Microsoft

Quantum impact: **Optimization solutions**

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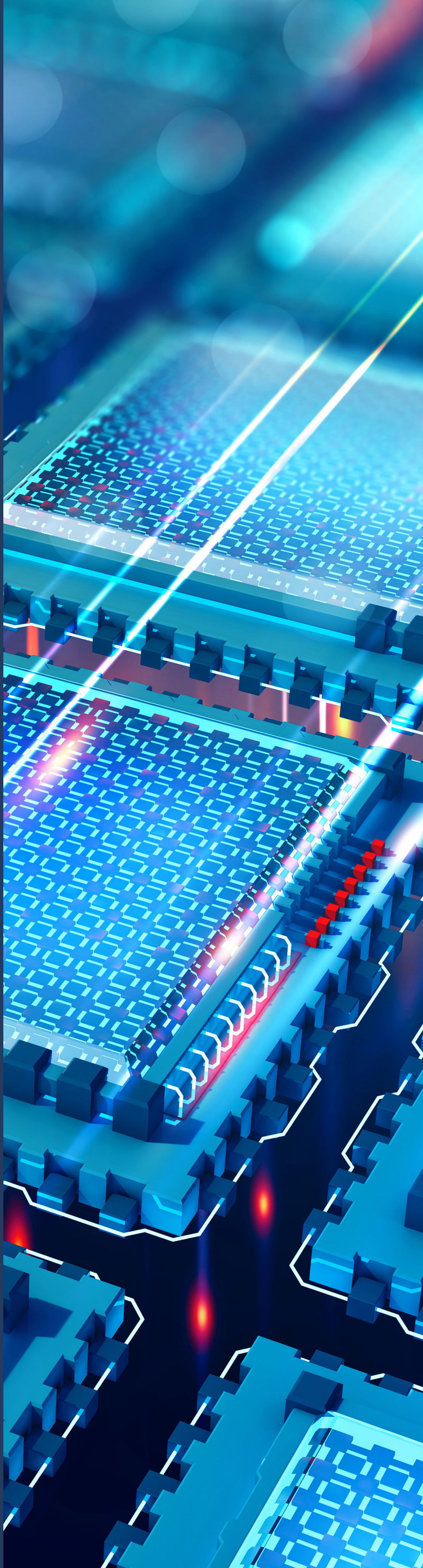
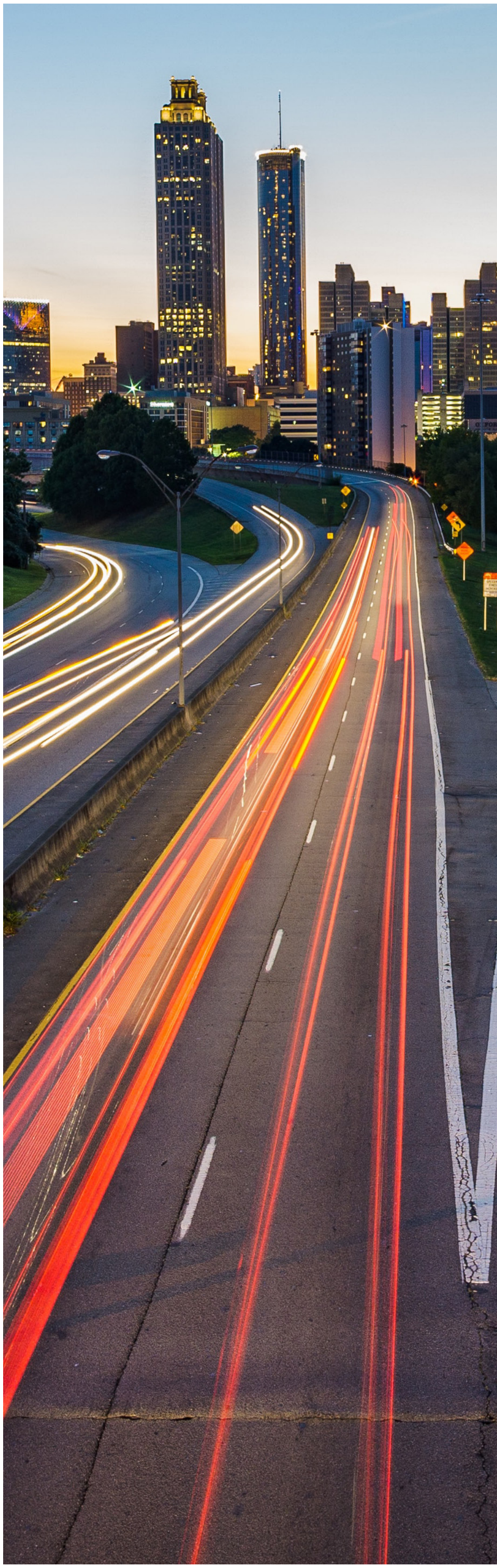


