha Advisors

At Green Alpha Advisors, we are in a unique position to envision the near-term outcomes that might be possible applying quantum computing capabilities within our own industry of asset management. Our economic thesis and stock selection processes are a bit outside of the mainstream, and so far, have not lent themselves to traditional quant-based, formula-ready duplication methods. Several vendors and potential partners have approached us, and together we have attempted to find a rules/algorithm-based way to replicate our processes. So far, none has worked sufficiently. But in a quantum world, that could change.

To explain why, let's briefly go through Green Alpha's research processes. Our top-level criterion, the factor that provides the go/no-go decision point for whether to research a given company and its stock, is an internal determination of whether the company is doing more on balance, as an aggregate of its overall business activities, to stabilize the world than to destabilize the world. We define impact investing as sending signals to the market that only the companies providing fixes to our biggest problems have value (and so we decline to purchase companies we define as destabilizing as, by definition, therefore, they will make poor long-term investments).

You might say, "That's not hard, just plug in ESG scores and boom, that'll be perfectly quantifiable and replicable by an algorithm." Except, no. ESG scores are not a reliable way to determine whether a company is helping advance sustainable economics or working to crush them. For example, oil super major Total SA has a good overall ESG score from Sustainalytics. MSCI ESG ratings give both Exxon Mobil and Chevron 'high average' ratings. Toyota, responsible for driving a huge quantity of oil demand, and notoriously resistant to a transition to electric vehicles, is an ESG darling, based largely on its very favorable ESG scores created by third-party asset management vendors. In the current ill-defined ESG landscape, there is no way to reach a 'stabilizing or destabilizing' conclusion based on these ESG ratings. Green Alpha therefore evaluates each company on its own merits, very carefully, in a similar way to how venture capitalists or private equity managers practice their craft, to determine if – on balance – a corporation's net activities are resulting in an economy working well for everyone's benefit.

This involves a lot of work, and in addition requires application of many heuristics that so far have been resistant to algorithmic reduction. As far as we have been able to determine, or have been shown, no algo has yet reproduced one of our strategies. The outputs are just not there.

But what if three or five or 10 algorithms, each optimizing along a different axis, could run in parallel? What if each of these individual algos could be 10 times more powerful than any that preceded it? That is a world not yet experienced by anyone, and a machine capable of that could very well learn to replicate Green Alpha's research processes, and even apply our philosophies to every publicly listed stock in the world, and therefore derive a kind of super strategy — an equities strategy reflecting all the companies that will define, and indeed constitute, the Next Economy™, say, 10 and 20 years hence. That would be great: Not only would it be potentially the highest-impact portfolio investors could own in terms of driving capital towards that economic transition, it may very well also provide a clear path to competitive returns as all the innovative solutions and brilliant approaches uncovered by this quantum-driven algorithm gain market share, and eventually grow to largely constitute the economy itself.

Of course, huge computing power alone won't result in this portfolio-building juggernaut. Each algo will require a long period of training, and the combination of algos longer still. Before the quantum-based portfolio construction system could completely take over as Green Alpha's Chief Investment Officer, we would need to operate as a centaur providing inputs and evaluating its decisions over some period of time. But it could replace us. We hope it will.

Green Alpha's portfolio construction approach depends on a lot of inputs that haven't been formally or commercially quantified yet. Therefore, it is resistant to automation so far. Many other equities strategies, most obviously index funds, have been run by algorithms for years. The simpler the strategy, the easier it is to automate. Automation ultimately will come for the whole asset management industry, in our view, but the more complex strategies will be among the last to hand over the keys to the machine. However*, no amount of complexity will be too great for a properly constructed and optimized series of quantum algos*. One of our dreams, in fact, is to work with a leader in quantum development to start the process of creating our own obsolescence. Hey DeepMind, give us a call! OpenAI, same offer.

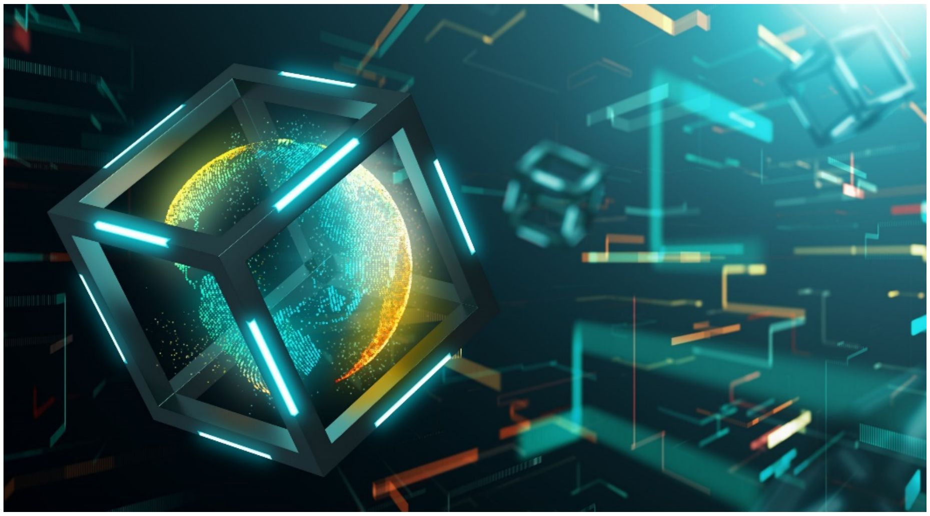
This all may sound a little whimsical, but it's not. It's deadly serious. Channeling capital to the highest-impact, most-scalable, and fastest-growing solutions might make the difference between innovation outrunning the climate crisis or not. Quantum computing will be a key tool in developing and optimizing these maximum-impact portfolios.

Every industry has its own transformational tale to spin about what the quantum computing revolution will mean for it. One of our jobs is to look at companies across industries to see who is planning ahead of this trend taking off and then getting client dollars in front of those compelling investment opportunities. It may seem a bit early, but being early is where investment gains come from.

The importance of the quantum computing revolution is difficult to overstate. Any asset manager or any executive in pretty much any industry who views this as an over-the-horizon thing they don't have to worry about yet is risking their own obsolescence. The quantum computing world is already beginning to emerge. Put up your tray tables, we may be landing there soon.

Crypto and Quantum: Here to Stay, Better Together

Jalak Jobanputra, FuturePerfect Ventures



Satoshi Nakamato's [Bitcoin white paper,] written in response to the 2008 financial crisis, stated (my **emphasis** added):

We have proposed a system for electronic transactions without relying on trust. We started with the usual framework of coins made from digital signatures, which provides strong control of ownership, but is incomplete without a way to prevent double spending. ***To solve this, we proposed a peer-to-peer network using proof-of-work to record a public history of transactions that quickly becomes computationally impractical for an attacker to change if honest nodes control a majority of CPU power.*** *The network is robust in its unstructured simplicity. Nodes work all at once with little coordination. They do not need to be identified, since messages are not routed to any particular place and only need to be delivered on a best effort basis. Nodes can leave and rejoin the network at will, accepting the proof-of-work chain as proof of what happened while they were gone. They vote with their CPU power, expressing their acceptance of valid blocks by working on extending them and rejecting invalid blocks by refusing to work on them. Any needed rules and incentives can be enforced with this consensus mechanism.*

The Bitcoin blockchain has become the basis for thousands of other cryptocurrencies that have been formed since its launch in 2009. In those early days, when the number of computers running the Bitcoin software numbered in the hundreds, there was concern that there would be a "51% attack" where 51% of the computers verifying transactions would fork and take the Bitcoin recorded on their ledgers with them. As the network has become more decentralized, with thousands of computers around the world verifying transactions, this concern of a coordinated attack has lessened significantly. More recently, there has been some discussion that quantum computing will break the algorithms that verify Bitcoin transactions, allowing an attack on the network. Two new algorithms derived from quantum infrastructure, Grover's and Schor's, have been cited in this context.

As an investor in the cryptocurrency space since 2013, I have encountered much pushback on the validity of the sector, ranging from lack of transparency (this is false, most crypto transactions are more traceable than other monetary transactions) to potential hacks (while poorly designed software on and off ramps have been hacked, the Bitcoin blockchain has never been hacked). While quantum computing could potentially pose a threat, I believe it is more likely that when quantum computers are ready from an economic and technological standpoint to participate in the crypto ecosystem, they will enable new and better applications of crypto rather than pose a threat.

Bitcoin and crypto: here to stay…

Other cryptocurrencies have moved from Bitcoin's computationally heavy "proof of work" algorithm (where computers running the software have to solve complex mathematical problems to verify and write a transaction to the master ledger, receiving some Bitcoin as a reward for doing so) to a "proof of stake" approach in which a smaller number of stakeholders are involved in the verification of transactions. However, Bitcoin is still considered the most secure and decentralized cryptocurrency. Because of this, and the fact that its code guarantees that only 21 million

Bitcoin will ever be mined, it has become a de facto store of value, like gold, in the current macro environment, with hedge funds and corporate treasuries accumulating the asset as a hedge against inflation and uncertain global monetary policies.

