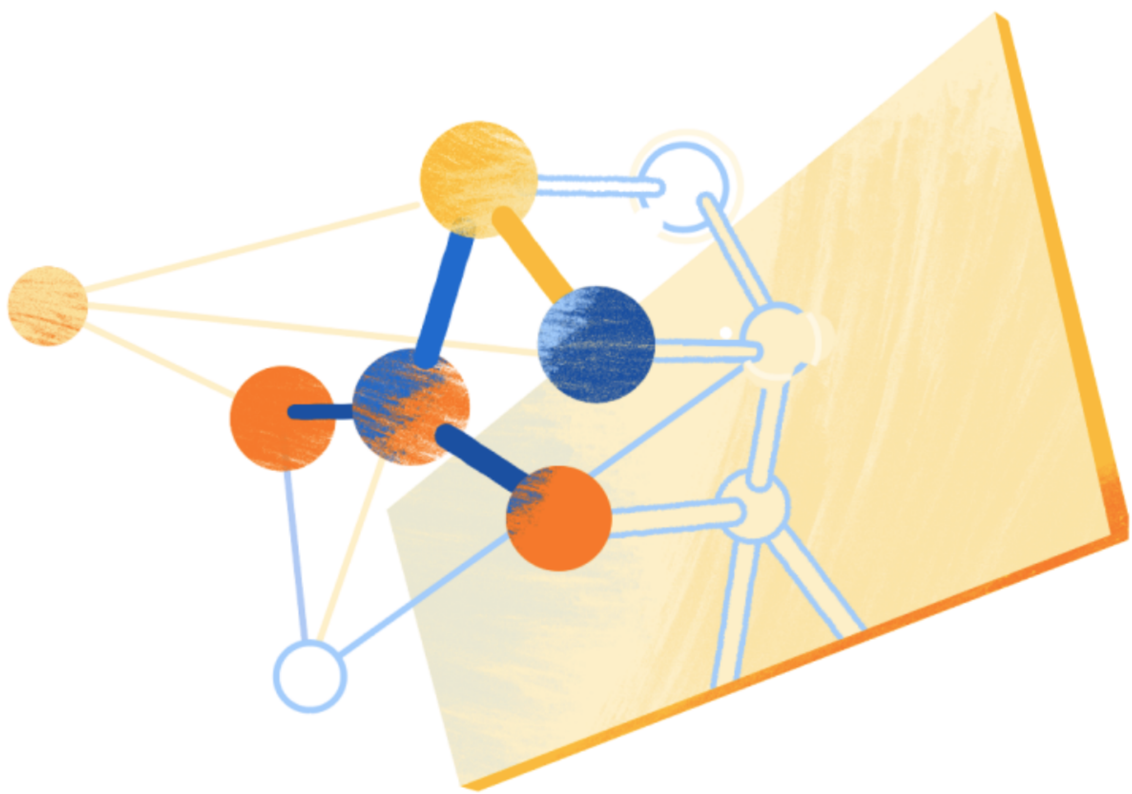
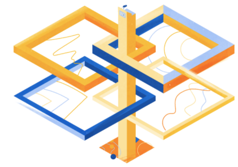
Google

Our focused and responsible approach to quantum computing



What is quantum computing?



Quantum computers use quantum physics to access different computational abilities from those of classical computers. Due to a property known as superposition, quantum bits (qubits) can take the value of a complex combination of 0 and 1; in contrast classical computers store information in classical bits as simply 0 or 1.

Superposition is used to simultaneously explore an exponentially large space of possible solutions to a problem. However, this 'superpower' comes with limitations – if we try to directly observe the state of the quantum computer, the superposition collapses.

Quantum algorithms rely on other properties like interference to exploit patterns in the space of potential solutions to amplify correct answers and cancel out incorrect ones. It's not easy to develop algorithms that can do this, and they are not well suited to solving all problems.

But we expect quantum computing will be able to tackle certain problems that are difficult or even impossible to answer with even the largest classical supercomputers.

Google Quantum AI: roadmap and mission

Google Quantum AI: roadmap and mission

The full potential of quantum computing will be unlocked with a large-scale computer capable of complex, error-corrected computations. Google Quantum AI aims to build this computer.

