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Guide to Advanced and Quantum Computing

How to Use This Guide

This guide is geared toward helping organizations to start asking the right questions when deciding on how to pursue advanced and quantum computing opportunities. Following an introduction to some of 1QBit's advanced and quantum computing experts, the guide will walk readers through recent trends and predictions for quantum computing. The guide concludes with high-level tips on becoming quantum ready now and in the future.

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Explanations of common misconceptions that could lead to improper understanding.

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Some of 1QBit's Over 100 Advanced and Quantum Computing Experts

Arman Zaribafiyan – Head, Quantum Computing

Arman leads an interdisciplinary team of researchers and software developers who are exploring the applications of quantum computing in solving computationally challenging industry problems. As the Head of Quantum Simulation at 1QBit, he has led several research and development client engagements with Fortune 500 companies that include Dow Chemicals, Biogen, and Accenture as well as collaborations and partnerships with Microsoft, IBM, and other quantum computing hardware manufacturers.

Pooya Ronagh – Head, Hardware Innovation Lab

Pooya is a Postdoctoral Fellow of the Institute for Quantum Computing and the Department of Physics and Astronomy at the University of Waterloo. He is an Associate Researcher at the Perimeter Institute for Theoretical Physics. His research is focused on the synergy between mathematical programming, machine learning, and quantum computation. Pooya is trained as an algebraic geometer and a theoretical computer scientist. He holds a Bachelor of Science degree in Computer Science and Mathematics from Sharif University of Technology, a Master of Science degree from the University of Pennsylvania, and a PhD in mathematics from University of British Columbia.

Jaspreet Oberoi – Director, Machine Learning and Quantum-Inspired Optimization

Jas has an honours bachelor's degree in Electronics and Communication Engineering from Thapar University. For his master's degree in Applied Sciences at Simon Fraser University, he developed optimization techniques in diverse communication engineering paradigms. Jas is currently a PhD researcher in the Engineering Science department at Simon Fraser University.

Herman Ho – Head, 1Qloud

Herman is responsible for the 1Qloud platform, which enables companies to create novel solutions to difficult problems in the world without the need to own a physical quantum computer. He studied biology and computer science at the University of Toronto. From there Herman worked in various startups and larger companies as a software developer until he joined the exciting world of investment banking in Hong Kong as a software developer specializing in high frequency algorithmic trading in equities technology. In a twist of fate he moved back to Canada this time in Vancouver entranced by the mountains and sea.

Some of 1QBit's Over 100 Advanced and Quantum Computing Experts

Takeshi Yamazaki – Materials Science Lead

Takeshi obtained his PhD in Computational Chemistry from the Institute for Molecular Sciences and the Graduate University for Advanced Studies in Japan, where he studied electronic structure theory to describe solvent-mediated chemical processes. Before joining 1QBit, he was engaged in the multiscale modelling project targeting self-assembled organic nanotube systems at the National Institute for Nanotechnology in Edmonton, and in the computer-aided drug discovery project for cancer-related biological targets at the Vancouver Prostate Centre.

Maritza Hernandez – Lead Scientist

Maritza obtained her PhD in Quantum Optics from the Pontificia Universidad Católica de Chile. Before joining 1QBit, Maritza held a postdoctoral fellowship at the University of British Columbia where she performed research on the dynamics of central spin systems and their quantum correlations.

Maliheh Aramon – Optimization Lead

Maliheh completed her PhD in Operations Research at the University of Toronto. Her research focus was on optimization under uncertainty and the probabilistic analysis of systems in the application area of engineering asset management. She works on developing new tools for improving the performance of quantum computing and on hybrid optimization algorithms to combine the strengths of quantum and classical computation.

Erika Lloyd – Quantum Algorithms Researcher

Erika recently joined 1QBit in the Quantum Simulation Division. She was previously a quantum algorithms researcher at a quantum computing start-up called Cambridge Quantum Computing (CQC), where she explored different aspects of quantum algorithms on near-term devices, especially as they pertain to quantum machine learning applications.