Future Perfect Ventures' thesis since its inception in 2014 has been that the intersection of blockchain technology, cryptoeconomics, data analytics, and artificial intelligence would lead to the creation of next-generation business models, similar to what the PC era did with hardware and software, and what the Internet era achieved with mobile applications and cloud computing. We are in "1998 Internet" with this next-stage evolution, one that has been enabled by Moore's Law and faster processing power as well as better mobile and broadband connectivity. Quantum computing would fit well into this paradigm once it becomes economically feasible.

…primed for the future

This next phase will be marked by peer-to-peer computing (including machine-to-machine and machine-to-person), which will generate much data and require the addition of smart contracts and more complex computing. Ethereum was conceived a few years after Bitcoin to add a programmability layer to its transactions – enabling the eventual birth of what we now call DeFi (Decentralized Finance) – the ability to lend, borrow, and collateralize crypto as well as real world assets without intermediaries. As the number of transactions through these crypto networks grows, the ability to intelligently analyze and route that data would be helped with a more complex quantum network. Just as the world is much more interconnected, our computing systems will reflect that complexity and increasingly mirror how we operate.

Quantum Computing…and Water??

Matt Sheldon, KBI Global Investors

Water and quantum computing: It is hard to find two more unrelated topics. Water technologies are, for the most part, practically ancient. Water is tangible, elemental, and life-giving. It's omnipresent; we are always surrounded by water in one of its forms and both the animate and inanimate features of our world that would not exist without it. Everybody "gets" water.

The opposite is true for quantum computing. It is futuristic, unseeable, and hard to wrap one's mind around. Few understand it. After all, it is based on science that even Einstein famously struggled with.

The good news is that advances in quantum computing are expected to have tangible outcomes—massively enhanced computing power—and these outcomes can make a big impact in society. In this simplified context, I'll address how quantum computing can make a difference and drive impact in the water industry.

Quantum's role in facilitating access to water

When it comes to addressing UN Sustainable Development Goal 6, Clean Water and Sanitation, the targets are achievable via political will, capital availability and affordability. Technology will not solve for political will, but it can help with affordability and the efficient use of capital.

Quantum computing acts as a facilitating technology to increase affordability by way of reducing capital requirements and teasing out operational efficiencies. How? Quantum computing has two primary use cases relevant to the water industry: 1) machine learning and 2) complex system simulation and optimization. There is also an indirect use case related to quantum computing's impact on advanced material science and chemistry to address water quality issues via development of advanced filtration media and membranes, but I'll leave this topic aside.

Machine learning

The water industry, for the most part, has had a love-hate relationship with data. They need ever increasing amounts to be efficient, meet regulations, and serve their customers well, but it can quickly become overwhelming.

Water utilities generate significant data at their treatment plants and increasingly throughout their geographically dispersed distribution systems. However, in the U.S., the water utility workforce skews older, a very high proportion of whom lack college degrees. Also, 85% of water utilities in the U.S. have three or fewer employees. The problem is thus twofold: computer literacy and adoption of technology are lagging, while a wave of retirements over the next decade threatens loss of significant institutional knowledge. Utilities want and need the data but lack capacity to handle it.

A common refrain from utility managers is that data by itself is not helpful. In fact, it is unhelpful—if they have data to be better (somewhere?!) but have not acted on it, then they are liable for poor outcomes. What they really need are decision management tools, preferably in real-time. They need all the data fed into a "box" that spits out useful suggestions.

Machine learning can take millions of data points and, through complex algorithms, facilitate optimal real-world decisions. One of the most frequent machine learning applications in water today relates to infrastructure diagnostics. In essence, it helps to answer the question of which pipe should be replaced first. It is much cheaper to fix a pipe before it breaks. But if you replace it too early, that would be a waste of capital. A pipe under a school is more important than a pipe crossing a field, just as a pipe acting as the sole source to a system is more important than one with alternative routing options. Some pipes are likely to crack and leak slowly while others, like a large-diameter prestressed concrete cylinder pipe, could explode, with peripheral damage that turns a street into a river. Variables like age, material, soil characteristics, and proximity to other burst pipes all feature into the algorithms. The more variables used, the better the assessment but the more computing power required.

Simulation & optimization

The water cycle we were taught in elementary school is both simple to comprehend at a high level and incredibly complex to simulate. Integrating the natural cycle (evaporation, condensation, precipitation, infiltration, runoff) with the engineered water systems for municipal and industrial uses (abstraction, water treatment, distribution, wastewater treatment, discharge) offers significant opportunities to improve operations, reduce system stress, and reduce the industry's contribution to climate change. For example, better predictive modeling of weather events within a watershed can provide insights into potential changes in operation, such as anticipating feedwater quality changes, and adjust the treatment approach or create additional available system capacity (e.g., preemptive emptying) to handle stormwater flows with less risk of overflow events.

Future climate is very relevant to designing infrastructure with intended lifespans upwards of a century or more. Water is the visible part of the climate change spectrum. We see climate change through rising seas, more droughts and floods, more severe weather events, and in water-quality degradation. Water infrastructure investments today may not make sense in a 1.5 degree or higher world. Those 1-in-a-100-year storms seem to come every few years these days. Climate models have advanced a lot over the years but are currently constrained by computing power capable of fully analyzing at smaller geographic resolution and ability to incorporate all the various feedback loops. Quantum computing advances our ability to understand what the world will one day look like.

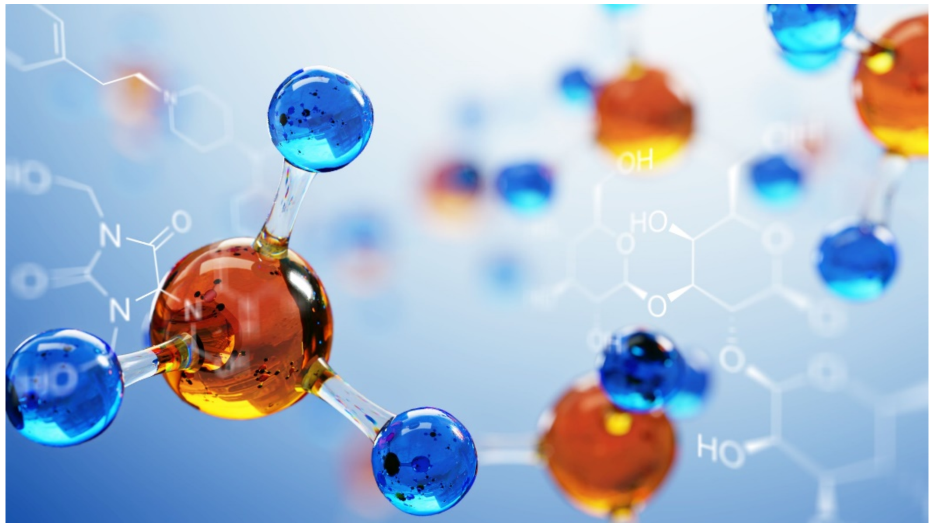
Recent years have seen increased adoption of digital twins, which are parallel computer simulations of process industries, such as water utilities, incorporating a vast array of dynamic variables. Think of it like a flight simulator for utilities. They can "operate" risk-free in various hypothetical environments to learn how best to manage real-world situations, thus driving operating efficiencies and improved customer outcomes. For capital optimization, generative design software enables the utility process to be altered virtually, becoming a tool for trialing multiple potential capital investments "for free" within the constraints of the real-world system. In other words, instead of engineering a few alternative design solutions to address new growth or quality regulations or simply fix a dilapidated part of their system, software enables the testing of thousands of alternatives in the virtual realm, thus saving significant time and capital to arrive at the optimal solution. One water industry contact suggests that rapid simulations, powered by quantum computing, may help accelerate adoption of new, more cost-efficient technologies.

While machine learning and complex system simulation and optimization are already used today in the water industry, the advent of quantum computing changes their nature and impact. Much of the analysis run on today's computing power is still sequenced—gather the data, run the models, spit out answers. The process could take seconds, or it could take hours or days. Data proliferation and the evolving nature of certain variables over time (think climate change) add to the wait. And to speed up models today, analysts might be using rule-of-thumbs or engineering algorithms instead of real-time data, which impacts the accuracy and usability of the results. The long waits and data shortcuts limit the analyses' use.

Quantum computing has the potential to change the nature of the analysis to real-time. The gathering, computing, and application of answers can happen nearly simultaneously. This can lead to not only lower-cost water utility operations but also reduced harm from natural events that might impact their functioning. It also leads to better capital decisions, which can mean more capital available for more projects. The improvements in customer outcomes and affordability of water and sanitation services ultimately generate genuine impact in the world, a world that will face evermore climate challenges, manifested in water.

