Quantum Computing
From Hardware to Society

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QUANTUM COMPUTING VISION TEAM

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Quantum Computing

From Hardware to Society

TU Delft

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This magazine is both an introduction into quantum computing and an exploration of its impact on our world. It follows on from our 2019 magazine on the quantum internet. Since 2019, much progress has been made in quantum technologies worldwide. In 2020, for instance, the first European quantum computer came online in Delft. Although this is meant for experiments only, it shows that quantum computing is becoming real.

We aim to present you with a basic picture of quantum computing, and sketch applications for which it can be used. The contents are meant to be accessible, but some texts may be more suitable for readers with a basic understanding of quantum technology. Let that not be a reason to stop exploring: the magazine is meant to be browsed, so you can find the articles that help you learn about quantum computers.

At TU Delft, we see it as our responsibility to investigate and inform you about the impact of the technologies we develop. Hence, we also explore the potential impact of quantum computing on the world: how the expected wave of applications may ripple through society. This exploration is partly guess-work. Quantum computing is a new technology and no doubt more applications will be discovered. Moreover, while as a university we are good at describing what quantum computing is, it will be future users who determine what meaning its applications will have. That is why we also asked the help of experts in and outside of academia when exploring the impact of quantum computing.

This magazine is the result of the work by the Quantum Computing Vision Team. Vision teams are composed of TU Delft scientists and engineers from many disciplines, and with vision teams TU Delft participates in public discussions on technologies. We hope this magazine offers you insights of what quantum computing can bring, and invites you to become part of the discussion of how we can make quantum computing meaningful to you and to society.

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Tim van der Hagen

Rector Magnificus & President of the Executive Board, TU Delft

TU Delft has taken scientific and technological leadership in developing quantum technlogies. Research at QuTech and at the Faculties of Applied Sciences and of Electrical Engineering, Mathematics & Computer Science is bringing quantum computation and quantum internet closer to realization. But what will be the impact of this on society and industry? As part of our social responsibility, we should also investigate this aspect of any new technology we work on. With that in mind, TU Delft's Executive Board launched an inquiry into the impact of quantum technologies, and you can read the outcomes in this magazine.

Lieven Vandersypen

Director of Research, QuTech

In front of you lies a magazine that presents quantum computing and explores the impact that this new technology may have on society. Delivering a fully functional, large-scale quantum computer is still a longer term effort, yet progress is accelerating. QuTech is an advanced research center for quantum computing and quantum internet, a collaboration founded in 2014 by TU Delft and the Netherlands Organisation for Applied Scientific Research (TNO). QuTech works on the scientific and engineering challenges of building a quantum computer, and in 2020 has launched Quantum Inspire, the first European experimental quantum computers that can be accessed through the cloud by researchers all over the world. Quantum computing is thus becoming a realistic prospect and I am therefore very excited with and grateful for the work of the TU Delft Quantum Vision Team and with this magazine.

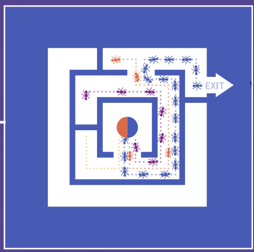
What is Quantum?

Hardware & Software

Applications

Impact

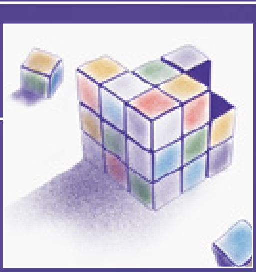
Reflections



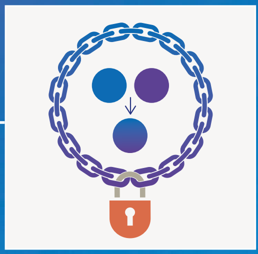
An introduction to quantum computing—by ants!

Who is involved in building a quantum computer?

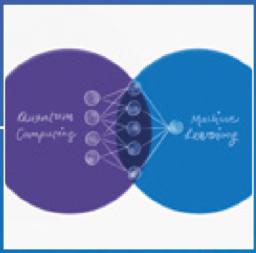
Understanding our world through a quantum lens



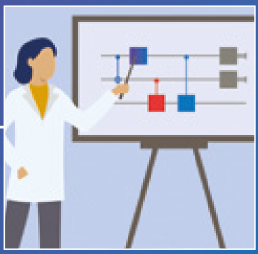
The factorizing process



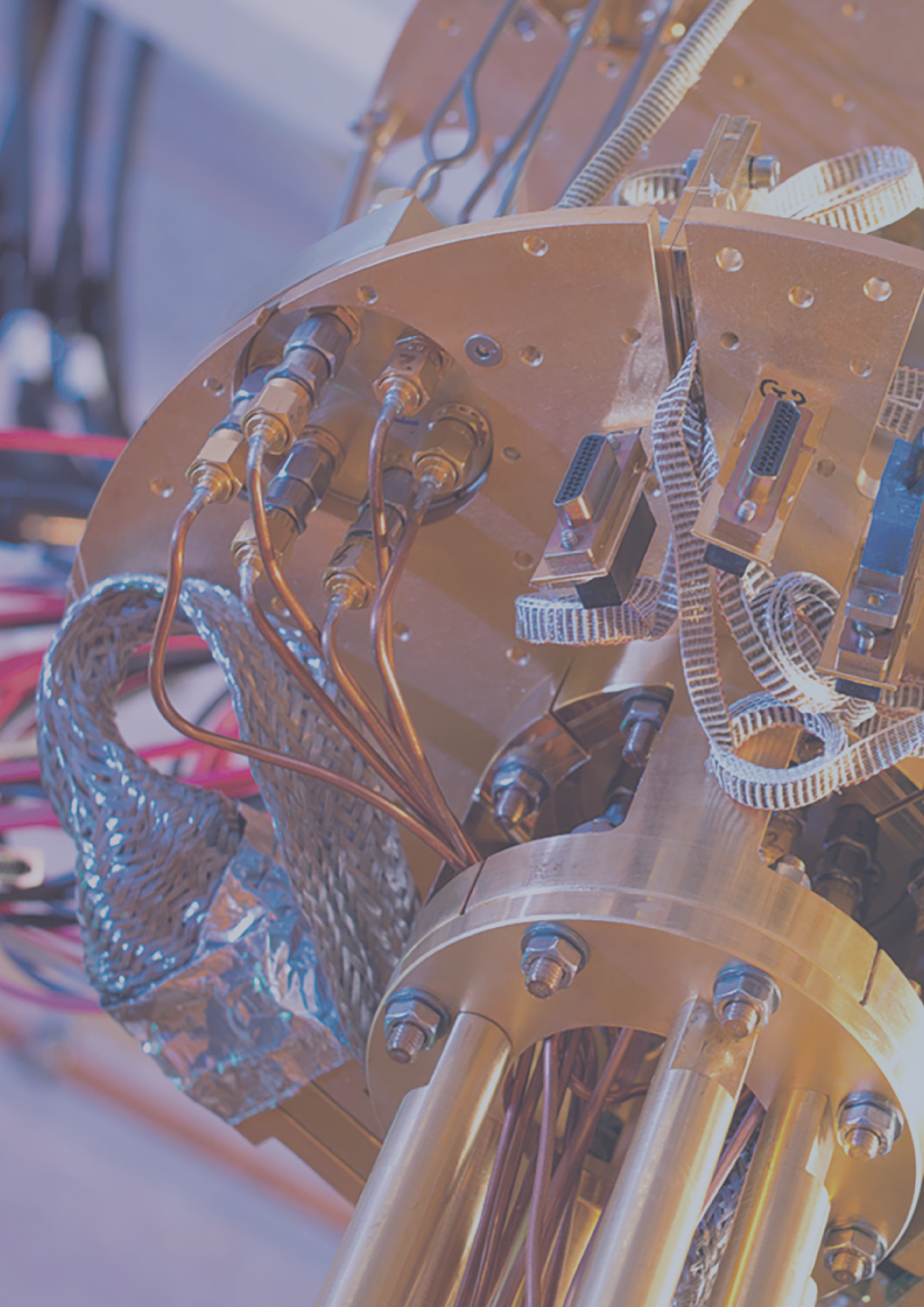
Should governments keep quantum technologies under wraps