Some of 1QBit's Over 100 Advanced and Quantum Computing Experts

Elisabetta Valiante – Computational Physicist

Elisabetta obtained her PhD from Ludwig Maximilian University of Munich after working on the observation and modelling of high-redshift galaxies' evolution at the Max Planck Institute for Extraterrestrial Physics. She followed astronomy with postdoctoral appointments at the University of British Columbia and Cardiff University. She works on optimization problems using both quantum and classical quantum-inspired solutions.

Ehsan Zahedinejad – Customer Solutions Lead

Ehsan holds a PhD in physics, with a focus on quantum information processing, in which he developed his expertise. His PhD thesis was on devising machine learning algorithms for the design of quantum logic gates.

Yukio Kawashima – Computational Chemist

Yukio received his PhD in theoretical chemistry and a BA in applied chemistry from the University of Tokyo. Before joining 1QBit, he enjoyed research in the field of theoretical chemistry at the Institute for Molecular Science, Nagoya University, Kyushu University, Yokohama City University, and RIKEN Advanced Institute for Computational Science.

Ugur Yildiz – Operations Research Scientist

Ugur obtained his undergraduate and master's degrees in Industrial Engineering from TOBB University of Economics and Technology in Turkey. During his PhD, he studied data-driven large-scale optimization at the University of Waterloo. He currently focuses on harnessing the power of quantum computing to solve real-life problems faster.

Krishanu Sankar – Researcher

Krishanu is a Postdoctoral Fellow in the Department of Mathematics at the University of British Columbia. He received his BS in mathematics from the Massachusetts Institute of Technology, and his PhD in mathematics from Harvard University under the supervision of M. Hopkins.

Valentin Senicourt – HPC Researcher

Valentin obtained his master's degree in Scientific Computing and HPC from USTL, in France. Since then, he has been developing and accelerating scientific applications in industry and academia. He is currently part of the Quantum Simulation Team, focusing on developing and accelerating both quantum and classical software.

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Recent Trends

"In 2012, I proposed the term 'quantum supremacy' to describe the point where quantum computers can do things that classical computers can't, regardless of whether those tasks are useful. With that new term, I wanted to emphasize that this is a privileged time in the history of our planet, when information technologies based on principles of quantum physics are ascendant."

—John Preskill, Physicist

A Milestone on the Road to Quantum Computing Devices of Practical Use

Google's quantum computing announcement

In 2012, John Preskill coined the term "quantum supremacy" to describe the point in time when a quantum computer could perform a task that a classical computer could not. The journal *Nature* (vol. 574) reported the results of a large flagship program, conducted by Google over several years, to demonstrate quantum supremacy in performing a specific computational task, achieved using 53 qubits. Prior to this, a quantum computer had never demonstrated a clear advantage over the most-powerful classical computers.

How will Google's announcement impact industry?

For the moment, this development is a strong indicator that quantum computers are on the horizon and the field is no longer in the realm of science fiction. It is likely, however, that quantum devices that will be used for production workloads are still several years out. Even with several hundred physical qubits, without the development of fault-tolerant quantum computation, quantum computers will be of limited utility in most industrial use cases.

It is important to note that the computational task used in the experiment was chosen for the very reason that it could demonstrate quantum supremacy. Whereas there may not be industrial applications for Google's device, it is useful in generating random numbers.

TECHNICAL DETAIL – BEHIND GOOGLE'S CLAIM

The problem chosen to demonstrate quantum supremacy is called "random circuit sampling". It works (roughly) as follows:

1. A family of quantum circuits programmable on a given quantum computer is selected.
2. From this family, random circuits are repeatedly selected and run.
3. This process is simulated on a classical computer to verify the results.
4. A quantum computer that has a greater number of qubits is selected and the process is repeated.

Eventually, for this sampling task, the experiment will reach a number of qubits beyond the simulation capabilities of the most-powerful classical computer.

2019 Saw Improved Quantum Hardware Become Available through the Cloud

A 53-qubit device on the cloud

IBM opened the Quantum Computation Center in September of 2019, making its fleet of quantum devices available through the cloud. The devices range in size from 5 to 53 qubits.