Quantum Computing for a Chemical World

Carly Anderson, Ph.D., Prime Movers Labs



I love thinking about quantum systems because they capture the complexity, uncertainty, and connectedness of the real world. In "classical" computing systems like a laptop or phone, every "bit" is either a 0 or 1 — there's no in-between. However, a quantum bit, or "qubit," can be part 0 and part 1 at the same time. Like a certain Meredith Brooks song, qubits can be "a little bit of everything, all rolled into one."

As Chemical Engineer and & Partner at Prime Movers Lab, a deeptech venture firm investing in breakthrough science companies, I get to live on the front lines of deeptech innovation in quantum computing, climate tech, and other exciting areas. One of our core tenets is to share learnings from the amazing people and technologies we meet with the broader community. In this short piece, I'll share examples of what quantum computing can enable in the context of chemistry and why it will be a powerful tool. I'll also point out some of its limitations, and areas where technology is rapidly advancing with classical systems.

To frame this discussion, here is my high-level take on quantum computing for chemistry and materials applications based on what we're seeing today:

1) Quantum computers that can help us understand molecules larger than a handful of atoms are still 10-20 years away.
2) Quantum computers will be faster at solving some chemistry problems but not all problems!
3) The first quantum computers to be useful in modeling chemicals and materials will be hybrid systems with BOTH classical and quantum computer elements, and they will be run from the cloud.

How will quantum computing add value to the chemicals sector?

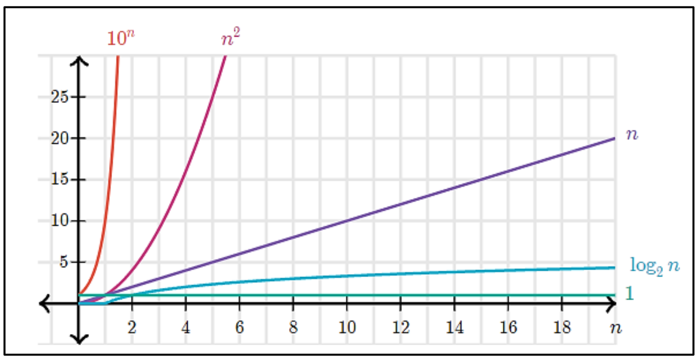
With the question of when we expect quantum computers to add value to the field of chemistry out of the way, let's get into the how. Quantum computers are much better suited to simulate molecules and materials (and to find better ones!) than today's "classical" computers. Why? Remembering back to Chem 101, molecules are atoms that are held together by shared (or stolen) electrons, which we call chemical bonds. The status of a particular electron in a molecule, and especially during a chemical reaction, has many possible values, each with some probability of being true — i.e., "a little bit of everything."

On a classical computer, the equations to describe the location and movement of electrons take a HUGE amount of processing power and memory. Even for today's supercomputers, using quantum mechanical equations to exactly calculate the properties of even simple molecules quickly becomes too complicated. Because of the limitations of classical computers, we can only get "exact solutions" for individual atoms and very small molecules like nitrogen (N_2), water (H_2O) and methane (CH_4), which have just a handful of electrons in a few energy levels.

Quantum computers can encode much more complex information in a single quantum bit, or qubit, due to superposition. This allows them to solve the complex equations for electrons (and other quantum systems) more easily. It's the difference between measuring derivatives over and over to find a minimum point in a mountain range and being able to see the entire landscape at once.

While quantum computers will speed up many chemical and materials calculations, the process still won't be effortless. As the molecule being simulated gets bigger and more complex, more qubits and computational time will be required to determine accurate properties. **The advantage for quantum computers is that the computation time generally scales only polynomially with the size of the problem vs. exponentially for classical computers**, making large systems tractable. Polynomial time is much, much shorter than exponential time as *n*, the number of inputs or parameters to calculate (e.g., the number of electrons to include), increases. This relationship is illustrated below.

Exponential vs polynomial scaling



If the y-axis is how long it takes your program to run, and n is the number of inputs to your model, you want to use a method that scales polynomially (n, n^2) rather than exponentially (10^n)!

Source: Prime Movers Lab

Quantum chemistry: already mature

It's also important to remember that **exact solutions (i.e., quantum computers) aren't always needed to design new and better molecules.** Quantum chemistry is a mature field. Researchers routinely calculate important chemical properties — ground-state energies, molecular geometries or what a spectrum will look like — by using approximations. Many of the approximations do a pretty decent job; scientists can comfortably calculate the chemical properties of molecules with a few hundred atoms within hours or days on a supercomputer.

The pace of computer-assisted drug discovery has in fact been accelerating for decades. The advent of density functional theory (DFT) for modeling quantum systems in the 1990s allowed chemists to make much more accurate structure predictions. Looking forward, the continued increase in the computation power, and the dawn of distributed cloud-based computational resources, will give chemists and biochemists more powerful tools. Dozens of startups, armed with machine learning and artificial intelligence routines, are on the hunt for better candidates for pharmaceuticals, battery materials, and even low-carbon cement formulations. Many such algorithms are producing good hits without using quantum computers.

The most exciting problems for quantum computers to work on are the ones where the approximations for classical computers break down. Prime examples of these are molecules that contain metal atoms (which have many associated electrons) and materials with large shared-electron systems. Examples of important chemical and biological molecules that are difficult to simulate with classical systems include:

1) A DNA regulation enzyme **histone demethylase**, which helps switch genes on/off.

biotin and the avidin protein, which has been used for nanoscale drug delivery systems.

3) Biological nitrogen fixation by the enzyme **nitrogenase**, which converts nitrogen into two ammonia molecules under ambient conditions.

4) The N-chromophore photosynthetic complex, which plants use to efficiently convert sunlight and CO2 into organic molecules.

5) Materials showing high-temperature superconductivity, which would be useful for applications in energy and electronics.

In addition to predicting the behavior of molecules with many electrons, quantum computers will also increase performance in modeling parts of molecules where super-high accuracy is key. This is particularly important in drug discovery studies (e.g., calculating the binding affinity of drug active regions in different liquids and protein environments).

Putting quantum computing in perspective

To zoom out and put computer-based chemistry in perspective: The ability to use quantum computers to create new, improved molecules is only the first step in the process. Let's take the example of creating a vaccine for a new virus.

Scientists use a range of computational tools to create a new molecule to bind to the receptor proteins on the virus's surface, blocking it or tagging it for destruction. (Simulations like this are already used today, just with more approximate fits between the simulated molecules.) As we experienced in 2020, finding a great "in silico" molecule to block the receptor is just the beginning. Scientists then need to find a way to make it correctly and to keep it from falling apart. The company then needs to scale up production, ensure quality control, make sales, and secure distribution channels — likely many years of additional work. In the case of COVID-19, the tens of billions of public funds contributed, together with "warp-speed" production scale-up efforts, shortened this process to 15 months, a monumental feat.

This question of the value added by quantum computers vs the rest of the chemical discovery, scale-up, and commercialization process has big implications for the business models that quantum computing (and quantum computing software) companies can implement. Business models of selling hardware (less revenue), selling compute time on quantum computers (better), or quantum-computing-as-a-service are all possible but not equally good outcomes for quantum computing companies. Many instead hope to secure "profit-sharing" contracts similar to the relationship between 23andMe and GlaxoSmithKline, through which 23andMe receives 50% of the profits from any GlaxoSmithKline drug for a target identified using data from their health app. The value of the quantum computer and quantum software tools in creating the final product will certainly be the topic of heated discussions.

Tying quantum chemistry back to Sustainable Development Goals (SDGs), discovering new chemicals and routes to making others more sustainably will certainly be a boon to meeting multiple SDGs. For example, creating synthetic enzymes to make fertilizer could improve agricultural yields and crop nutrition (SDG 2, Zero Hunger). Faster, more precise drug discovery could help combat disease (SDG 3, Good Health and Well-Being).

My prediction is that we will experience the impact of quantum computers on drug discovery and medicine as a gradual improvement in patient outcomes, rather than a sharp step change. Cancer death rates have fallen by 31% in the past 30 years… in the next 30 years, a growing number of cancers will become a minor inconvenience. Quantum computers will further increase the number and the rate that new chemicals are discovered through "in silico" methods that have fantastic energy, industrial or agricultural applications. A word of caution is that these technologies will still face the same challenges and valleys of death that innovative companies see today. In a decade or two, quantum computers will give us the tools to answer previously unsolvable chemistry problems and will certainly lead to breakthrough discoveries. To fully take advantage of quantum computers, we need to apply them to the right problems, and also think critically about where the bottlenecks for breakthrough technologies are.

A Quantum Leap: Travel and Transportation

Erika Karp, Pathstone

"Quantum leap" has come to mean a major advance in achievement. Ironically, the phrase is derived from "quantum jump," a scientific term referring to an abrupt change in molecular or sub-molecular energy or state. In other words, a shift in the smallest possible amount—a quantum—has become slang for major change. This misperception shows how most of us simply can't fathom what "quantum" computing is, but it is also prescient given the potential power of quantum computing to produce solutions to the tremendous and complex environmental and social imperatives facing the world today.