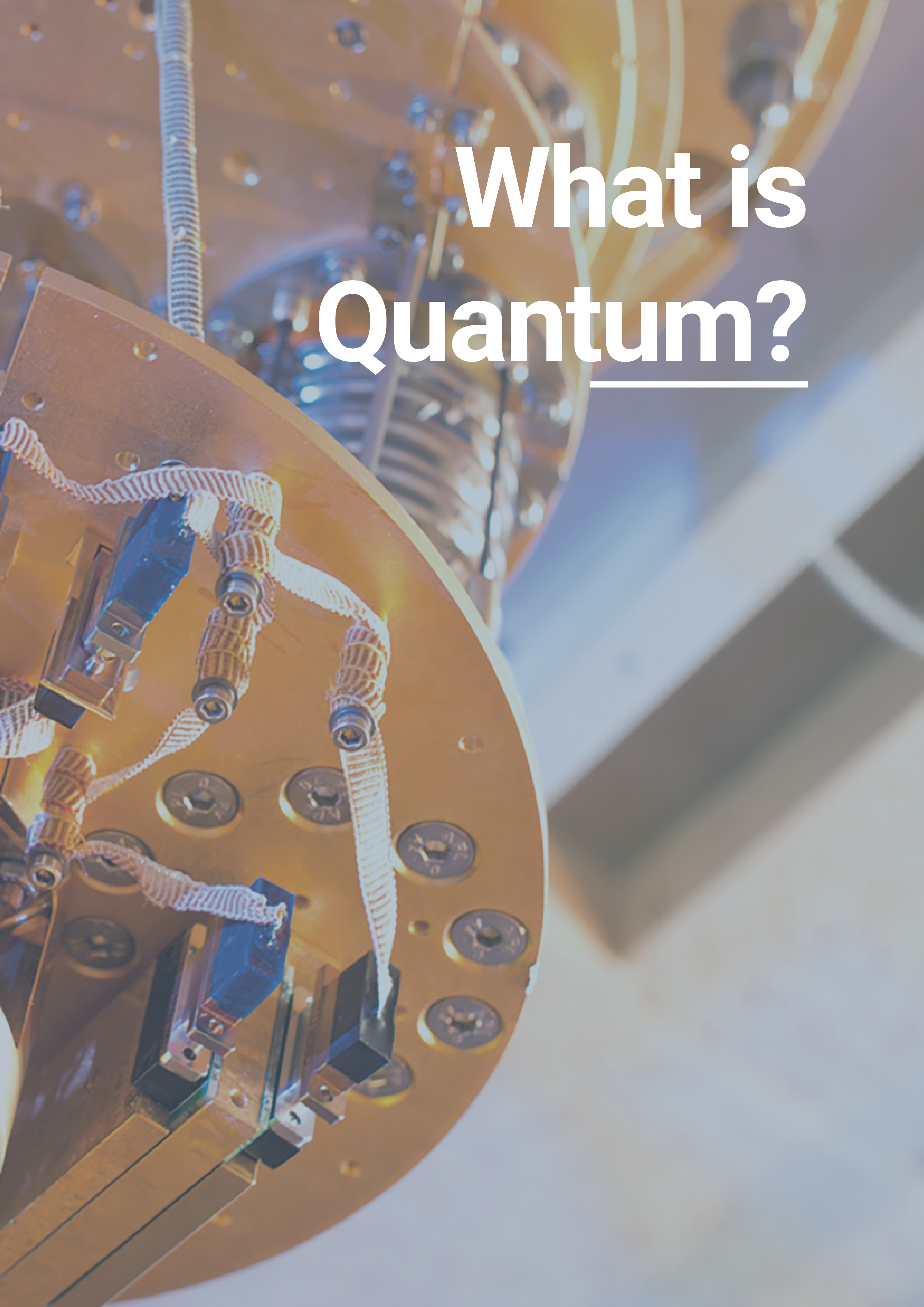
New possibilities for the future of science



Visions for the quantum future from TU Delft students



What is Quantum?



A Brief History of Quantum

Although quantum technology is relatively new, its history stretches back further than you might think.

The Origins of Quantum

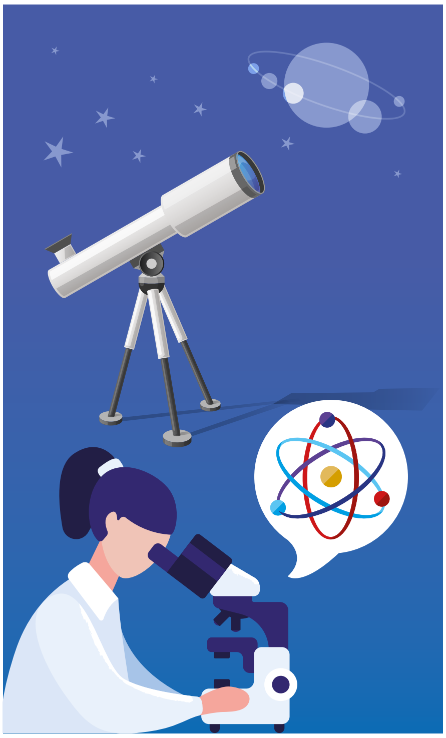
What makes something "quantum"? The first scientist to answer this question was the 23 year old Werner Heisenberg, a student of Niels Bohr. Prior to 1925, Bohr had put forward a mix of old and new ideas in physics that seemed to explain extremely well how the hydrogen atom worked. But there was much confusion as to why the model worked so well. It was Heisenberg who first connected the dots. His inspiration was to focus **only on what can be observed**.