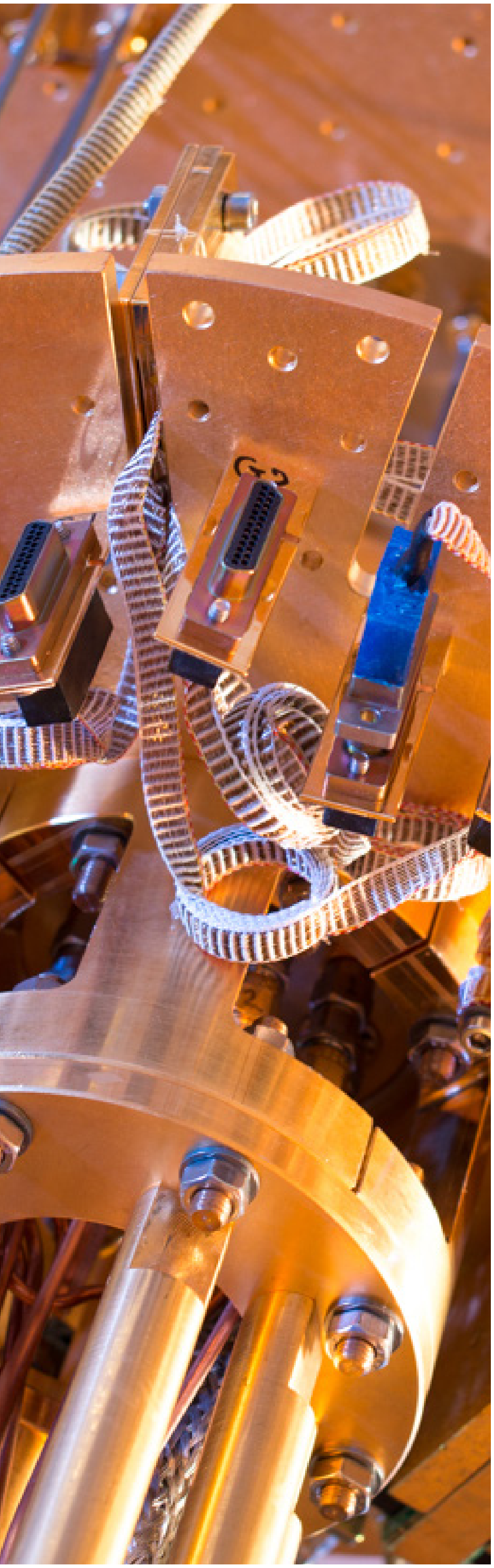
Quantum impact: Optimization solutions



Complex optimization problems exist across every industry, such as vehicle routing, supply chain management, portfolio optimization, power grid management, and many others. Optimization algorithms are also at the core of many machine learning methods. These real-world problems are very valuable to solve in order to reduce costs, accelerate processes, or reduce risk.

However, many of these real-world problems remain hard to optimize despite the remarkable advancements in both algorithms and computing power over the past decades. These scenarios usually involve many variables and the problem complexity scales exponentially with the problem size when using traditional methods.

Quantum computers might be able help solve complex optimization problems, from combinatorial optimization to partial differential equations. Quantum computers can naturally represent random distributions as quantum states, and therefore have the potential to provide better solutions than today's classical optimization algorithms.



The promise of quantum

Quantum computing makes use of wave-like properties of nature to encode information in qubits that can process highly complex calculations more quickly. Where current computers would require billions of years to solve the world's most challenging problems, with the right algorithm, a scaled quantum computer could find a solution in weeks, days, or hours.

When designed to scale, quantum systems will have capabilities that exceed our most powerful supercomputers. As the global community of quantum researchers, scientists, engineers, and business leaders continue to collaborate to advance the quantum ecosystem, we expect to see quantum impact accelerate across every industry.