Our roadmap is shown below, and includes six technical milestones towards top quality quantum computing hardware and software for meaningful applications.

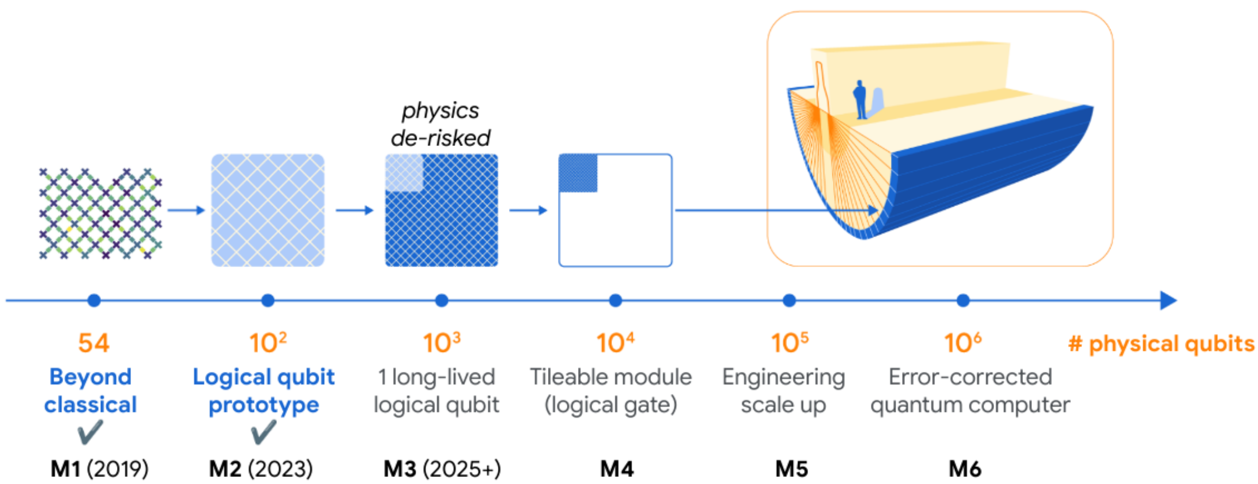


Figure 1. *Google Quantum AI roadmap towards the ultimate goal of a large-scale, error-corrected quantum computer. Google is currently working towards Milestone 3 (M3), a long-lived logical qubit (that is, capable of "living" for 1 million computational steps with less than 1 error).*

Our progress towards building a quantum computer

Google has been working on quantum computing since 2014. In 2019, we announced that we were the first to demonstrate "beyond classical"[1] performance (Milestone 1 on our roadmap), proving that quantum computers could outperform classical computers. In 2023, we announced the first-ever experimental demonstration that it is possible to scale quantum error correction (Milestone 2).[2]

Qubits are highly sensitive to their external environments and even stray particles of light can introduce errors. For meaningful computation, these errors must be corrected, and error correction must be improved as quantum processors are scaled to larger numbers of qubits. We view achievement of scalable error correction as a necessary step towards Milestone 3 — a long-lived logical qubit (that is, capable of "living" for 1 million computational steps with less than 1 error).