This subtle idea separates the quantum world – one of small things and small energies – from the larger objects of our normal, or *classical*, world, which includes grains of sand, coffee cups and planets. For example, consider the moon. On a clear night, we can see light from the sun brightly reflected off of it. On overcast nights, or when it is below the horizon, we can't see it at all, but we know it's somewhere. Astronomers who carefully collect data can predict with extremely high accuracy exactly where in the night sky it will appear a great deal into the future. Very small things, such as the electrons in atoms and molecules, do not behave this way. They are not always somewhere. If you assume that an electron is in one particular place when you aren't immediately observing it, you will not be able to explain a great deal of natural phenomena.

The quantum idea is a radical departure from our usual intuition: it predicts concepts like *superposition* and *entanglement* that we do not experience in everyday life. In spite of that, quantum mechanics has proven to be the most accurate physical theory ever conceived, and now underpins our knowledge of far more than the humble hydrogen atom. For instance, it is essential for understanding the operation of the semiconductor chips inside computers, and how chemicals, such as our DNA, bond together. In less than a century, quantum mechanics has transformed from a strange idea into a cornerstone of modern technology.

The Solvay Conference

The 1927 Solvay International Conference on Electrons and Photons was attended by many of the 20th century's greatest minds in physics. Werner Heisenberg is third from the right in the top row; Niels Bohr is most right in the middle row.



1925
Understanding Hydrogen

1938
Nuclear Fission

Nuclear fission was discovered in 1938. The process of the nucleus – the quantum-mechanical innards of an atom – splitting apart would go on to be harnessed for power generation (as well as nuclear warheads).

1947
Transistors

Transistors – the essential building blocks of modern computers – are the most numerous objects created by humanity. Quantum mechanics is necessary to design these small and ubiquitous devices, found in laptops, smartphones and cars.

1954
Solar Cells

Solar cells work by converting light energy into electrical energy. Understanding this quantum process is critical to building these efficient renewable energy sources.

1960
Lasers

Lasers are near-perfect sources of light that are engineered into everyday devices, such as printers and barcode scanners. They are an essential tool in much of modern science, including approaches to building quantum computers.

1971
MRI

What is now a commonplace medical scan is really quite high-tech. **Magnetic fields** and **radio waves** are used to accurately image tissue by proving the behavior of proton spins: little quantum systems in the body. What's more, the strong magnets required are typically superconducting – another quantum behavior.

1990s
Flash Memory

Many USB sticks make use of **flash memory**: memory that can easily be erased with a single 'flash' of voltage. Flash memory makes use of the effect that quantum particles can pass seemingly insurmountable barriers – a phenomenon known as quantum tunneling.

Quantum Computing

Ants in a Maze

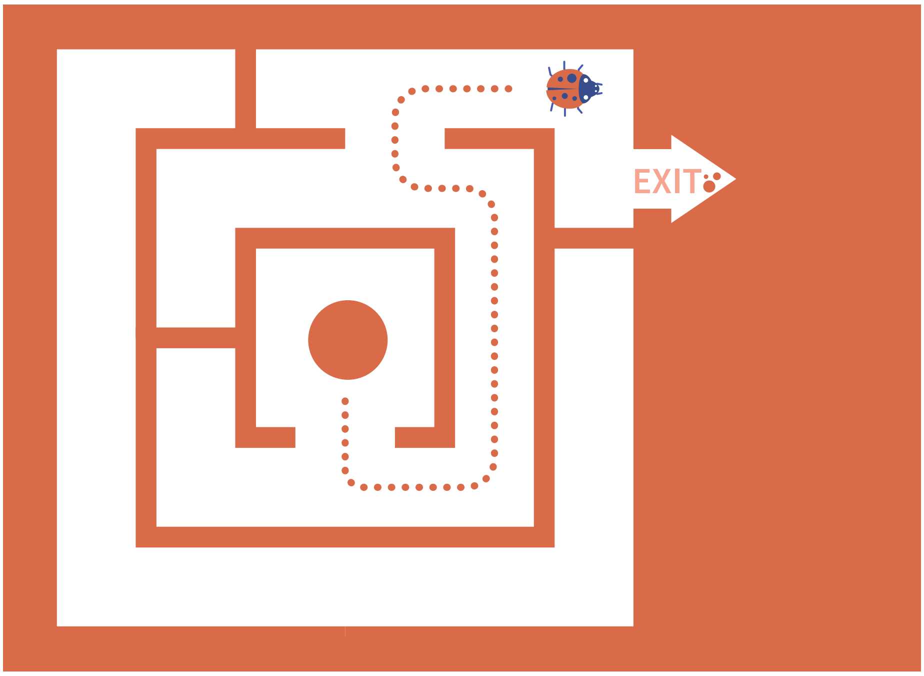
In the maze of computation, quantum computers divde and conquer to find the exit.