From bits to qubits

The quantum bit, or qubit, is the basic unit of quantum information. Whereas a classical bit holds a single binary value, 0 or 1, a qubit can be in a "superposition" of both values at the same time. This enables quantum mechanical effects such as interference, tunneling, and entanglement, which in turn empower quantum algorithms for faster searching, better optimization, and greater security. When multiple qubits are connected, these properties can deliver significantly more processing power than the same number of classical bits. For instance, four bits is enough for a classical computer to represent any number between 0 and 15. But four qubits is enough for a quantum computer to represent every number between 0 and 15 at the same time.

Quantum optimization on classical hardware

Annealing and tempering are ancient metalworking methods that have inspired a multitude of optimization techniques. Many optimization algorithms, such as simulated annealing,[1] parallel tempering Monte Carlo,[2] or genetic algorithms[3] mimic natural processes.

Moving into the quantum age, optimizers[4] have been developed that make use of quantum mechanics to accelerate optimization and escape local minima in the cost function landscape through quantum tunneling.

Emulating these quantum effects on classical computers has led to the development of new types of quantum solutions that run on classical hardware, also called quantum-inspired algorithms. These algorithms allow us to exploit some of the advantages of quantum computing approaches today on classical based hardware, providing a speedup over traditional approaches.

Quantum-inspired optimization (QIO) requires the same preparation and mapping of an application problem as would be needed in future scalable quantum hardware and can emulate some of the quantum tunneling phenomena that are responsible for the acceleration.

Once scalable quantum hardware is available, these algorithms will be further accelerated by replacing the classical stochastic random walk at the core of many heuristic optimization techniques with a corresponding quantum walk that delivers polynomial speedup.

Optimization with Azure Quantum

Azure Quantum enables customers to run optimization algorithms on industry-scale hardware in a way that is simple and scalable. Currently, the self-service quantum solutions are designed to solve binary optimization problems (binary optimization problems usually amount to minimizing a cost function by choosing values for N binary variables) on CPUs, GPUs, and FPGAs in Azure. However, the portfolio of solvers is continuously expanding beyond binary problems and our Early Access Program customers

Microsoft has also partnered with 1QBit to offer additional quantum solutions for optimization through Azure Quantum. Our partnership brings forward integration with their 1Qloud platform as well as third-party quantum-inspired solutions by Fujitsu.

Ideal problems for quantum-inspired optimization

Some QIO algorithms can be applied broadly and work in a generic fashion for wide ranges of optimization problems. However, QIO methods produce the largest gains over traditional approaches for hard non-convex problems with many local minima in the cost function space, ideally with tall barriers between local minima that are hard to overcome by standard optimization methods.

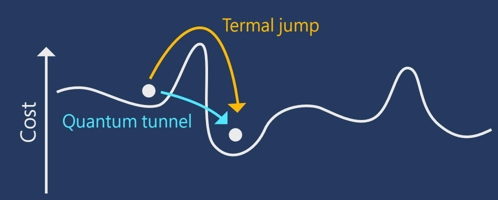
These problems tend to be NP-complete. The numerical effort needed to solve typical problem instances still tends to scale exponentially with the size of the input, on both classical and quantum hardware. Quantum approaches, however, can still have significant speed advantages (albeit not necessarily exponential) over classical ones.

Direct evidence for the utility of QIO algorithms—quantum solutions on classical hardware—stems from the observation that they can solve hard binary application problems far more efficiently than with a quantum annealing device—an analog machine that uses quantum fluctuations to find minima in a cost function via an annealing schedule.

There is no overhead for embedding a binary problem to the hardware; QIO directly tackles the native problem. Since QIO is built on digital precision, it does not suffer from analog noise. In turn, it can leverage efficient algorithmic engines far superior to simple quantum annealers. QIO methods are not restricted to binary cost functions like quantum and digital annealers and thus can be adapted to specific application problems natively delivering unprecedented speedup over conventional technologies.

> **"If a problem is well-suited for a quantum annealer, our generic QIO offerings can solve the problem faster, more optimally, and in a more scalable way. With custom quantum solutions on classical hardware, applications can scale to large, industrial-class instances leveraging different types of hardware."**

Ideal problems for QIO



Use cases for a given optimization problem

- For a fixed solution quality, find a better solution faster
- For a fixed solution time, find a better solution
- Solve more complex versions of the problem at fixed cost

Desired problem characteristics

- Rugged high-dimensional cost function landscape
- Reasonably large number of variables
- Quick evaluation of the cost function

With quantum solutions on classical hardware, Microsoft has demonstrated significant speedups over the current state-of-the-art in optimization on problems ranging from synthetic benchmarks to real-world applications (refs. 5-9), sometimes achieving speed-ups of many millions over conventional industry approaches. Quantum-inspired optimization demonstrates that quantum technology delivers commercial value well before the development and deployment of large-scale fault-tolerant quantum computers.