The travel and transportation sector offers an excellent example of quantum computing's potential. It encompasses commercial shipping, air transport and trucking, as well as passenger transportation in all its forms. There is limited logistical connectivity across modes of transportation, and it's a major carbon emitter. Moreover, travel and transportation are hugely affected by weather, which is difficult to predict accurately despite many modern advances. In turn, unpredictable delivery timelines and arrival outcomes affect manufacturing output and human productivity. In this section of our report, we explore the applications of quantum computing for supply chain and logistics optimization as well as managing carbon emissions in this critical sector.

But first, the weather

The earth's atmosphere behaves in a chaotic way, with small changes holding the potential for big impacts – the so-called "butterfly effect." Our current capacity to predict the weather, a major factor influencing transportation and travel, uses approximations of approximations.

There will be a time in the not-so-distant future when meteorologists will gain a greater understanding and ability to model weather patterns, hurricanes, tornados, forest fires, and various extreme weather events. There will be quantum-inspired algorithms using massive amounts of data and variables to get us closer to true accuracy. It's exciting to consider what that will that mean for the travel and transportation industry. What will it mean for managing the logistics of air travel and related carbon emissions? What will it mean for automotive design and traffic congestion? And what will it mean for productivity when one's flight is not delayed, or cancelled, or circling the airport in a holding pattern?

Optimization opportunities

Private sector actors are leading the way in advancing quantum computing across industries. For example, **Microsoft** has developed Azure Quantum, an open ecosystem of quantum partners and technologies. Through Azure, enterprises will be able to create their own paths to scalable quantum computing by using open-source technologies.

In viewing problems of transportation and logistics through a quantum lens, Microsoft sees a profound impact on how goods, services, and people move through cities and around the world. They envision more sustainable cities where motor vehicles, bicycles, scooters, taxis, buses, and pedestrians are routed in the safest, most efficient ways in real time. Such optimized route guidance can minimize time idling in traffic, reduce fuel consumption, improve safety, and boost the ability of city planners to model the impact of major infrastructure projects like public transportation and road construction.

Microsoft also highlights fleet management for routing and scheduling deliveries for drop-off and installations. Currently, ships, trains, planes, and trucks are scheduled independently because calculations to solve for all the variables in the whole commercial transportation ecosystem not possible today. But companies need to prepare for the time when quantum computing does become widely available. An example of this effort is **Delta** partnering with the **IBM** Quantum Network to explore application development. This collaboration will allow Delta to explore potential transformational experiences for customers and employees.

Regarding the possibilities to improve ground transportation, **Ford** is leading the way in terms of investments and patents in navigation and control systems. They discuss the extent to which there can be advances in every field from robotics to aerodynamics. And in the context of building a more future-capable workforce, in the past few years Ford has brought in more than 3,000 employees with advanced computing, analytical and technical skills to help prepare and transform the company for leadership in all-electric SUVs, advanced connectivity technologies and new mobility solutions.

Supply chain optimization is also well suited for quantum. Optimizing resources and inventory levels with dependencies on suppliers from all over the world is crucial for efficient operations, scenario planning, capital allocation, disaster preparedness, and cash flow management.

Cutting CO2 emissions: exponential possibilities

Human activity puts about 36 gigatons of carbon into the atmosphere every year. Transport emissions account for more than 24% of that amount.

With even modest progress in the design and logistics associated with travel and transportation, we can see a dramatic impact on the progress towards a reduction in emissions and the impact of climate change. For example, in the U.S., where 29% of all emissions are from the transportation sector, there are many opportunities to deliver greenhouse gas reductions. Low-carbon fuels, new and improved vehicle technologies, strategies to reduce the number of vehicle-miles traveled, and more efficient vehicle operation are all approaches to reducing greenhouse gases from transportation.

Notably, the International Air Transport Association (IATA) recently announced a resolution to achieve net-zero carbon emissions by 2050. The airlines are seeking to build sustainability into "the ability to explore, learn, trade, build markets, appreciate cultures, and connect with people the world over," according to Willie Walsh, the IATA's Director General. In the global shipping industry, several leading names have launched the non-profit Maersk Mc-Kinney Moller Center for Zero Carbon Shipping, committed to driving development of new fuel types and systemic change to drive decarbonization in the sector.

The operational data and scenario analyses allowing for the decarbonization of supply chains can be dramatically enhanced by quantum computing. It will allow for the accelerated implementation of CO2 abatement by supporting sustainable aviation fuels, new aircraft technology, more efficient operations and infrastructure, and the development of new zero-emissions energy sources such as electric and hydrogen power.

The bottom line

The travel and transportation sector may be among those most demonstrably affected by the evolution of quantum computing. Even though we are still a way off from mainstream deployment, the evolution itself is showing promising impact. Challenges involving the level of complexity involved in this arena cannot be solved by the sequential problem-solving of classical computing. To tackle them we need lightning-fast, simultaneous/parallel processing of data. We need signals rather than noise. We need quantum computing.

Resources:

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https://news.delta.com/delta-partners-ibm-explore-quantum-computing-airline-industry-first
https://www.bloomberg.com/news/articles/2021-01-12/ibm-leads-in-quantum-computing-ford-in-driverless-car-patents
https://www.quantumcomputinginc.com/blog/quantum-computing-transportation/
https://www.climateaction.org/news/iata-approves-resolution-for-global-aviation-industry-to-achieve-net-zero-c?vgo_ee=N8bsKYJlCu%2Bim5Ex%2FuMrAFw4q%2F%2BB3Uh%2Bzdg3Wo4qv3Q%3D
https://azure.microsoft.com/mediahandler/files/resourcefiles/quantum-impact-transportation-logistics/Quantum%20impact%20-%20Transportation%20and%20logistics.pdf
https://www.epa.gov/transportation-air-pollution-and-climate-change/carbon-pollution-transportation#transportation
https://www.pnas.org/content/116/45/22413

The Path to Revolutionary Healthcare

Camilla Ozada, Dartmouth College Class of 2022

In this piece we focus on how quantum computing might change the face of healthcare and save millions of lives in the process. Three key areas stand out: diagnostic advancement, precision medicine, and drug discovery.

Diagnosis advancement

IBM has asserted that quantum computing could contribute to diagnostic assistance through early, accurate, and efficient diagnosis. Current diagnostic tools include medical imaging techniques, such as CT, MRI, and X-ray scans. The margin of error with those tools remains significant, with 5-20% of diagnostic results incorrect.[4] With the current technologies, traditional computing is approaching a plateau in its ability to help the healthcare industry. With the development of quantum computing, however, misdiagnoses can be avoided with greatly improved medical image analysis (including edge detection and image matching) and enhanced cell classification. Quantum computing can leverage its information systems to discover and characterize biomarkers which "may necessitate analysis of complex '-omics' datasets" (such as genomics, transcriptomics, proteomics, and metabolomics).[5]

Advancing diagnostic methods would create much-needed benefits for low-income countries, where on average there are just 0.3 physicians per 1,000 people[6] and only 0.7 hospital beds per 1,000 people. Upper middle-income countries have over five times that amount.[7] Better tools could alleviate pressure on both physicians and hospital resources by providing earlier and more reliable diagnoses, and by avoiding the need for additional diagnostic testing.

There are indirect knock-on effects that can help the most vulnerable communities as well. For example, during the COVID-19 pandemic, quantum computing assisted diagnostics might have eliminated the need for repetitive visits to healthcare sites, helping communities minimize their exposure to contagion. Historical accounts "clearly demonstrate that poverty, inequality, and social determinants of health create conditions for the transmission of infectious diseases."[8] Through quantum computing, diagnostic advancement doesn't present just an efficiency gain, but a chance to reduce global inequalities in the most vulnerable communities.

Precision medicine

Quantum simulation can help expand our understanding of molecular and sub-molecular interactions, leading to prospective breakthroughs in chemistry, biology, healthcare, and nanotechnology.[9] A great challenge in healthcare is accurately predicting molecular interactions with the limitless other factors involved in individualized

4 https://doi.org/10.1136/bmjqs-2012-001615
5 https://www.ibm.com/thoughtleadership/institute-business-value/report/quantum-healthcare
6 https://data.worldbank.org/indicator/SH.MED.PHYS.Z
7 https://data.worldbank.org/indicator/SH.MED.BEDS.ZS
8 https://doi.org/10.1089/bsp.2014.0032
9 https://research.aimultiple.com/quantum-computing-applications/

care. The degree of complexity and interdependency results in less precise medicine designed for each patient. Quantum computing could be the bridge towards optimized treatment effectiveness. This would be further enhanced when preceded by diagnostic advancements. It is predicted that both supervised and unsupervised quantum-enhanced machine learning techniques can aid granular risk predictions, ultimately benefiting patients through earlier and more accurate results. "Eventually, medical practitioners might even have the tools to understand how an individual's risk for any given condition changes over time."[10] This is revolutionary, as it immensely surpasses existing capabilities of traditional computing worldwide.