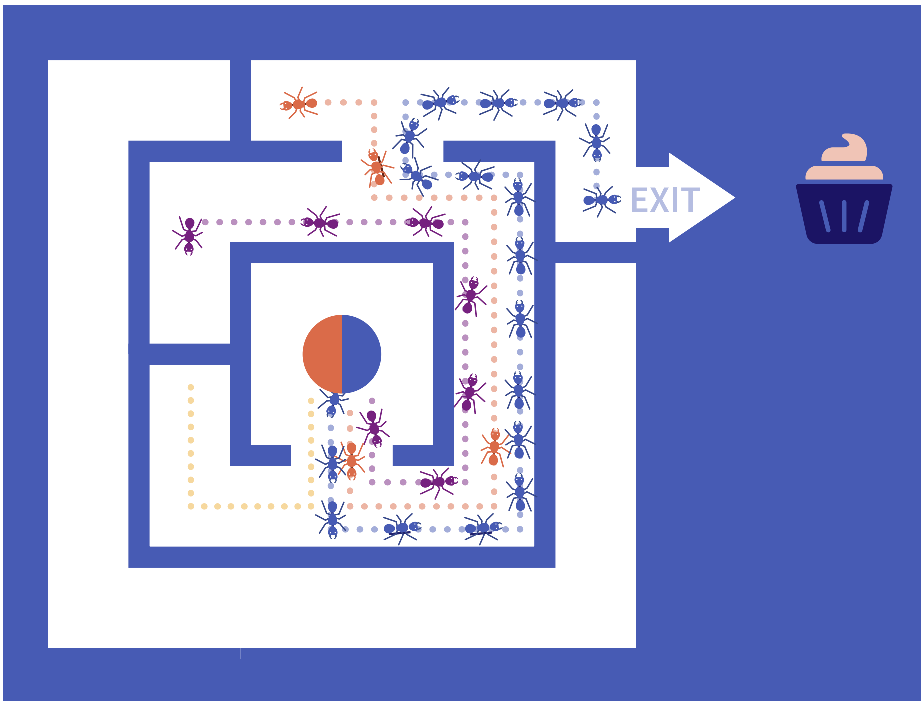
So how can a quantum computer perform certain tasks faster than our current 'classical' computers? We, the Quantum Computing Vision Team, created an animation to explain this – you can access it using the QR code.

Imagine a maze with one exit. In order to find the exit, a classical computer will try all possible paths until it has found the exit: just like a ladybug would if we placed it at the start of the maze.

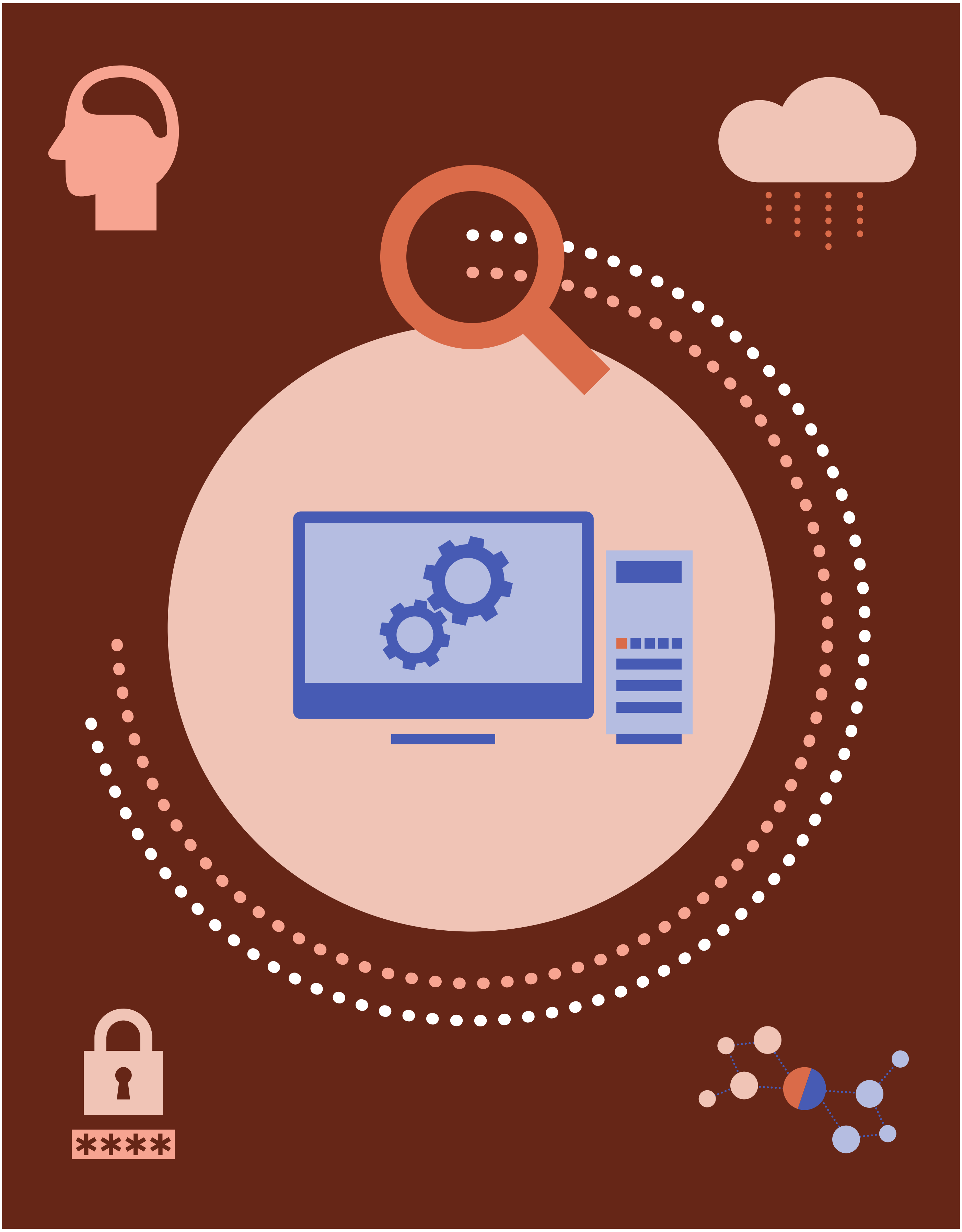
A quantum computer takes a radically different approach: all different paths are explored and interacting simultaneously – a bit like a colony with many ants working together to find the best path to some food – and the quantum computer finds the exit much faster.

Are you curious to find out how the quantum ants can accomplish this task faster than the ladybug? Scan the QR code to find out.





Ladybugs and Ants
A classical computer (top) tries every route one by one, whilst in a quantum computer (bottom) all paths are explored and interact simultaneously — like a colony of ants.



From Theory to Reality
Quantum computers could make a significant impact in a variety of areas, such as cryptography, machine learning, meteorology and chemistry, to name a few.

Why Quantum Computers?

Researchers all over the world are investigating quantum technology. But what makes it so special, and what can we use it for?

Quantum Tech 2.0

Inventions such as the transistor are often called Quantum Technology 1.0. Their behavior is a consequence of quantum mechanical phenomena. Now, it is possible to control the quantum properties individually, and this opens up a new arena of possible technologies, dubbed Quantum Technology 2.0.

A Classical Algorithm

Humans have thought about computation for millennia. For instance, in 300 BCE Euclid, a famous Greek mathematician, wrote about an algorithm – a set of mathematical steps – that could be used to simplify fractions. For small fractions, we may do this in our heads without second thought. But for bigger fractions, it's not so easy.