Azure Quantum

Quantum computing applies the properties of quantum physics to process information. Where current computers would require billions of years to solve some of the world's most challenging problems, a scaled quantum computer may find a solution in weeks, days, or hours. Azure Quantum is an open ecosystem of quantum partners and technologies. Building on decades of quantum research and scalable enterprise cloud offerings, it is a complete solution that gives you the freedom to create your own path to scalable quantum computing.

Azure Quantum is also your entry point to integrate quantum inspired optimization running on classical Azure hardware for immediate results. Through a familiar Azure environment, you'll have access to all the tools and resources you need to quickly ramp up on your journey to a quantum future and have an impact with quantum technology today.

An open ecosystem, enabling you to access diverse quantum software, hardware, and solutions from Microsoft and our partners.

A trusted, scalable, and secure platform that will continue to adapt to our rapidly evolving quantum future.

Quantum impact today, with pre-built solutions that run on classical and accelerated compute resources (also referred to as optimization solutions).

Get ready for your Azure Quantum experience with the Quantum Development Kit

The Quantum development kit is an open-source development kit to develop quantum applications and solve optimization problems. It includes the high-level quantum programming language Q#, a set of libraries, simulators, support for Q# in environments like Visual Studio Code and Jupyter Notebooks, and interoperability with Python or .NET languages.

As quantum systems evolve, your code endures.

Learn more at https://azure.com/quantum

Case study:

Optimization of MRI pulse sequences

agnetic Resonance Imaging (MRI) is a key diagnostics tool in healthcare and has played a pivotal role in the treatment of the most harming diseases for humanity ranging from cancer to heart disease to Alzheimer's. While much progress has been made in recent decades, improvements in imaging and scan times have been incremental, with significant improvements limited by computational challenges.

Working with Mark Griswold, professor of radiology and director of MRI research, Microsoft Quantum has teamed up with Case Western Reserve University[10] to use bespoke quantum-inspired optimization solutions running on classical hardware to develop new pulse sequences for MRI scans. The discoveries were significant:

- **When optimizing for speed, the pulse sequences generated are typically shorter, resulting in up to three times faster scans, and delivery of comparable image quality (Figure 1). A compelling real-world benefit for this solution is that shorter scans may not require children to be sedated for an MRI, not to mention significant reduction in patient waiting times.**

- **When optimizing for scan precision, these sequences can yield as much as 30% improvement in resolution, potentially leading to earlier diagnostics and treatment.**

Faster imaging, as well as imaging with better precision at fixed scan time, can lead to new diagnostics tools that may help tackle today's medical challenges while reducing the cost and side effects of the scans.

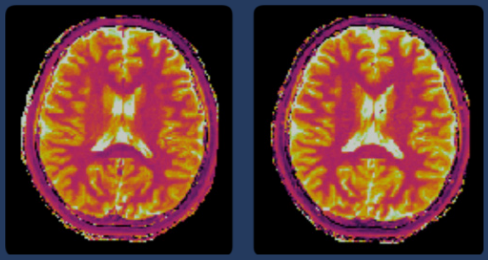


Figure 1—The left panel shows an MRI scan of the brain using a sequence that stems from quantum-inspired pulse sequences, while the right image uses traditional approaches. Scan quality is comparable, yet the left image was generated three times faster.