Medical professionals today try to assess optimal treatments for their patients based on self-reported symptoms, diagnoses (assumed to be from non-QC assisted processes), and historical data attached to medical conditions. As it currently stands, identifying the effectiveness of treatments based on historical outcomes is inaccurate given that medical care only has a relative contribution of 10-20% towards outcomes while health-related behaviors, socioeconomic status, and environmental factors account for the remaining 80-90%. This means that the industry must maximize its effectiveness of <20%, especially for patients subject to adverse environments. Experts compare existing medical diagnoses and treatments to "an umbrella diagnosis" that frequently fails. Applying QC to this field will replace the umbrella approach with precise medicine, thanks to insights from more extensive datasets and more complex analysis to match the plethora of contributing factors pertaining to an individual's health status.

Drug discovery

Accelerating research and development in drug discovery is a highly promising application for quantum computing as it enables investigations of disease effects on a molecular level. Pharmaceutical companies struggle to ascertain the exact molecular structure of most enzymes since they are complex and impossible for classical computers to model. Quantum computing can transform modeling and analysis to accurately predict the properties, structure, and reactivity of enzymes, contributing to the potential alleviation of the major diseases of our time. [11] Not to mention, this could be done in a matter of hours.

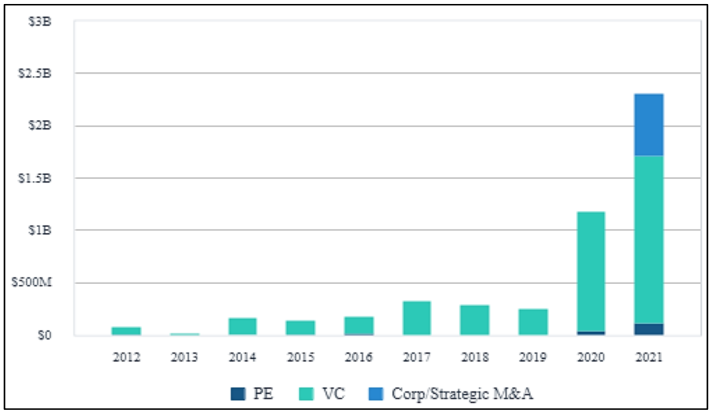
The dream of near instant computational drug design has never been achieved. Drug discovery is delayed by the inadequacy of even the fastest computers today, leaving it to trial and error in highly controlled labs around the world. The process of designing a vaccine, for instance, involves identifying the drivers of the disease and disease pathways in the body, screening millions of candidate activators, and extensive drug trial stages. This process is not only challenging and subject to several limitations in accuracy, but it can take years and costs pharmaceutical companies ~$2.7 billion to release one drug.[12] Cost minimization stemming from more efficient drug discovery processes could benefit consumers in the form of more affordable prescriptions worldwide, contributing to more equitable access to medicine.

[10] Exploring Quantum Computing Use Cases for Healthcare
[11] https://www.mckinsey.com/businessfunctions/mckinsey-digital/our-insights/a-game-plan-for-quantum-computing
[12] https://www.forbes.com/sites/matthewherper/2017/10/16/the-cost-of-developing-drugs-isinsane-a-paper-that-argued-otherwise-was-insanely-bad/

Is Quantum Computing Investable?

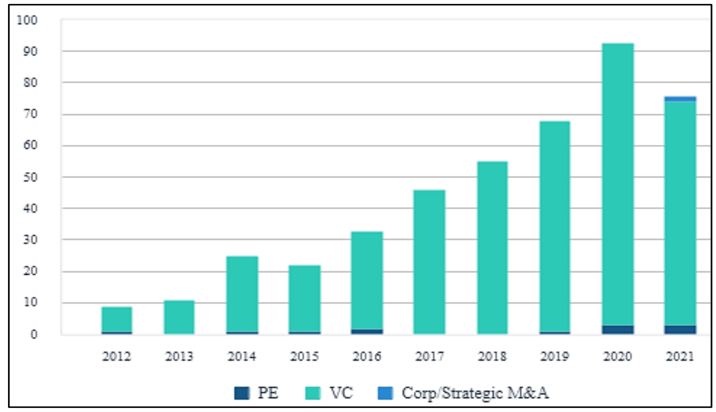
Alex Hart, AJ Levine, Pathstone

Capital raised for quantum investments, past ten years



Source: Pitchbook.

Number of quantum investment deals, past ten years



Source: Pitchbook.

The potential impacts of advancements in quantum computing are wide and far-reaching. Investors today must balance significant future impact and disruption potential against equally significant unknowns. While many investors might write off these unknowns as an unanalyzable future problem, others are doing to work to prepare for these changes. In this section of our paper, we will look at what opportunities are presenting themselves both today and in the future across public and private markets, as well as offer some thoughts on Pathstone's approach against this backdrop.

Investment opportunities may fall into two broad categories:

1) Investing in the technology and supply chain of the quantum computing industry

2) Investing in companies that are early adopters and users of quantum computing power.

The first category is an early but active opportunity, while the latter category will develop as the technology advances.

Public markets

In a seeming paradox, the investment landscape for quantum computing in the public markets is both narrow and broad. Opportunities for investments in public companies building quantum computing technologies (hardware or software) are generally limited to a few large companies today. However, thinking forward to the possibilities as quantum computing is commercialized, many companies across industries will face significant and potentially swift changes in the competitive landscape.

Most of the companies attempting to build and research quantum computers in the publicly traded markets are large, brand-name technology companies including Google, Amazon, Microsoft, IBM Honeywell, Baidu, and Alibaba, among others. While many of these companies are making significant capital investments in this segment of their business, it is not a driver of revenue for them today. Stock prices for these companies are likely more tied to revenue and expectations for their market-ready business segments, and as such the drivers of return for investors are not likely to be tied to quantum computing advancements in the near future.

There are two publicly traded pure play companies, Quantum Computing Inc. (QUBT) and IonQ (IONQ). The former has a market cap of less than $200m and has reported no revenues. The latter recently went public through the acquisition of a Special Purpose Acquisition Company (SPAC), and today trades at a valuation of more than $4 billion despite the expectation that they are years away from a competitive product.

There is clearly already excitement about the possibilities, and as the technology hurdles are cleared and these computers become scalable to solve real-world problems, we expect the opportunities to invest in public companies delivering value in this space could change rapidly.

Looking ahead, the implications for investors are much wider than just those companies involved in the production of quantum computers. We would expect many industries to become users of quantum computing power. Those that are first to adopt may benefit from significant competitive advantages, while those that lag may find themselves on their heels in a rapidly changing environment. We believe this type of change will present opportunities to thoughtful and engaged active managers.

Private markets

Within the private markets, the opportunity set is fast developing. Certain private market investors are accelerating the pace of change by actively investing in companies that are developing quantum-related technologies.

In the first nine months of 2021 alone, fundraising for quantum-related companies eclipsed the total activity over the prior three years in aggregate. There have been two $100m+ capital raises by companies developing quantum computing technologies. The volume and magnitude of deal activity, diverse nature of the active investors, and geographic dispersion of the deal making are all notable.

It is not surprising that the pace of deal making in the space has accelerated meaningfully over the past two calendar years. The earliest-stage bets that investors placed over half a decade ago are maturing and early winners are beginning to emerge. These emerging leaders are actively proving out the feasibility of quantum technologies across various applications, while simultaneously building the foundation on which many other solutions providers will operate.

The range of active investors is also notable. Given the advances made in the past five years or so, there are now select later-stage opportunities attracting large institutional investors. For example, in 2021 BlackRock led a $450m fundraising round for PsiQuantum. The round was closed at a $3.15 billion post-money valuation. Other large later-stage investors such as Tiger Global, SoftBank's Vision Fund II, and Baillie Gifford all participated in at least one quantum-related deal during the year. Corporate investors, e.g., Amazon Web Services, Airbus Ventures, and Samsung NextVentures, similarly ramped participation during the year.

Those select later-stage deals notwithstanding, much of the deal activity continues to be at the early-venture stage and involves significant technology risk. The relative nascency of the space currently affords investors a limited number of sizable opportunities. Accordingly, pure-play venture or private equity funds are few and far between.

While large investment firms and strategic corporations have made select investments at the large end of the market, state-owned or related enterprises continue to be the most prolific deal makers in the realm of quantum technology. According to data from Pitchbook, the top three most active investors include Innovate U.K., the U.S. National Science Foundation, and the U.S. Department of Defense. Each is a government-related entity. Other incubator programs trail close behind as the next most active set of investors. While the data available indicates that Western nations are leading the private investment charge, we recognize that much of the activity globally, particularly in nations such as China, is likely not captured in the datasets that we reviewed.