2/4	→	1/2
16/24	→	2/3
243/432	→	9/16

Euclid's algorithm works by finding the largest number that can evenly divide both the top and bottom of the fraction by using some clever subtraction. For example, if we want to reduce 243/432 (to 9/16) with Euclid's algorithm, the steps look like this:

432 - 243 = 189

243 - 189 = 54

189 - 54 - 54 - 54 = **27**

54-27 = **27**

243/27 = **9** and 432/27 = **16**

For bigger fractions, the subtraction isn't too hard, but it is a bit tedious. Lucky for us, we can ask a normal classical computer to do this, and the computer can do it quickly even for very large fractions. We can say that there is an efficient classical algorithm for simplifying fractions.

A Quantum Algorithm

Here's another problem we do on a daily basis - factoring.

15	→	3 x 5
91	→	7 x 13
1961	→	37 x 53

Again, as the numbers get bigger, this becomes tricky. We might start by guessing and checking if a number is divided evenly:

1961/2	→	✗
1961/3	→	✗
	....	
1961/37		✓

This is also tedious. But unlucky for us, a computer can't do much better. If we ask a computer to factor a big number, maybe one containing 500 digits, it would take over a lifetime. There is no known efficient classical algorithm for factoring.

In 1994, the mathematician Peter Shor discovered an efficient quantum algorithm that could help us out. Why can't we ask our classical computers to run this algorithm? In short, they would run out of space. In fact, even if we could use every particle in the galaxy to build the computer, it would still run out of space. Shor's algorithm is unsuited for a classical computer because it makes use of superposition, and that is a quantum concept. So, for running this algorithm we need to build a new computer that computes with superposition: the quantum computer.

Development

Although people have thought about computers for millennia, it wasn't until the 1930s that the mathematician Alan Turing proposed the concept of what we consider a modern classical computer. During World War II, Turing and his colleagues at Bletchley Park built the "bombe", an example of an early computer, which was used to decrypt Nazi communications.

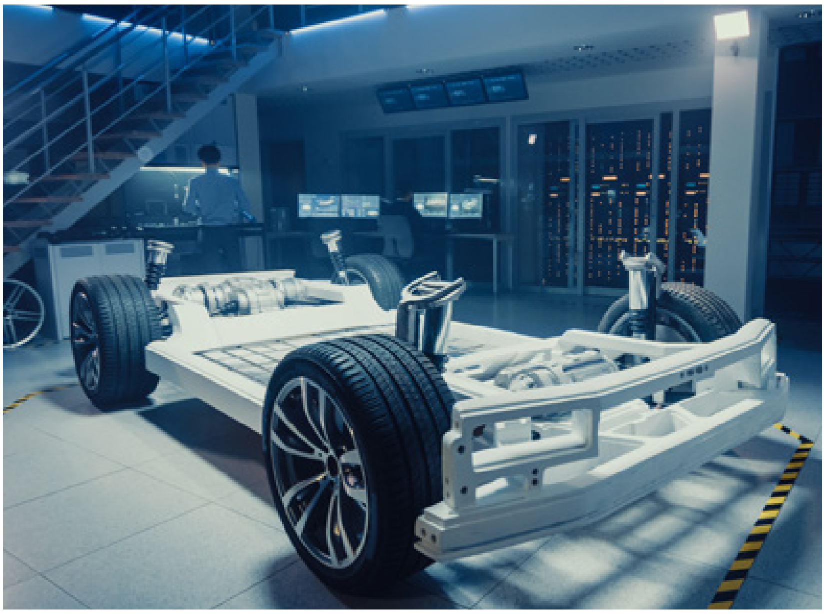
In the 1940s and 1950s, the inventions of the transistor and the integrated circuit – the semiconductor "chip" – set the stage for computers to become smaller and more powerful. A famous rule of thumb, called Moore's law, stated that computers could approximately double in power every two years due to the rapid speed of technological improvement. However, this improvement of classical computers is coming to an end because we have reached the limits of how small we can make chips, and it is widely believed that we are now at the end of the Moore's Law era. As a result, researchers worldwide are investigating ways that computers could still be made more powerful, with one of the most promising approaches being quantum computing.

Beyond Shor's Algorithm

Factoring is both interesting and important, but quantum computers can do a lot more than just that. Quantum computers are also believed to be excellent in modeling and understanding complicated chemical reactions and in testing new pharmaceuticals. The famous physicist Richard Feynman summed it up best:

"Nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy."

Optimizing industry
Quantum computers may help us to better understand catalysts that play an important role in many industrial chemical processes.



A greener economy
Transitioning to a greener economy requires good quality batteries, and quantum computers may be able to optimize the chemical bonds which store a battery's energy.

"Nature isn't classical...if you want to make a simulation of nature, you'd better make it quantum mechanical."

- Richard Feynman

Better pharmaceuticals
New pharmaceuticals require a lot of money and energy to develop, because testing the performance of drug molecules is difficult to simulate on ordinary computers. Using quantum computers could vastly speed up this process.

Comparing Computers

Quantum computers and classical computers are made of the same building blocks—but the ways they behave couldn't be more different.

A quantum computer is made out of the same building blocks as everyday computers – which scientists refer to as classical computers – the main difference being that the quantum counterparts obey the laws of the smallest particles: quantum mechanics. The laws of quantum mechanics allow these building blocks to exist in **superposition** – in multiple states at once.

In both classical computers and quantum computers information (stored on either classical bits or quantum qubits) is manipulated by performing logical operations. When the computation is completed, we need to retrieve the answer, which for quantum computers is done by measuring the qubits. An additional property quantum computers can exploit is the surprising phenomenon of **entanglement**.

Bits and Qubits

As we have the alphabet as a basis for communication in English – all words can be built out of these 26 letters – computers also have an 'alphabet': bits. Rather than 26 letters, bits can take two values: "0" or "1". Just as letters are combined in books to form nice stories, your PC or smartphone combines millions of "0"s and "1"s for performing calculations, displaying a movie or loading your favorite cat gifs!

In quantum computers, the fundamental units of information are represented by quantum bits (qubits) – the quantum counterpart of the classical bit. Besides being exactly 0 or 1, a quantum bit can also be in any combination of 0 and 1, called a superposition.

Superposition

Superposition refers to the phenomenon that quantum objects can be multiple things at once. For our qubits, this means they can be any arbitrary combination of "0" and "1", such as 40% "0" and 60% "1". Although we do not experience superposition in our daily lives, it is a regular phenomenon on the quantum level. To get a feeling of what superposition means, imagine spinning a coin on its side on a table. Before it collapses to the table, you are uncertain of whether it is head or tails, and you may take it as being both. Similarly, a qubit can be both "0" and "1".