Case study:

Reducing traffic congestion

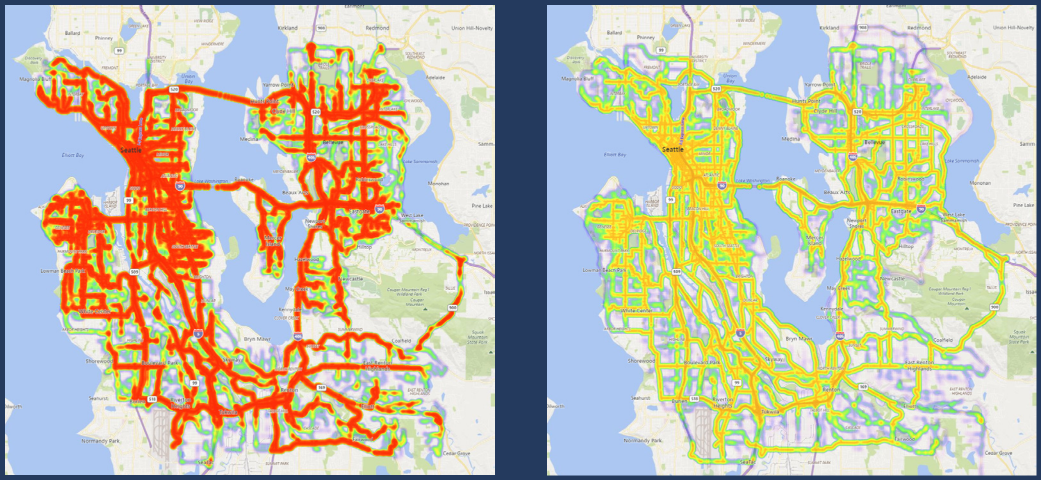


Figure 2—The left panel shows vehicles traveling around the Seattle metropolitan area during rush hour (traffic data provided by Bing). The right panel shows traffic patterns after the routes have been optimized with quantum-inspired methods.

Traffic congestion results in a significant time and cost burden in many metropolitan areas. Another important use case for vehicle routing is the efficient evacuation of large urban areas.

Using quantum-inspired methods paired with a sophisticated mathematical representation of the problem, Ford and Microsoft worked together [11] to significantly reduce both congestion and travel time versus the routing recommendations from Bing Maps.

Preliminary studies with up to 5,000 vehicles show more than a 70% decrease in congestion, as well as a reduction of average travel time of approximately 8% (compared to the best routes provided by Bing Maps)

Figure 2 shows travel patterns for 5,000 vehicles in the Seattle metropolitan area during rush hour. The quantum-inspired algorithm-optimized routes, represented by a heatmap (right panel), show less congestion than the Bing Maps suggestions (left panel).

While traffic optimizations of approximately 400 vehicles takes 20 seconds on a quantum annealing machine,[12] our quantum-inspired algorithms tackle a comparable problem in only 0.02 seconds on a single core. This can be further accelerated using specialized hardware, such as FPGAs available in Azure, by at least two orders of magnitude.

Case study:
Accelerating materials design

OTI Lumionics has developed a fast materials design approach, tailored to OLEDs and other electronic materials.[13] They work with the largest electronics companies in the world to design new materials that are mass-production ready, enabling the next generation of consumer electronics.

OTI Lumionics has developed software tools to simulate and predict the properties of new materials, allowing a larger pool of candidates to be screened than could otherwise be experimentally synthesized and tested in the lab. Thus, new materials that meet the precise requirements of the largest electronics manufacturers can be “designed” rather than discovered by chance.

OTI Lumionics has been investigating new approximation techniques using quantum-inspired methods to help accelerate computational chemistry simulations of new materials. As quantum-inspired algorithms run on classical hardware, they can test this enhanced workflow for material discovery today.

With their algorithms now running on Azure Quantum, OTI Lumionics is able to demonstrate meaningful results on problems of commercially relevant size, today. For example, by using Azure Quantum’s optimization tools in their pipeline, OTI Lumionics successfully performed a complete active space configuration interaction simulation of an archetype green light emitting OLED material—Alq3 [Tris (8-hydroxyquinolinato) aluminum].

Mapping the Alq3 simulation problem to an industry-standard quadratic unconstrained binary optimization (QUBO) problem would result 58,265 variables. Solving a QUBO problem with this many variables is intractable for both classical optimization methods and quantum annealers. In contrast, using Azure Quantum, the higher-order binary problem can be handled natively, meaning that this problem only requires 132 variables on classical hardware to perform the simulation.

Prepare your organization

Tackling the world's toughest challenges requires computational power that exceeds that of today's most powerful computers. Where classical computing may take a billion years to address some of these challenging problems, quantum computing has the power to solve these problems in weeks, days, or even hours.

1. Find relevant use cases for your business

See how organizations like yours are using quantum solutions. The Microsoft Quantum website has case studies that show how companies are using quantum technology for their businesses, today.