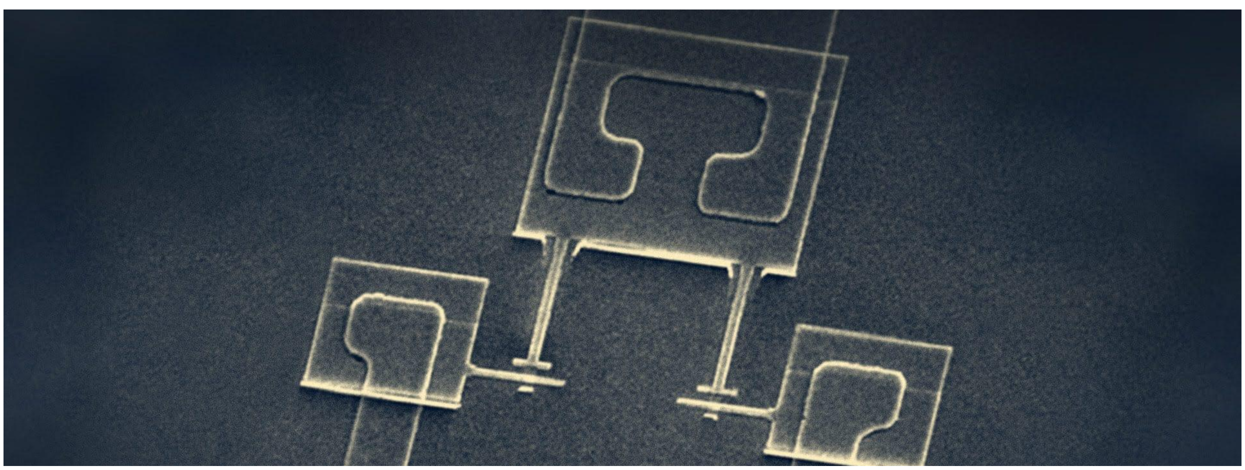


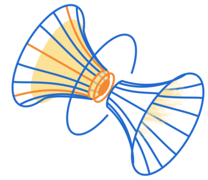
Figure 2. *A single physical qubit circuit on the Sycamore processor, measuring about 0.2 millimeters wide (seen through a scanning electron microscope).*

Looking forward, we continue to work on improving our qubit performance, scaling up our architecture and infrastructure, and refining our approach to quantum error correction, aiming to reduce errors by multiple orders of magnitude, even as we increase the number of qubits. We plan to tile thousands of surface-encoded logical qubits together to comprise a fully fault-tolerant quantum computer.

[1] Google Quantum AI. Quantum supremacy using a programmable superconducting processor. *Nature* 574, 505–510 (2019). https://doi.org/10.1038/s41586-019-1666-5

[2] Google Quantum AI. Suppressing quantum errors by scaling a surface code logical qubit. *Nature* 614, 676–681 (2023). https://doi.org/10.1038/s41586-022-05434-1

Why quantum computing matters



Google is committed[3] to significantly improving the lives of as many people as possible. We continue to pursue quantum computing because—if achieved—it will be uniquely capable of solving some of the world's most pressing issues.

We believe quantum computers will be particularly useful for (a) problems where we need to model phenomena that are inherently quantum mechanical (e.g. electron interactions), or (b) problems that have a "hidden structure" that can't be seen with a classical computer. Though we're confident we have yet to discover even a small portion of the ways quantum computing will benefit society in the future, Google is actively working with collaborators on a variety of potential near- and long-term applications for quantum computing. Here are a few examples that we are most excited about.