IBM's quantum devices have been available through the cloud since 2016, yet this announcement demonstrates that there is increasing investment in dedicated quantum facilities to support a growing user base.

POTENTIAL PITFALL

Care should be taken when evaluating the capabilities of different types of quantum hardware—simply comparing the raw numbers of qubits presents a flawed picture of the relative effectiveness of a given machine.

The overall "power" of a quantum device is a combination of how long it can maintain a quantum state (the coherence time), how consistently operations can be performed (the gate fidelity), the speed at which those operations can be performed, and the particular problems that can be translated into a form suitable for its particular architecture.

Improved ion trap devices

Hardware startup IonQ published a paper showing that its ion trap technology device was able to execute quantum logic gates reliably. Honeywell also announced its own ion trap quantum computing effort.

TECHNICAL DETAIL – CREATING A QUBIT

There are many ways to make a qubit.

Google and IBM are developing superconducting qubits, while IonQ and Honeywell are developing ion trap qubits.
To make a qubit, there must be a way to represent a two-dimensional Hilbert space. One dimension represents the state "zero" and the other represents the state "one". Superconducting qubits represent states by using the first two levels of a quantized property of a superconducting nanowire. Ion trap systems electromagnetically trap ions of atoms such as Ytterbium using motional ground states and the hyperfine sub-levels to encode qubits. Other implementations of qubits are done via quantum dots, vacancy centres, and photons. Each of these technologies has advantages and challenges for usage in quantum information processing.

Hardware players teamed up with cloud providers

Honeywell, IonQ, and QCI partnered with Microsoft, making quantum hardware accessible through Azure Quantum. IonQ, Rigetti Computing, and D-Wave Systems were announced as hardware partners with AWS Braket.

Searching for Quantum Speedups

How fast can we go?

For which tasks is quantum computation faster than classical computation? Super-polynomial (e.g., exponential) quantum speedups have been achieved only for certain *structured* problems. Researchers have been searching for a general theory for determining for which problems such speedups are (and are not) possible.

What is meant by "structure"?

Shor's algorithm is a quantum algorithm for integer factorization that uses structure—it relies on finding periods in sequences of integers, and knowing such periods in fact exist. The mere existence of a period makes the problem "structured". Grover's search algorithm, however, makes no use of such a premise. Shor's algorithm shows super-polynomial quantum speedup compared to classical competitors, while Grover's offers only a quadratic (polynomial) quantum speedup.

A decade of waiting

Scott Aaronson and Andris Ambainis's 2009 paper "The Need for Structure in Quantum Speedups" presented an important conjecture: for *unstructured* problems, quantum computing can offer, at most, a polynomial speedup. A decade later, Nathan Keller and Ohad Klein's "Quantum speedups need structure" proved this conjecture.

Moving forward

It is important to note that achieving even polynomial speedups is extremely valuable. Indeed, classical polynomial speedups have shaped how many industries operate today. The speedup of fast Fourier transforms over discrete Fourier transforms is one such example. Another is seen with algorithms used for matrix completion (e.g., in recommendation systems; cf. the *Netflix Prize*). Keller and Klein's result is crucial. It enables the R&D community to set realistic goals and prevent the pursuit of exponential speedups where none are possible. Instead, it encourages the development of algorithms of practical use.

TECHNICAL DETAIL

The term "quantum speedup" describes how much faster the runtime of a quantum algorithm scales compared to classical ones solving the same problem.

Quadratic quantum speedup — example of a polynomial speedup: if a quantum algorithm takes n seconds to run on an input of size n, and its classical counterpart takes n^2 seconds, then, on an input of size 1000 the quantum algorithm will take ~16 minutes, whereas the classical one will take ~12 days..

Exponential quantum speedup — example of a super-polynomial speedup: if a quantum algorithm takes n seconds to run on an input of size n, and its classical competitor takes 2^n seconds, then, if $n = 10$, the quantum algorithm will take 10 seconds to run but the classical one will take ~17 minutes. Now, if $n = 60$, the quantum algorithm will take about a minute, whereas the classical algorithm would take over 36 billion years.