Pathstone's approach

While the impacts quantum computing are real and far reaching, the opportunities to invest directly in this space are nascent, though growing. Our approach broadly is to position our clients with investment managers who apply critical forward-thinking research in the selection of their investments and construction of portfolios. Conducting this primary research ourselves and drawing from expertise in the field better positions our due diligence team to evaluate how investment strategies might perform or adapt as this technology develops.

Within public equities this means we prefer active managers that research and evaluate trends and are able to quickly forecast and adapt to changing market dynamics. On the private investment side, where investment horizons are long, we continue to partner with managers who possess deep sectoral expertise and keen eyes for innovation, and who we believe have the foresight to understand potential disruption and prudently allocate to select opportunities in emerging themes.

Quantum Boosts for Sustainable Development

Jude Erondu, Pathstone

Quantum computers have the potential to accelerate the achievement of the 17 Sustainable Development Goals (SDGs) established by the United Nations. The SDGs, adopted by all UN member states in 2015, have become driving factors for initiatives and projects around the world. They provide "a common road map for the peace and prosperity of mankind and the earth now and in the future." Companies and political decisionmakers regard the SDGs as a framework and blueprint for achieving environmental protection and ensuring prosperity for all by 2030. Achieving the SDGs will require a holistic, sustainable approach.

Witold Kowalczyk, Global Channel Partnership Director for quantum computing firm Zapata Computing, has identified five SDGs that will be affected by the advent of quantum computing: [13]

- **SDG 2: Zero hunger** — More efficient nitrogen fixation to enhance food supplies
- **SDG 3: Good health and well-being** — Faster and cheaper drug development
- **SDG 6: Clean water and sanitation** — Enhanced water treatment capabilities
- **SDG 7: Affordable, clean energy** — Energy system optimization
- **SDG 13: Climate action** — Improved weather modeling and analysis

Other contributors to our report have cited the SDGs in the context of their sector-oriented discussions. As they highlight, both the private and public sectors are increasingly using the Goals as a reference point for their efforts. In this section, we look at the potential of QC from this "SDG perspective," and where relevant, provide additional promising use cases.

SDG 2: Zero hunger — More efficient nitrogen fixation to enhance food supplies

Achieving food security is more complicated than "just" eradicating hunger. The 2019 UN World Population Forecast report stated that the world population is expected to increase by 2 billion in the next 30 years, to 10 billion in 2050. According to the UN Food and Agriculture Organization, we must produce 60% more food by 2050 to feed this projected population.[14]

Further, even as conflict continues to displace people, disrupt livelihoods, and undermine economies, the COVID-19 pandemic and related containment measures have exacerbated and exposed the vulnerabilities and inequalities that are pervasive throughout local and global food systems. Economically vulnerable families have been hit particularly hard. In 2020, more than one-third of the world's population – around 2.4 billion people -- was affected by moderate or severe food insecurity, an increase of nearly 14% from 2019. In the worst cases, people went without food for one or more days. Sub-Saharan Africa saw the highest incidence of

[13] https://www.zapatacomputing.com/lets-make-quantum-computing-about-sustainability/

[14] https://www.un.org/en/chronicle/article/feeding-world-sustainably

food insecurity (56.8%), while Latin America and the Caribbean experienced the most rapid growth in food insecurity, with the percentage of the population at risk increasing from 25% in 2014 to 41% in 2020. The World Bank estimates that as the economic impact of COVID-19 worsens, the number of people suffering from severe hunger has increased. [15]

How can quantum computing help?

Traditional farming techniques may not be able to meet the growing demand for food, and the effort to do so will put excessive pressure on our natural resources. [16] This worrying situation requires that the food and agricultural sectors look for more effective and sustainable ways to meet these needs. Quantum computing may offer critical solutions. One specific example is achieving more efficient, less energy-intensive ways to produce fertilizer.

Currently, it takes one ton of fossil fuel to process nitrogen, a key soil nutrient, into enough nitrate for use in one ton of fertilizer. Although nitrogen, along with potassium and phosphorous, is essential to soil health, it can only be absorbed in the form of nitrate. This is currently achieved using an industrial technology called the HaberBosch process, which requires high heat and temperature to trigger the process of "fixing" nitrogen and accounts for 1-2.5% of global CO2 emissions annually.[17]

Quantum's tremendous computing power may well open the door to a more effective method of fixing nitrogen for use in fertilizer, by enabling biochemical experts to better decipher how the various stages of ammonia production work at the molecular level. [18] Such a development could have far-reaching social consequences. Most importantly, the less energy-intensive process yields cheaper compost, thereby reducing the cost of providing food. This is an important step in solving the global hunger problem in accordance with the UN's zero hunger goal.

SDG 3: Good health and well-being: Faster and cheaper drug development

The COVID-19 pandemic revealed deeply ingrained weaknesses in healthcare systems around the world. Lack of funding as well as insufficient drugs and equipment all left hospitals ill prepared for the outbreak. The pandemic also highlighted the critical connections between SDG 3 and other global goals such as SDG 8 (Decent Work & Economic Growth) and SDG 4 (Education). Further, the pandemic made painfully obvious the economic disparities across nations and communities; lack of access to quality care, medicines and medical supplies, and more recently to vaccines, in economically disadvantaged areas has led to greater mortality. [19] [20]

A 2017 Report of the World Health Organization states that "1 out of 10 circulating medical products in the lower and medium income countries is already lacking or counterfeit."[21] Substandard drugs "do nothing but prolong sickness, waste money and erode hope. At worst, they kill, cause serious harm, and fan the flames of drug resistance."

More recently, a report by the United Nations Office on Drugs and Crime notes that in March 2020, Interpol reported global seizures of counterfeit medical products related to COVID-19, including $14 million in counterfeit and substandard face masks. The report states, "Compared to an earlier operation in 2018, Interpol reported an increase of about 18% in seizures of unauthorized antiviral medication and a more than 100% increase in seizures of unauthorized chloroquine (an antimalarial), indicating a surge in substandard and falsified medical products and unauthorized medication circulating in the market that likely to be connected to the COVID-19 pandemic." [22]

How can quantum computing help?

As noted by contributor Carly Anderson, traditional drug discovery and development processes are complex and lengthy, with trial and error an accepted cost. Quantum computing allows for more in-depth research on complex,

[15] https://www.wfp.org/news/covid-19-will-double-number-people-facing-food-crises-unless-swift-action-taken
[16] https://www.pnas.org/content/104/33/13268
[17] https://www.bloombergquint.com/onweb/synthetic-fertilizer-ammonium-nitrate-makes-climate-change-worse
[18] https://sustainability.colostate.edu/humannature/cassidy-jackson/
[19] https://www.who.int/news/item/13-05-2020-people-living-longer-and-healthier-lives-but-covid-19-threatens-to-throw-progress-off-track
[20] https://doi.org/10.4269/ajtmh.20-0903
[21] https://www.who.int/news/item/28-11-2017-1-in-10-medical-products-in-developing-countries-is-substandard-or-falsified
[22] https://www.ctvnews.ca/health/coronavirus/interpol-121-arrests-made-over-counterfeit-covid-19-supplies-medications-1.4861432

multifactorial diseases that require adjustment of many targets. It should minimize the need for expensive and time-consuming in vitro testing. In the future, quantum computing may even enable end-to-end drug development within a chip. [23]

Quantum computers may not only help the world solve complex health problems, but also enable progress toward the aspect of SDG 3 that pertains to targeting drug research and development efforts toward "diseases that primarily affect developing countries," providing access to medicines for all."

As more effective drugs are more produced more efficiently, it becomes more profitable to distribute them widely, and to make them available within lower income communities across the globe. As this happens, the quality drug solutions should crowd out the ineffective and harmful imposters that are touted as medical solutions.

SDG 6: Clean water and sanitation — Enhanced water treatment capabilities

Sustainable Development Goal 6, "Ensure access to water and sanitation facilities for all," is important for long-term economic development. Clean water and sanitation are essential for improving diet, preventing disease, and promoting health care, as well as the normal operation of schools, workplaces, and political institutions, and the full integration of women, girls and vulnerable groups into society. [24]

Global water and sanitation problems affect hundreds of millions of people every day. Unsafe water and lack of access to basic sanitation facilities combine to cause extreme poverty.[25] As noted by the International Finance Corp in a 2020 report, cites alarming risks, including "(a) global warming, which has led to an increase in extreme floods and droughts, challenging the resilience of water and sanitation systems, (b) increasing number of people living in areas facing water stress (currently 2 billion), which increases supply vulnerabilities, (c) rapid urbanization, which strains existing water resources and ecosystems, (d) the emergence of megacities, which adds the challenge of extending water and sanitation services to about 1 billion people living in informal settlements not served by water grids, (e) aging infrastructure, which has increased pressure to accelerate investments in more advanced markets, following decades of underinvestment." Climate change continues to threaten the progress made in reducing the severity of the global water and sanitation crisis. [26]

How can quantum computing help?