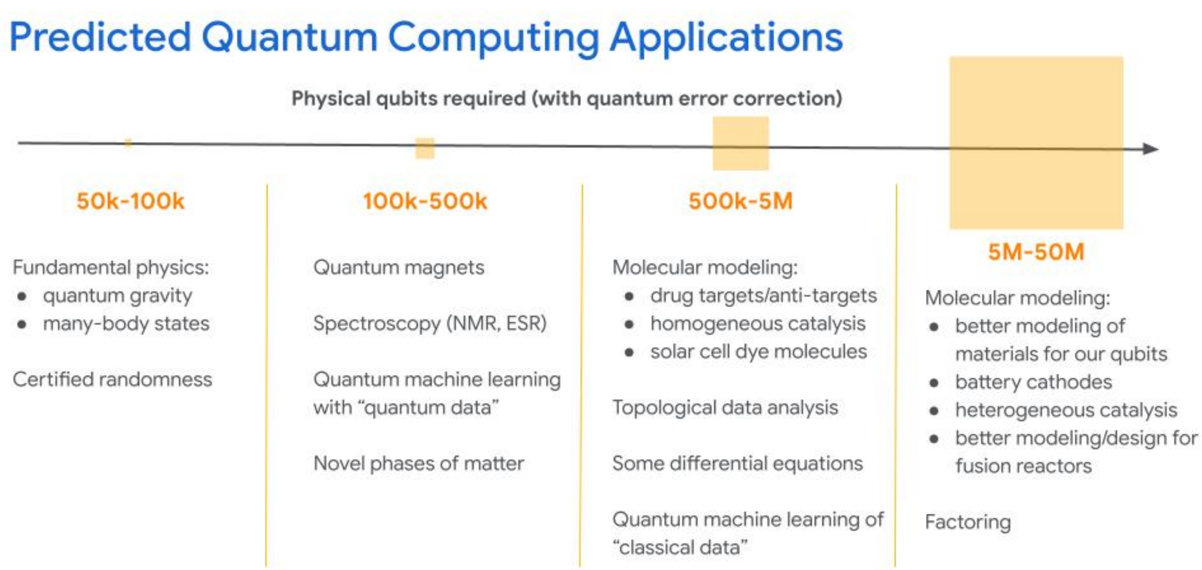


Figure 3. *We expect quantum computers to unlock chemical simulation and other applications. Note that this graphic outlines predicted number of qubits with error-correction for simplicity, but some of the applications in the first two columns may also be good targets for today's smaller, error-prone processors.*

[3] Google's Mission, Values & Commitments https://about.google/commitments/

Drug discovery	Advances in classical computing have greatly aided drug discovery by modeling behavior of candidate drugs before synthesis and testing in the lab, and clinical trials. However, classical computers cannot exactly simulate candidate drug molecules, so significant experimental trial-and-error is still needed to screen promising drug candidates. Quantum computers are particularly well-suited for precise simulations of potential drugs and their interactions with complex biological molecules. This may help researchers more accurately identify drug candidates – and ultimately improve health outcomes for the world.[4]
Industrial chemistry	Chemical catalysts play an important role in many industries, and quantum computers could help identify catalysts that make critical processes safer and more efficient – and benefit both people and the environment. For example, ammonia is one of the most common industrial chemicals in the world, used as an agricultural fertilizer and in chemical manufacturing and pharmaceuticals. Without ammonia, we would be unable to sustain the world's current population. However, ammonia production requires incredibly high temperatures and pressures, and alone contributes 2-3% of global greenhouse gas emissions. More effectively simulating the chemical reactions used to produce ammonia could help identify ways to make the ammonia manufacturing process more efficient, and lower emissions.
Sustainable technology	Batteries are a keystone to an electrified economy, enabling vehicles that charge faster and drive further, and a grid that can supply power 24/7 using only renewable power. However, battery technology has not advanced at the same pace as other green technologies. The reactions within batteries are quantum mechanical, and cannot be precisely simulated by classical computers. However, quantum computers will enable detailed electrochemical battery simulations[5], which can lead to more efficient and higher performance batteries. Quantum computers may also help fight climate change in other areas, such as unlocking better nuclear fusion reactor designs through physics simulations and engineering optimization.
Fundamental physics research	While today's small and error-prone quantum processors do not have nearly the power of their future fault-tolerant counterparts, they can still support breakthrough physics research. For example, recently, a team[6] at Google and collaborators performed experiments aimed at studying quantum gravity. Other recent experiments from the Google Quantum AI team include studying molecular structure[7], interacting particles of light[8], and exotic phases of matter[9]. In addition to their scientific interest, physics breakthroughs may also unlock new technologies such as loss-free power grids. After all, while general relativity and quantum mechanics seemed esoteric at first, they seeded now-ubiquitous technologies like GPS, silicon computer chips, and MRI machines.

[4] Goings et al., Reliably assessing the electronic structure of cytochrome P450 on today's classical computers and tomorrow's quantum computers. *PNAS* 119 (38) e2203533119. https://doi.org/10.1073/pnas.2203533119
[5] Rubin et al., Fault-tolerant quantum simulation of materials using Bloch orbitals. arXiv:2302.05531
[6] Jafferis, D., Zlokapa, A., Lykken, J.D. *et al.* Traversable wormhole dynamics on a quantum processor. *Nature* 612, 51–55 (2022). https://doi.org/10.1038/s41586-022-05424-3
[7] O'Brien et al., *PRX Quantum* 3, 030345 (2022). https://doi.org/10.1103/PRXQuantum.3.030345
[8] Morvan, A., Andersen, T.I., Mi, X. *et al.* Formation of robust bound states of interacting microwave photons. *Nature* 612, 240–245 (2022). https://doi.org/10.1038/s41586-022-05348-y
[9] Google Quantum AI, Noise-resilient edge modes on a chain of superconducting qubits, *Science* 378, 785-790 (2022). DOI: 10.1126/science.abq5769

The examples above are just some problems that quantum computers may address. There are other promising research areas – such as machine learning, linear algebra, and differential equations – in which quantum computers may have unique advantages over classical computers. We're confident there will be numerous ways for quantum computing to benefit society in the future. In the 1950s, the idea that computers could be used to share information across the globe must have seemed like science fiction. While it is still early days for quantum computing, we are excited to help make its promise a reality.