Other Advances Are Powering Improvements in Near-Term Devices

Bravyi–Gosset–Koenig and shallow circuit speedups

It is often extremely challenging to rigorously prove separations between computational-complexity classes. Indeed, the technology industry has thus far not ruled out the existence of classical algorithms comparable to quantum computers in solving the problems of integer factorization and the simulation of quantum systems.

In October of 2018, the journal *Science* (vol. 362) published a paper by Sergei Bravyi, David Gosset, and Robert Koenig that shows an unconditional separation between the power of quantum and classical circuits. The researchers considered *shallow circuits*—those with few layers of gates, where the gates in each layer do not involve common qubits and hence can be performed in parallel. They found an explicit family of problems that can be solved with a quantum circuit of constant depth, whereas any classical circuit solving this problem with a sufficiently small rate of failure must have depth that scales logarithmically with problem size.

Although their proof is based on the study of a specifically crafted theoretical problem, the conditions considered for the quantum computer (constant depth and nearest-neighbour interactions) are quite compatible with today's quantum computers.

This discovery has sparked a wave of new studies dedicated to furthering our understanding of today's limited quantum computers and, perhaps, their practical application.

Benchmarking ion traps with IonQ

IonQ's 2019 paper in *Nature Communications*, "Benchmarking an 11-qubit quantum computer", showcased the performance of the IonQ system. This was the first demonstration of quantum algorithms (the Bernstein–Vazirani and hidden shift algorithms) with acceptable success rates with 11 qubits.

Trapped ions have the highest fidelities of any qubit technology, but their absolute gate speeds are much slower than those of some other types of qubits. High-fidelity, two-qubit gates for trapped ions have been shown that are as fast as about a microsecond, but two-qubit gates in superconducting qubits take tens of nanoseconds.

Of course, this increase in accuracy has a trade-off, in this case a slowdown of one order of magnitude in the speed of the operation (on the order of microseconds versus nanoseconds on a superconducting device), another important factor in determining the usefulness of a quantum device.

Predictions

"We don't yet have the quantum computing version of the transistor—that would be quantum error correction. Getting there will surely require immense engineering, and probably further insights as well. In the meantime, though, the significance of Google's quantum supremacy demonstration is this: after a quarter century of effort, we are now, finally, in the early vacuum tube era of quantum computing."

—Scott Aaronson, Computer Scientist

Hybrid Quantum–Classical Algorithms Will Make the Most of Near-Term Devices

Near-term quantum devices will remain noisy

The devices being built during this early era of quantum hardware have been collectively dubbed “noisy, intermediate-scale quantum” (NISQ) devices by John Preskill. The term “noisy” refers to the errors introduced over time in performing experiments on qubits. These errors compound, adding statistical inconsistency in experimentation. If left unchecked, the noise can overwhelm a calculation entirely, rendering results useless. Thus, to use NISQ devices, calculations must be kept manageable.

Limitations of NISQ devices present challenges for circuit design

When designing quantum circuits, the limitations of NISQ hardware present several constraints. If a circuit is too deep, there is a greater chance for undesired events to affect the quantum state used in a computation.

How, then, should shallow, noisy circuits be used? By combining a quantum circuit with a classical optimizer, the parameters can be tweaked each time the circuit is run and the effects on the results can be observed. At first, the results will tend to swing wildly. As the selected parameter configuration, the results will (ideally) converge to a consistent value, which, if the experiment has been set up correctly, will provide the desired solution.

An experiment typically consists of at least 1000 runs, with the possible outcomes being plotted to show how often each one occurred. This data allows statistical inferences to be made about the accuracy of the results, helping to further refine calculations.

Hybrid quantum–classical architectures are increasingly common

Hybrid architectures configured to support variational algorithms are often made available through the cloud with a variety of open source packages, such as Microsoft’s QDK and IBM’s Qiskit. The amount of documentation and educational material rendering these platforms more accessible for industry, academia, and for more technically inclined members of the general public is also increasing.