Report contributor Matthew Sheldon offers potential applications for quantum computing in the water utilities space. In addition to the use cases he cites, advances in quantum computing and molecular simulations may increase global efforts and capabilities for effective water treatment. In terms of reverse osmosis water purification, quantum computers can promote the progress of membrane technology through quantum simulation. In addition, quantum computers could also accelerate the use of heterogeneous catalysts, which could directly convert toxic molecules within the water into nontoxic products, similar to how catalytic converters in cars transform pollutants from fuel combustion.[27]

SDG 7: Affordable and clean energy — Energy system optimization

"Energy poverty" affects both developing and industrialized countries. According to the G20's Energy Transition Working Group and Climate Sustainability Working Group,[28] energy poverty "occurs when households or territorial units cannot fulfill all of their domestic energy needs (lighting, cooking, heating, cooling, information-communication) as a result of lack of access to energy services, an inability to afford them, or their poor quality or unreliability …" Currently, millions of people endure extreme energy shortages, and suitable, cheap electricity is not available on an equitable basis. [29] In addition, global energy demand and consumption are

[23] https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6205278/
[24] https://www.who.int/life-course/partners/global-strategy/globalstrategyreport2016-2030-lowres.pdf
[25] http://www.fao.org/3/i7754e/i7754e.pdf
[26] https://www.ifc.org/wps/wcm/connect/126b1a18-23d9-46f3-beb7-047c20885bf6/The+Impact+of+COVID_Water&Sanitation_final_web.pdf?MOD=AJPERES&CVID=ncaG-hA
[27] https://doi.org/10.1021/acs.accounts.8b00642
[28] Executive Note for the G20 Energy Transition Working Group and the G20 Climate Sustainability Working Group *Energy Poverty: addressing the intersection of Sustainable Development Goal 7 (SDG7), development and resilience*,
[29] https://doi.org/10.1007/978-1-4615-5997-9_1

expected to increase, especially in countries with higher economic growth, such as India and China. [30]

SDG 7 aims to "universalize cheap, reliable and modern energy services" by 2030 along with improving the efficiency and technology of energy services. Achievement of SDG 7 would generate many health, economic, and climate benefits, improving the resilience of communities and economies in the face of health or climate disasters. Further, access to reliable and sustainable energy can improve irrigation, increase agricultural production and increase the productivity of local agriculture. [31] Farmers can ensure harvest value through refrigeration or increase profits through further processing,[32] and small businesses can enter new markets. [33] Ending global poverty begins with the elimination or resolution of energy poverty by investing in effective, efficient, and reliable renewable energy. [34]

How can quantum computing help?

The growing demand for energy has prompted business leaders and policymakers to rethink the complexity of the global energy system, which increases with its expansion.[35] For instance, the growth of distributed energy and the emergence of new load categories such as electric vehicles have exponentially increased the amount of data required for network maintenance, analysis, and optimization. This expansion also places additional requirements on the existing security and communications infrastructure.[36] The manufacture of efficient and reliable batteries for solar panels, which is essential for renewable energy sources such as solar energy, is another complex challenge that must be solved in order to end global energy poverty.

Quantum computers can help address these issues through the development of decentralized energy systems that are not too complex and are optimized to meet ever-increasing energy demand. Quantum computing is expected to be able to solve the complex challenges of optimizing power plants, large wind turbines, and dynamic heating, which require more robust solutions than those provided by today's analytical approaches. Similarly, quantum computers can help optimize energy networks that are comprised of thousands of distributed energy ("DER") systems, thereby increasing the vitality of energy systems. [37]

Energy security is another challenge that quantum computers can help solve. Quantum computers can be used to protect critical energy infrastructure from cyber threats. [38] Furthermore, quantum computation techniques could help develop new materials for better batteries, more efficient solar cells, and lighter and more efficient wind turbine blades, all of which will scale up the renewable energy production that is essential to closing global energy poverty gaps and achieving SDG 7, thereby "ensuring access to affordable, reliable, sustainable, and modern energy for all."[39]

SDG 13: Climate action — Improve weather modeling and analysis

Sustainable Development Goal 13 remains one of the most important SDGs because it calls for urgent global action to address the existential threats posed by climate change. [40] Climate change affects all aspects of human life, from agricultural production to health and safety. In fact, the U.S. government's March 2021 Interim Strategic National Security Guidelines identified climate change as a national security

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[30]. https://www.eia.gov/todayinenergy/detail.php?id=32912
[31] Ugo Bardi, Toufic El Asmar, and Alessandro Lavacchi. "Turning electricity into food: the role of renewable energy in the future of agriculture." Journal of Cleaner Production Volume 53, 15 August 2013, Pages 224-231. Accessed September 13, 2021. https://www.sciencedirect.com/science/article/abs/pii/S0959652613002291
[32] Duc Anh Dang and Hai Anh La. "Does electricity reliability matter? Evidence from rural Viet Nam." Energy Policy Volume 131, August 2019, Pages 399-409. Accessed September 13, 2021. https://www.sciencedirect.com/science/article/abs/pii/S030142151930285X
[33] Hemen Mark Butu, Benyoh Emmanuel Kigha Nsafon, Sang Wook Park, Jeung Soo Huh. "Leveraging community-based organizations and fintech to improve small-scale renewable energy financing in sub-Saharan Africa." Energy Research & Social Science Volume 73, March 2021, 101949. Accessed September 13, 2021. https://www.sciencedirect.com/science/article/pii/S2214629621000426
[34] Pye Steve, Dobbins Audrey, Baffert Claire, Brajkovic Jurica, Miglio Rocco, and Deane Paul. "Energy poverty and vulnerable consumers in the energy sector across the EU: analysis of policies and measures." Insight Observatory: Policy Report. May 2015. Accessed September 13, 2021. http://knjiznica.sabor.hr/pdf/E_publikacije/Energy_poverty_and_vulnerable_consumers_in_the_energy_sector_across_the_EU.pdf
[35] Aleh Cherp, Jessica Jewell, and Andreas Goldthau. "Governing Global Energy: Systems, Transitions, Complexity." Global Policy. January 5, 2011. Accessed September 14, 2021. https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1758-5899.2010.00059.x
[36] B. Gillessen, H. Heinrichs, J.-F. Hake, and H.-J. Allelein. "Natural gas as a bridge to sustainability: Infrastructure expansion regarding energy security and system transition." Applied Energy Volume 251, 1 October 2019, 113377. Accessed September 14, 2021. https://www.sciencedirect.com/science/article/abs/pii/S0306261919310517
[37]https://ieeexplore.ieee.org/abstract/document/9494203
[38] https://ieeexplore.ieee.org/abstract/document/6997535
[39] http://pure.iiasa.ac.at/id/eprint/14621/1/SDGs-interactions-7-clean-energy.pdf
[40] Myers, T. C. (2014) "Understanding Climate Change as an Existential Threat: Confronting Climate Denial as a Challenge to Climate Ethics", De Ethica, 1(1), pp. 53–70. Accessed September 13, 2021. https://de-ethica.com/article/view/1728

issue that will affect health, the economy, security, and the planet.[41]

According to the IPCC 2021 climate change report, "recent changes in the climate are widespread, rapid, and intensifying, and impacts are affecting every region on Earth, including the oceans. Many weather and climate extremes such as heatwaves, heavy rainfall, droughts, and tropical cyclones have become more frequent and severe." [42]

Global drought. Drought is expected to worsen in the next few decades, causing famine and hindering efforts to achieve SDG 2: "end global hunger by 2030".[43] It is becoming more common in vast sections of Africa, the Mediterranean region, portions of North and South America, and Southeast Asia.[44] Madagascar, for example, is on the edge of famine as a result of climate change, with the worst drought in decades threatening half a million children under the age of five. Countries that are susceptible to drought are less likely to meet their SDG targets by 2030 because drought will compound the severe hardships they already face. Their already struggling agrarian economies will remain weak without investments that introduce stability and decrease fragility.[45]

Heavy rain. Changes in climate can influence precipitation intensity and frequency. While some regions will suffer more drought, other regions will be impacted by higher rainfall. The warmer waters add moisture to the atmosphere, increasing the incidence of heavy rain and storms. In 2021 alone, heavy and frequent rainfall and hurricanes have flooded countries in Western Europe and the United States, wiping away livelihoods, causing death and creating billions of dollars in property damage. A combined study by the U.K. Meteorological Office and the Institute of Atmospheric Physics of the Chinese Academy of Sciences concluded that communities around the world could experience extreme precipitation as global temperature rises. Extreme precipitation would lead to flood risk, severely impact drinking water, sanitation systems, agriculture activities, and the hydroelectric power supply.