Somewhere between
A quantum bit can be in a superposition, that is in a state somewhere between "0"and "1".

Logic Gates

In order to get anything meaningful out of our (qu)bits, we need to manipulate them. Say we have two numbers, 16 and 312, and we wish to multiply them. In a classical computer, we can convert these numbers into bits (see encoding information) and manipulate them, such that we get the correct answer. This is done using operations which are called logic gates – a sequence of actions which in our case represent multiplication. The result of this manipulation is passed on to new bits, which we can read out to get the result (which is 4992 if you're curious).

Likewise, we need to manipulate our qubits in order to get anything meaningful out of the quantum computer. The major

Encoding Information

There are many ways of going from our human alphabet to the binary alphabet of computers. One such way is using the ASCII table, which is like a dictionary that translates "words" of eight bits (one byte) to our alphabet. For example, if we'd like to write DELFT, we'd need a total of 5x8=40 bits.

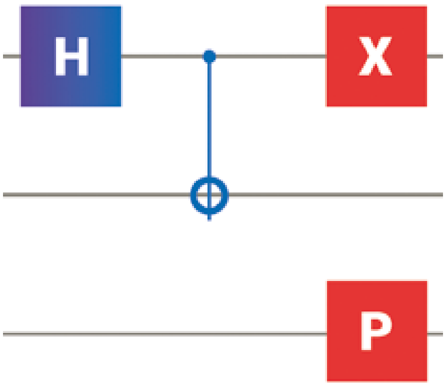
D - 01000100 **E** - 01000101 **L** - 01001100 **F** - 01000110 **T** - 01010100

Quantum computing is more efficient with its qubits. Instead of using 40 qubits, we can encode "DELFT" in just 8 qubits by using a superposition of the ASCII codes of the five letters in this word. The downside is that we cannot readily get the entire word at once from this superposition – measurement will prevent us from obtaining "DELFT" in one go (see Measurement). Instead, when we measure these qubits, we will randomly get any of the letters in "DELFT", each with a 20% probability.

difference is that quantum logic gates do not compare bits and pass on the result to new bits – they manipulate the qubits directly. This means that as our quantum computer is running, it is constantly changing in which superposition of "0" and "1" each qubit is.

Measurement

When the calculations are done, we'd like to know the results. For quantum computers, this is done by measuring the final data encoded in the qubits. However, what will you get when you measure something that can be 40% "0" and 60% "1"? The laws of quantum mechanics dictate that you will always measure either "0" or "1", in our



Quantum and classical gates
Individual logical operations, called gates, are combined to carry out quantum algorithms.

case with 40% and 60% probability – just like when you slap a spinning coin flat on the table, you will sometimes end up with heads and sometimes with tails. This means that when you run the exact same procedure twice, you may get different outcomes.

That is why quantum programmers need to be very careful to end with 100% "0" or 100% "1" when designing their algorithms. This means that when quantum computers explore many different possibilities in parallel, algorithms need to be cleverly designed so that they do not end up with just as many different solutions, each with a very small probability. They do so by minimizing the chances that you get the incorrect solutions, and amplifying the chance of the correct outcomes.

Entanglement

Qubits have another property which knows no classical analogue: entanglement. This property is that they can be correlated in a surprisingly tight way, even over long distances. Imagine you have two coins spinning on a table, and you measure them by smashing them one after the other. The probability that the first coin gives heads is 50%, and then when the first coin indeed came out as heads, the probability that the second coin gives heads is still 50%. If these coins were entangled, like we can do with qubits, this can change. We can entangle them such that if one coin ends up heads, then the other coin always gives heads too (and the same holds for tails).

The surprising property of entanglement is that this correlation persists over long distances. Let's say I send you to Australia with one spinning coin of our entangled pair, and I remain in Delft with the other one. When you slap your spinning coin in Australia, and you find tails, you will immediately know what the outcome is when I slap my spinning coin in Delft – it will be tails too! This is something we do not experience at all in our daily lives – Einstein even referred to it as "spooky action at a distance".

"One qubit can store the value of two numbers, and with each qubit that we add, we can store the value of twice as many possibilities."

Exponential Power

It is common to see claims that quantum computers offer "exponential speedup" to computation or that they are "exponentially fast". But what does this mean? In essence, quantum computers are not a kind of magical machine that will make all our devices faster. On the contrary: although quantum computers can be faster, this depends on the design of very specialized algorithms that can solve certain problems (see also Applications on page 36).

So what is this "exponential speedup"? Quantum computing is efficient with the information it can process through its qubits. It needs less qubits to encode the word "DELFT" than classical computers need bits. And this efficiency grows immensely when the number of qubits increases. One qubit can store the value of two numbers, and with each qubit that we add to our computer, we can store the value of twice as many possibilities. This exponential growth means that a 50-qubit quantum computer can capture a thousand million million numbers – more than there are stars in the Milky Way. Imagine what amount of information we can process with a 100- or even 1000-qubit quantum computer.

Measuring entanglement
Entanglement, a unique property of qubits, means that two qubits can be closely correlated even when separated by a large physical distance.

Quantum Circuits

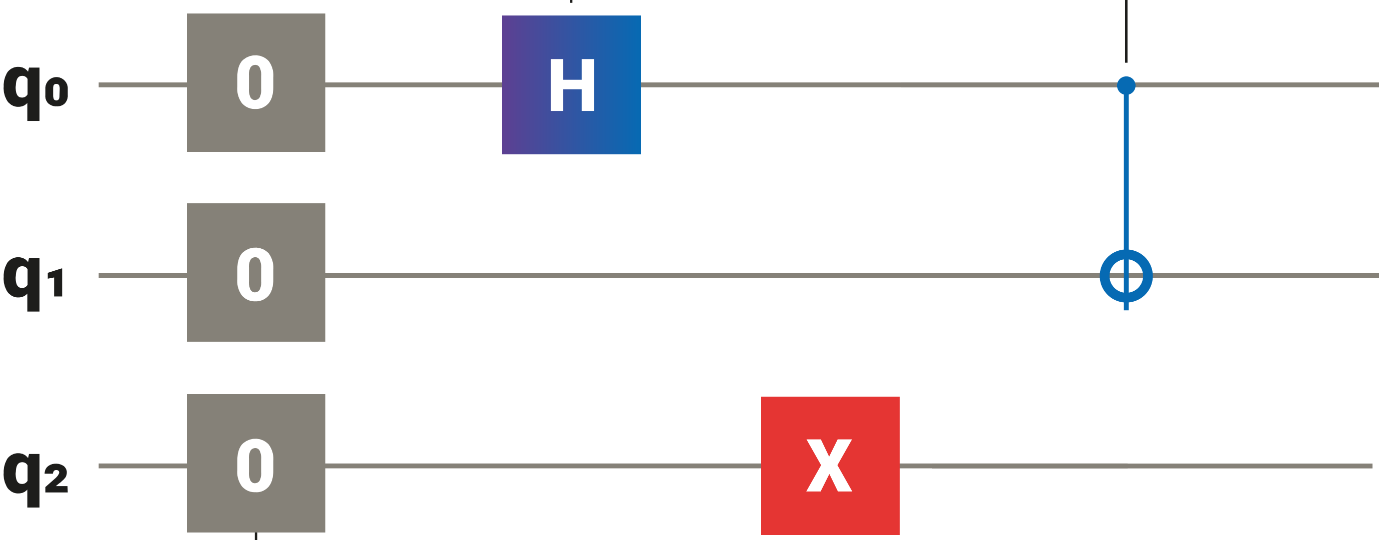
What does quantum computing look like? Exploring the basic units of quantum algorithms is a good place to start.