STRATEGIC IMPLICATION

Taking advantage of near-term quantum devices will require a tightly integrated classical infrastructure in order to work around limitations.

STRATEGIC IMPLICATION

One type of quantum computation in need of immediate investigation is variational quantum algorithms. Barring any near-future, step-change advances, these algorithms will constitute the primary near-term use for quantum devices.

Quantum Computing as a Service on the Cloud

Quantum devices are well-suited for cloud access

Like many specialized hardware devices, quantum computers require extensive investments of capital in both hardware and R&D, making them impractical as part of on-premise infrastructure for any organization that does not have a strategic interest in the technology and the budget to explore it.

To operate a quantum device, a great deal of tuning and tweaking must happen at the hardware level. Superconducting qubits require expensive dilution refrigerators, ion traps need roomfuls of expensive control hardware with extremely low manufacturing tolerances, and optics and photonics are incredibly delicate, often requiring bulky setups in addition to being very sensitive to vibrations or other environmental interference.

The major cloud providers have long offered access to commodity hardware resources and also more-advanced, special-purpose hardware. Quantum computers being made available alongside existing cloud infrastructure is a natural extension of this framework, and should be the source of many developments in 2020.

Since D-Wave Systems and Rigetti Computing pioneered access to quantum devices over the cloud, major cloud providers have been showing increasing interest in the space, often following the model established by these players and releasing open source software packages to support and extend the quantum devices themselves.

The recent trend, however, is for quantum hardware manufacturers to partner with existing cloud providers. Evidence for this includes the Q4 2019 announcements of Azure Quantum, AWS Braket, and others.

Increased Public Investments in Quantum Technologies Are Expected

A recap of recent government investments

- In the United States, the National Quantum Initiative Act, passed in late December 2018, is devoting more than $1.5 USD billion over five years to support quantum computing research and development.
- China has invested $10 billion in the National Laboratory for Quantum Information Science.
- The UK National Quantum Technologies program is investing EUR 270 million into the development and commercialization of quantum technologies.
- Canadian provincial governments expanded commitment to advancing quantum computing with the announcement of the Quantum Algorithms Institute in British Columbia, and the opening of a new 1QBit office in Sherbrooke in collaboration with Institut Quantique.

Increased investment is leading to growing quantum computing ecosystems

Quantum computing ecosystems in North America, Asia, and Europe are strengthening due to public–private partnerships, investments in education, and strategic commitments from national and subnational governments.

STRATEGIC IMPLICATION

The quantum computing industry is truly global. Thriving partnerships are helping to create innovative solutions by bridging the gaps between hardware manufacturers, researchers, and software companies looking for a competitive edge.

Quantum computing has a long way to go

A variety of hardware architectures are competing for market leadership, from the creation of superconducting devices and ion trap devices to more-exotic options that use individual atoms, electrons within small molecules, or photons as qubits. Not to be ignored is quantum annealing with improved technological advancements announced by D-Wave Systems.

While gate devices created by IBM, Google, and IonQ are currently the preeminent type of architecture, the race has by no means been decided.

Innovative Alternative Computing Architectures Show Great Promise

CPUs are hitting a computational plateau

As transistors become small enough to bump up against the limits of quantum mechanics, advancements are still being made in classical hardware and other alternative computing methods. While classical high-performance computing hardware will continue to improve, new architectures (including application-specific hardware) present additional opportunities for enhanced performance.

New architectures show potential as specialized hardware

- **Silicon photonics** have the potential to provide extremely fast and very power-efficient classical calculations; these will likely be application specific so as to strike a balance between performance and programmability.
- **Memristor-based Hopfield neural networks** are early-stage electronic devices proposed by Hewlett Packard Enterprise that use a process similar to quantum annealing to solve problems; these machines have shown promise as low-power-consumption computers.
- The **coherent Ising machine** "LASOLV" built by NTT is a quantum photonics mechanism, leveraging laser pulses and built on a fibre-optic system, in which the control pulses are manipulated to perform classical calculations.

STRATEGIC IMPLICATION

There are a great many advanced hardware options available. Finding the right fit can take time, so space should be made in R&D budgets for the targeted exploration of promising technologies.