Our technological and societal responsibilities

Given the potential, powerful capabilities of quantum computers, it is important that we work together across sectors to ensure they are put towards useful applications that will benefit society, and developed in a responsible manner.

One of the Google AI Principles[10]—which outline our commitment to the development of AI and advanced technologies—is to "Uphold high standards of scientific excellence." In line with this tenet, we strive to be honest and realistic about the progress and limitations of quantum computing – particularly at a time when many in the industry are exaggerating its current capabilities. The government and academic sectors will play a critical role in ensuring a realistic view of quantum computing's potential, and accelerating quantum computing innovation for societal good. Continued and increased government investment in quantum computing R&D is important, especially in areas like materials, methods, and applications development for fault-tolerant quantum computers and quantum error correction.

There is a critical need for continued collaboration across sectors, institutions, and geographies to prevent potential misuse. For example, quantum computing has the potential to break public key cryptosystems such as RSA that protect most internet traffic today.

Breaking RSA encryption will be possible with the ability to factor the products of large prime numbers. Even for today's best supercomputers, this is an effectively impossible task that would take longer than the age of the universe. A future fault-tolerant quantum computer could do so in a matter of hours, greatly compromising the integrity of electronic communication and posing serious privacy and security risks.

[10] AI at Google: our principles https://ai.google/principles/

To address this challenge, the security community is developing systems that are secure against attacks from quantum computers, known as post-quantum cryptography. NIST, the US government agency responsible for encryption standards, recently announced[11] a first set of post-quantum cryptographic tools to be standardized, one of which (SPHINCS+) was developed with Google's contributions. We are also taking our own steps[12] to ensure that services like Google Cloud, Android, and Chrome remain secure in a quantum future, and to engage with the community to share our learnings.[13] And, we continue to keep the community informed on our research progress and timeline towards a fault-tolerant quantum computer with the potential to break public key encryption.

The field of quantum computing is growing rapidly, and dedicated educational efforts will be critical to maintain the pace of innovation, and build a diverse workforce across the quantum computing value chain. Google is actively advising, supporting, and collaborating with academic institutions around the world including UC Santa Barbara, Santa Barbara City College, UC Berkeley, MIT, Harvard University, CU Denver, Leiden University, Oxford University, University of Sydney, University of New South Wales, University of Toronto, University of Waterloo, and many more.

Through these relationships, we aim to expand access to quantum computing and train a diverse range of talent across skill sets, backgrounds, and geographies. We have released open source tools[14] to ensure quantum computing resources (including software for quantum computing algorithm development and simulation) are widely accessible. Governments have an important role to play, including via increased R&D funding (leading to more trained students and professionals in the field); dedicated funding for workforce development initiatives, including re-training and training for technicians and engineers; and policies that encourage collaboration between institutions in like-minded countries and facilitate access to international quantum computing talent.

> We are excited about what quantum computing means for the future of Google and the world. Our vision is that one day, people will use classical computers as well as quantum computers to expand the boundaries of human knowledge and solve some of the world's most complex problems.

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[11] PQC Standardization Process: Announcing Four Candidates to be Standardized, Plus Fourth Round Candidates https://csrc.nist.gov/News/2022/pqc-candidates-to-be-standardized-and-round-4

[12] Why Google now uses post-quantum cryptography for internal comms https://cloud.google.com/blog/products/identity-security/why-google-now-uses-post-quantum-cryptography-for-internal-comms

[13] Joseph, D., Misoczki, R., Manzano, M. *et al.* Transitioning organizations to post-quantum cryptography. *Nature* 605, 237–243 (2022). https://doi.org/10.1038/s41586-022-04623-2

[14] Software | Google Quantum AI https://quantumai.google/software