2 Superposition

The squares on each line represent gates. A gate is a transformation applied to a qubit. This one—the **Hadamard gate**—puts a qubit in **superposition**.

4 Entanglement

This line represents a **CNOT-gate**, which is conditional. If qubit 0's state equals "1", it applies the same transformation as the X-gate to qubit "1". Because qubit "0" is in superposition, this causes qubits "0" and "1" to be **entangled**.



1 Initialising

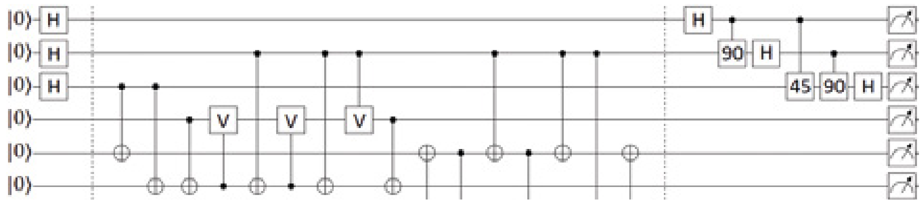
Each qubit in a circuit is denoted by a vector, representing its state. Here, all three qubits' initial states are set to "0".

3 Switching

This gate, known as the **Pauli-X gate** (or simply X-gate), 'flips' the state of a qubit from "0" to "1" or. "1" to "0". More specifically, it switches the amplitudes of the states "0" and "1".

Building Quantum Circuits

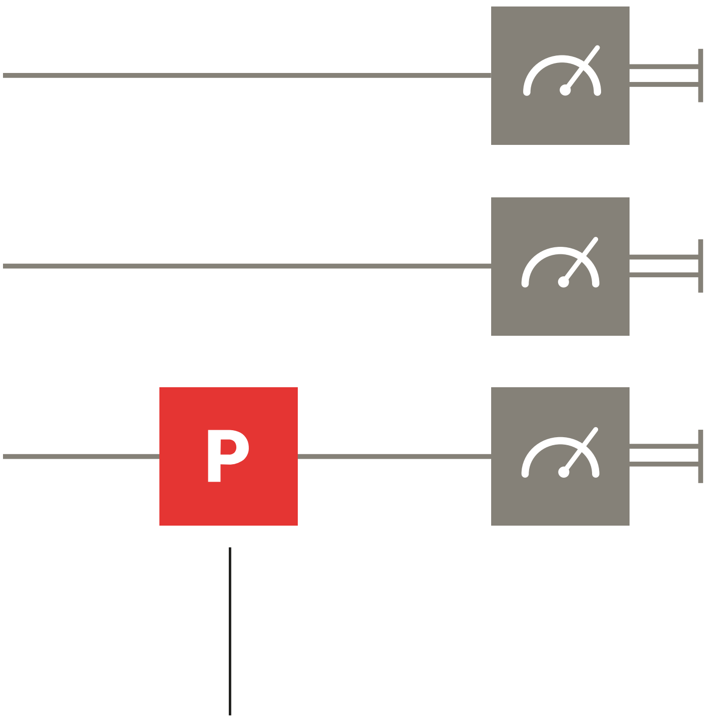
Quantum circuits are made by combining multiple successive gates. Cumulatively, they manipulate qubits – both individually and in multiples – to perform complex calculations known as algorithms. Shor's algorithm, shown below, is used to factorize integers.



Composing algorithms
Quantum algorithms, such as Shor's algorithm, are built using a composition of successive gates.

6 Measurement

Measuring a qubit makes it collapse into one defined state (known as an eigenstate). The measured value we get reflects this state.



5 Rotating

This gate, known as the **phase gate** (or simply P-gate), rotates the vector representing a qubit's state around the z-axis by a specified amount.

A quantum computing interface

Most quantum programming frameworks offer interfaces which represent the qubit operations as shown in the image on this and the previous page". In such a diagram, each line represents one qubit, which in this case all start in "0". The different squares indicate manipulation of a qubit via a gate. The H gate, for example, creates a superposition from the "0" state, whereas the X gate flips a qubit from "0" to "1" and vice versa.

Lastly, we see connections between different qubits. These indicate a conditional gate, in which depending on the state of a neighbor we do or do not manipulate the qubit itself.

Learn more: fundamentals
To learn more about the fundamental principles of quantum computing with videos and references, scan the QR code above!

Learn more: technical details
If you want to know more technical details and the mathematics behind quantum principles, scan the QR code above!

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Instruments
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QTD1242

Hardware & Software

From theory to reality

To make a quantum computer we need many tangible components, from quantum chips, control electronics and refrigerators to quantum algorithms and software.

Building the future

The laws of quantum mechanics were conceived well over a century ago, and since then they have found their way to technological applications such as transistors and lasers. But only in the past decades have we had the technological know-how to accurately create small, fragile quantum systems for computing. These systems – the quantum brain cells of the quantum computer – exist in all sorts and flavors: some are over a thousand times smaller than a hair, whereas others can be a few hairs thick. Some require giant refrigerators which are hoisted from the ceiling to keep them sufficiently cool, where others can be operated near room temperature. And they all need a plethora of wires and electronics, often stacked in man-high racks.

Scientists and engineers from many different disciplines – from physics to computer science and electrical engineering to design engineering – cooperate to create the many components of a quantum computer. Some may work on qubits and their connectivity, some on correcting errors that accumulate in the quantum computer, where others work on making software or creating user-friendly interfaces. But when can you say you have succeeded in building a quantum computer, and what does it take to build one? In this chapter, we highlight the building blocks of a quantum computer – from quantum chips to software stacks.