Quantum-inspired hardware is a twist on classical computing

Improvements in classical and quantum computing technology are occurring in parallel. In fact, a subset of recent innovations has come about as a result of new quantum solutions inspiring fresh classical approaches to certain problems.

- Hitachi developed **simulated quantum annealing** using FPGAs (field-programmable gate arrays), performing a process similar to quantum annealing but using entirely classical hardware.
- The Fujitsu **Digital Annealer** solves similar problems to state-of-the-art quantum annealers, also using entirely classical hardware, and achieves comparable results but with less-complex manufacturing requirements.

Becoming Quantum Ready

"Sometimes the public says, 'What's in it for Numero Uno? Am I going to get better television reception? Am I going to get better Internet reception?' Well, in some sense, yeah. ... All the wonders of quantum physics were learned basically from looking at atom-smasher technology. ... But let me let you in on a secret: We physicists are not driven to do this because of better colour television. ... That's a spin-off. We do this because we want to understand our role and our place in the universe."

*—Michio Kaku, **Physicist***

Planning for a Quantum-Enabled Future

Quantum computers are not ready—yet

Despite the staggering advances in quantum technology in recent years, quantum devices are yet to provide immediate value over existing classical solutions. However, the signposts from the past couple years indicate that the creation of general-purpose quantum computer is a realistic goal.

In the interim, companies should focus on using quantum algorithms on advanced computing devices with a lens on the following:

1. Having **a real-world mindset** is crucial for cutting through hype and being realistic about the implications of a given technological innovation. Organizations should look to the companies that have invested the most in learning the intricacies of how to derive practical value with quantum computing technologies in order to educate their R&D teams.
2. **Problem identification** helps target those computational workloads within an organization that are the most viable for leveraging quantum algorithms on advanced computing devices. Companies should build a framework that can translate quantum capabilities into specific use cases.
3. **Value-driven approaches** for assessing use cases can help ensure a fine focus on applications that are worthy of investment. Companies should be specific about the cost and criticality of workloads, and ensure the potential speedups achieved using quantum devices make a use case worthy of investment.

Having clarity about business goals and value is vital

Through quantum algorithms implemented on classical computers, companies can attain a solid understanding of the types of practical problems that are solvable using quantum computing hardware. This perspective will alleviate fears that the technology is merely a passing fad by motivating companies by presenting them with a solid picture of where the potential value of a given approach or technology may lie.

To recap:

- Becoming overly concerned with the specifics of new technology should be avoided, with a focus instead placed on potential short- and long-term business value.
- It is important to understand that solutions based on advanced and quantum hardware will likely be domain specific in the near term.
- Technology projections from the quantum computing industry should be validated against business needs before investing in a solution.

Why Do These Trends & Developments Matter?

We are on a real journey to quantum computing

Recent developments have accentuated the fact that quantum computing will be a viable computing option in the future. The improvements in advanced classical and near-term quantum computing technologies have laid a solid foundation for experimentation, early business impact, and continued innovation.

In the next few years, it will be imperative to have realistic expectations for what technology can deliver. It will be important to not overpromise and under deliver to end-customers just to be seen as a “leader” in leveraging new technology. This occurred with AI, and it is even more critical to be careful of this trap with quantum computing. However, do not let this prevent cloud-based experimentation in the near future.

As demonstrated by recent momentum, there will likely be plenty of strategic opportunities for organizations to begin building practical plans for short and long-term implementation of computing advances by leveraging new cloud-based services.

Where to go from here—the value of the 1QBit blog

As we are in the early days of a new computing era, collaboration and knowledge-sharing will be a vital element of our collective success. The 1QBit blog will aim to be an extension of corporations, academic institutions, healthcare providers, and governments in providing up-to-date and informative articles as the path to quantum computing continues to take shape.

The blog will feature bi-weekly publications illuminating advanced and quantum computing developments and their industry impact.

For many organizations, the next couple of years may be too early to invest in hiring a dedicated quantum computing team. The 1QBit blog can provide high-value and digestible reading during this interim phase.

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