Heatwaves. Heatwaves are increasing in frequency and intensity, adversely impacting health by worsening droughts, and fueling forest fires worldwide.[46] The European Space Agency cites that "fire affects an estimated four million square kilometers of Earth's land each year and is responsible for releasing aerosols and greenhouse gases to the atmosphere." [47]

How can quantum computers help deal with the existential threats posed by climate change?

Hurricanes, heatwaves, and other extreme weather events sometimes miss the radar of metrologists. In order for metrologists to predict extreme weather events, a large amount of data needs to be analyzed, including variables such as temperature, density, and pressure. Today's classic computers are limited by their design and are prone to errors at moderate speeds.[48] Even traditional mainframe supercomputers are not fast enough to calculate the complex data used for weather modeling. [49]

Quantum computers will help meteorologists understand various weather patterns. After quantum computers are fully developed and deployed, traditional numerical techniques may be improved. [50] This can improve the tracking and prediction of weather conditions by effectively and quickly using the computing power of qubits and quantum-inspired optimization algorithms using a large amount of data with many variables. [51] Quantum machine learning can also be used to improve pattern recognition, which is important for understanding meteorological events.[52]

The ability to accurately predict various extreme weather events will help communities and governments proactively prepare to avoid loss of life and property related to weather

[41] https://www.whitehouse.gov/wp-content/uploads/2021/03/NSC-1v2.pdf
[42] https://unfccc.int/news/un-climate-change-welcomes-ipcc-s-summary-for-policy-makers-on-the-physical-science-basis-of-climate
[43] https://doi.org/10.3390/su10030622
[44] https://www.ipcc.ch/sr15/chapter/chapter-3/
[45] https://doi.org/10.1007/978-981-16-0902-2_6
[46] https://www.nationalacademies.org/based-on-science/global-warming-makes-heat-waves-hotter-longer-and-more-common
[47] https://climate.esa.int/de/news-events/multi-decade-global-fire-dataset-set-support-trend-analysis/
[48] https://ai4esp.org/files/AI4ESP1067_Kim_Grace2.pdf
[49] https://royalsocietypublishing.org/doi/10.1098/rsta.2020.0097
[50] Andreas Trabesinger. "Quantum leaps, bit by bit." Nature volume 543, pagesS2–S3. March 23, 2017. Accessed September 16, 2021. https://www.nature.com/articles/543S2a
[51] Marcelo C. Cardoso, Marco Silva, Marley M.B.R. Vellasco, and Edson Cataldo. "Quantum-Inspired Features and Parameter Optimization of Spiking Neural Networks for a Case Study from Atmospheric." Procedia Computer Science Volume 53, 2015, Pages 74-81. August 10, 2015. Accessed September 16, 2021. https://www.sciencedirect.com/science/article/pii/S1877050915017846
[52] https://www.energy.gov/sites/prod/files/2020/08/f77/OTT-Spotlight-Quantum-Information-Science-and-Technology.pdf

events such as flooding, droughts, hurricanes, heat waves, forest fires, etc.

Conclusion

The global community is on the verge of a technological revolution that will fundamentally change the way humans work, live, and communicate. The scope and complexity of this transformation will be different from anything humans have experienced in the past. As the world move more closer to the realization of the coming changes driven by advanced technologies, it is important to pay close attention to the revolutionary computing power that a quantum computer may soon deliver, and how this can help attain the 17 Sustainable Development Goals.

Quantum "Moonshots"

In January 2020 the World Economic Forum (WEF), in collaboration with PricewaterhouseCoopers (PwC), published "Unlocking Technology for the Global Goals." The report is part of their "Frontier 2030" initiative, intended to mobilize efforts to "apply advanced technologies" to achieving the SDGs. In addition to presenting a comprehensive set of existing solutions at a range of maturities, the report also highlights research under way on potentially transformative solutions, which it dubs "moonshots" — see below. The WEF provides ongoing research and analysis into quantum computing and offers useful insights to track.

Source: World Economic Forum, PwC.

Report Contributors

Erika Karp is Executive Managing Director and Chief Impact Officer at Pathstone. Erika's mission is to bring the disciplines of finance, economics, and sustainability to bear in pursuit of a more regenerative and inclusive form of capitalism. Over the course of her 25-plus years on Wall Street, she developed a deep belief in environmental, social, and governance (ESG) analysis as a critical input to investment decision-making. Before joining Pathstone, Erika was CEO of Cornerstone Capital Group, the impact investment advisory firm she founded in 2013. Cornerstone joined forces with Pathstone in March 2021.

Mark Peters, CFA, is a Managing Director of Pathstone. Mark brings more than twenty-five years of experience to his work designing, implementing and managing investment portfolios for high net worth individuals and their families, and for investment committees of charitable foundation clients. He is a voting member of Pathstone's Investment Committee and a partner of the firm. Mark is also the Chair of the Impact Committee and a member of the Alternatives and Strategy Investment Subcommittees.

John Workman is a Managing Director of Pathstone. As a member of the firm's Chief Investment Office and Investment Committee, John is responsible for charting the strategic direction of Pathstone's client investment portfolios. John's twenty-plus years of experience has groomed him for a hybrid role that encompasses both client and portfolio management responsibilities as well as leadership of the research team's investment strategy efforts. He serves as the lead investment consultant for several of Pathstone's largest clients, providing highly customized asset management solutions for individuals, families, and foundations.

Jude Erondu is an Analyst on the Client Advisory team with a primary focus on ESG and Impact solutions. Jude supports the Impact Committee with investment and impact research and analysis, client meetings and relevant deliverables. Jude is also responsible for assisting with thought leadership programs with relation to Impact and ESG.

Eric Hsueh, CAIA, is an Associate Director at Pathstone. He has deep experience in manager due diligence and portfolio construction. Before joining Pathstone, Eric was a Director, Manager Research, at Cornerstone Capital Group. He led the firm's manager research activities and provided analytical support for portfolio allocations on behalf of clients.

Heng Yang is Associate Director at Pathstone. He has more than 10 years of quantitative data management and analytics experience and brings deep knowledge of financial metrics and analysis, particularly as applied to the alternative investment space

Garvin Jabusch is Co-Founder and Chief Investment Officer for Green Alpha Advisors, where he leads investment research; conducts macroeconomic, scientific, and technological analysis; and develops and communicates the Next Economy investment approach.

Jalak Jobanputra is Founding Partner of Future\Perfect Ventures, an early-stage venture capital fund investing in decentralized technology. FPV's portfolio includes Abra, Blockstream, Bitpesa, FuseMachines, Everledger and Blockchain. Jalak was awarded Institutional Investor's Most Powerful Fintech Dealmakers from 2016-2018. In May 2018, Jobanputra was awarded Microsoft's VC Trailblazer Award for "her early and bold" investments in the sector. She has been listed as a 100 Most Influential Fintech Leader of 2016 and 2017 based on her investment strategy at FPV. In 2017, she was cited as a "Top 5 Investor Powering the Blockchain Boom" and Crunchbase noted FPV as one of the top VC funds in blockchain "before it was cool"

Matt Sheldon is Senior Portfolio Manager at KBI Global Investors. He is responsible for the development of investment strategy as well as the day-to-day management of the Water strategy. Matt joined the Water team in April 2011. He has extensive specialist knowledge and experience in investing in the water sector, including both global public listed equities and private equity.

Carly Anderson is Principal Chemical Engineer and Partner for Prime Movers Lab. As a chemical engineer, she performs in-depth due diligence into potential investments across areas including nuclear, solar, energy storage, water, agriculture, synthetic biology, and materials. She also supports portfolio companies in evaluating and overcoming key process design, scalability and implementation challenges. Carly has supported new technologies through fundamental research, prototyping, and techno-economic assessments for applications across the energy, materials, industrial chemicals, bioproducts, and water treatment spaces

Alex Hart, CFA, CAIA, is the Executive Managing Director of Investment Research for Pathstone. His responsibilities include overseeing Pathstone's investment research team, the selection and due diligence of investment strategies for the firm's clients, and portfolio management duties. Alex is a member of the firm's Chief Investment Office and a voting member of the Investment Committee. He also serves on the firm's Impact Committee.

AJ Levine is a Senior Analyst at Pathstone. He conducts due diligence on prospective managers and actively covers recommended and legacy strategies for the firm. AJ currently covers private market investment strategies such as private equity, venture capital, private credit, and private real estate. He is also responsible for covering ESG and Impact-related private market opportunities and serves on Pathstone's Impact Committee.

Camilla Ozada is a senior at Dartmouth College, originally from Cyprus. She is double majoring in Economics and Middle Eastern Studies and aims to explore finance through the diverse spaces of crypto, and ESG/CSR work. The positive and global impact of transformative money excites her. This passion has developed further through interning with the UN Foundation, Brian Kelly Capital Management, and most recently Fidelity Digital Assets.

Disclosures