2. Build a quantum workforce

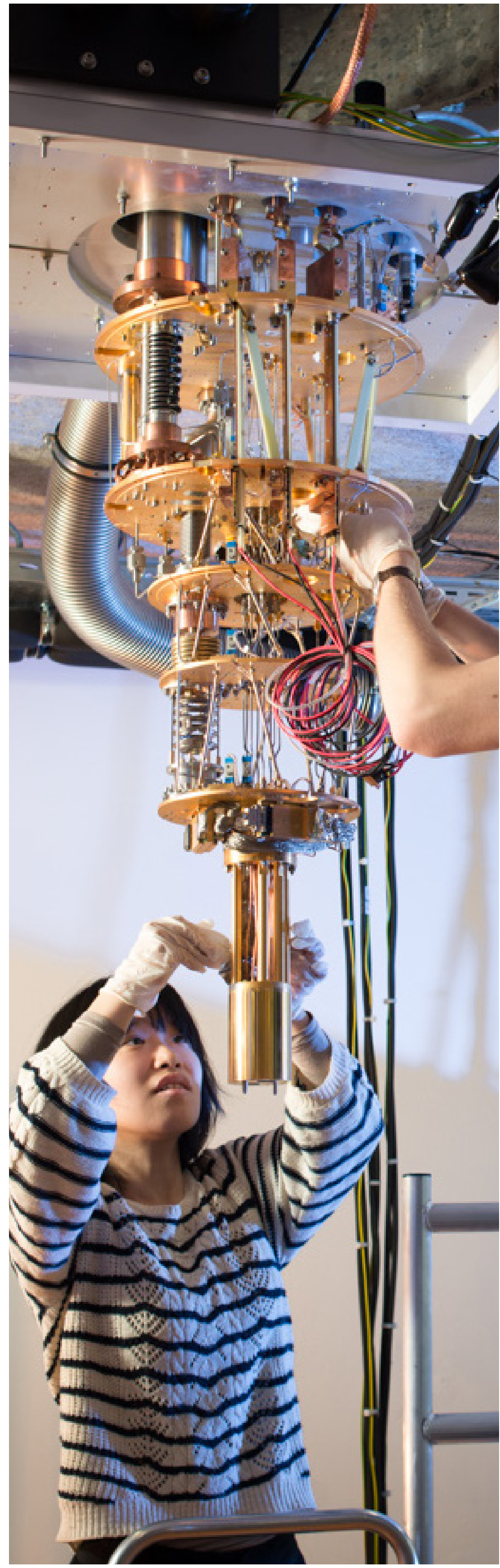
Ensure your organization is ready for quantum computing by assembling a quantum task force comprised of C-suite sponsors, business unit managers, and developers. Augment over time with quantum specialists and mathematicians that are familiar with applications and algorithms that are most relevant for your business.

3. Join the Microsoft Quantum Enterprise Acceleration Program

Microsoft offers the Enterprise Acceleration Program to develop high-value, custom quantum solutions alongside the world's best quantum talent. This is a paid offering for Microsoft's most advanced enterprise customers to accelerate quantum adoption through direct collaboration with the Quantum team. Contact us to get started.

4. Experience impact today through Azure Quantum

Microsoft is building a full-stack quantum ecosystem, delivered through the power and scale of Azure's global cloud services platform. Apply to become an early adopter for preview access to Azure Quantum.



Authors

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Brad Lackey is a Quantum Solutions Architect, specializing in creating quantum and quantum-inspired algorithms to solve real-world industrial problems. He also does foundational research in quantum information theory, post-quantum cryptography, and quantum programming languages.

Dr. Mattias Troyer

Distinguished Scientist, Microsoft

Matthias is a Fellow of the American Physical Society, Vice President of the Aspen Center for Physics, a recipient of the Rahman Prize for Computational Physics of the American Physical Society for "for pioneering numerical work in many seemingly intractable areas of quantum many body physics and for providing efficient sophisticated computer codes to the community" and recipient of the Hamburg Prize for Theoretical Physics.

He has received his PhD in 1994 from ETH Zurich in Switzerland, spent three years as postdoc at the University of Tokyo, and has later been professor of Computational Physics at ETH Zurich until joining Microsoft's quantum computing program at the beginning of 2017.

At Microsoft he works on quantum architecture and leads the development of applications for quantum computers. His broader research interests span from high performance computing and quantum computing to the simulations of quantum devices and island ecosystems.

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