Texts and infographics in this section were produced by Brennan Undseth, Timo van Abswoude and Caiseal Beardow.

Building the future
Scientists and engineers at TU Delft and QuTech are helping to build the future of quantum computing.

A team effort
Many different components, and disciplines, contribute to the building of a quantum computer.

Building a Quantum Computer

Building a universal quantum computer is one of the most ambitious scientific challenges of the 21st century. Luckily, there's many professions that can help.

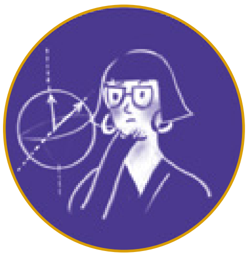
Who can help to build a quantum computer?

Engineers

Building the extreme conditions required to operate qubits: cryogenics, vacuum systems, and advanced electronics, to name a few.

Physicists

Designing qubits and realizing logical operations.



Programmers

Implement the necessary software tools used to control and operate quantum computers.

Mathematicians

Optimizing the power of quantum computers.

Designers

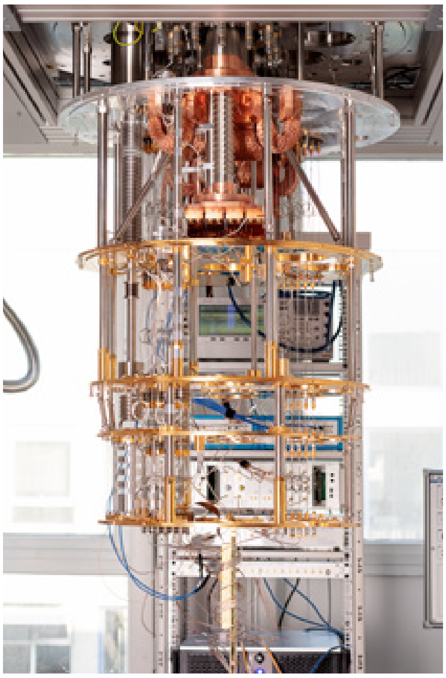
Finding ways for people to easily and productively interact with quantum computers.

Computer Scientists

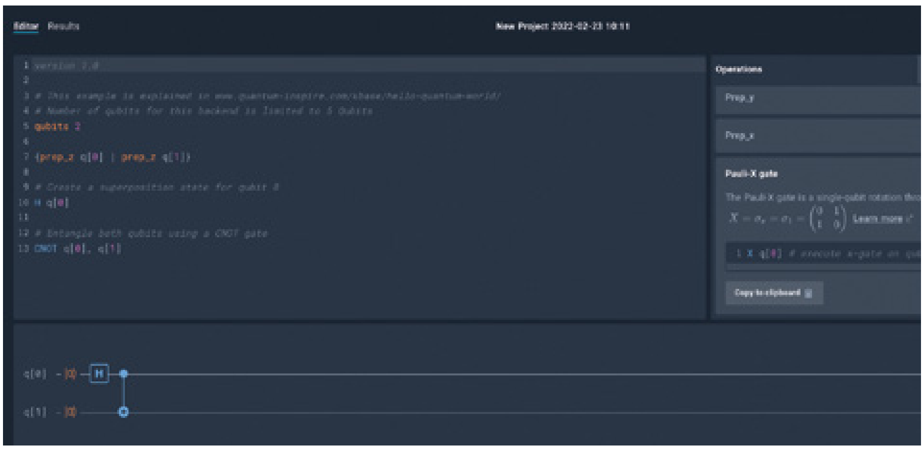
Inventing quantum algorithms that can be put to use on real-world tasks.

The DiVincenzo Criteria

We are in the early stages of the development of a quantum computer. Today's prototypes literally come in all shapes and sizes, but all share the same requirements necessary to be called "quantum computers". These five requirements were codified by David DiVincenzo in 2000, and are now commonly called **The DiVincenzo Criteria**.

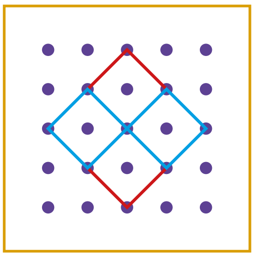


Hardware
A quantum computer requires qubit hardware, but also additional traditional electronics as well as powerful refrigerators.



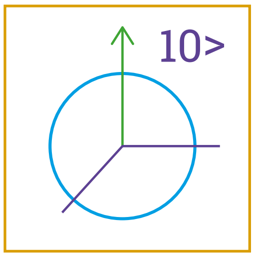
Software
Programming a quantum computer can be done using various high-level languages which facilitate generating the proper quantum circuit.

1 Have well-defined, scalable qubits



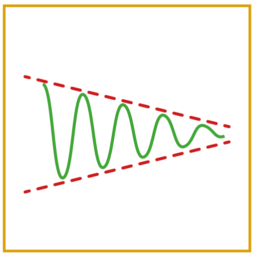
You can't have a quantum computer without qubits. There are many, many ways to make qubits, as we'll see later.

2 Begin computations in a reliably initialized state



The computer must start in a known state prior to running a program, otherwise the answer would be meaningless. Generating this known state is called initialization.

3 Have a sufficiently long coherence time

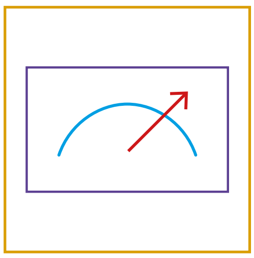


Qubits are extremely fragile and inevitably lose information. The timescale over which this happens is known as the **coherence time**, which must be sufficiently long to complete the computation.

4 Have access to a universal gate set

To run all quantum algorithms, a full set of operations – or gates – must be available. Otherwise, the power of the quantum computer will be limited. Having a set of universal **gates** requires full control over individual qubits as well as the ability to make two or more qubits interact with each other.

5 End computations with reliable measurement



At the end of a quantum program, we must be able to measure the qubits in order to get a result. This means that a qubit is only useful if there is a way to reliably distinguish between the "0" and "1" states.

The Qubit Zoo

There's many different ways to build a qubit—but choosing the right approach depends on what we want to do with it.

The fundamental building block of classical computers, from smartphones to supercomputers, is the bit. Bits are built out of semiconductor-based devices called transistors. They are a feat of modern engineering: billions of transistors can be fabricated on a single chip and are operated with tremendous reliability.

In contrast to classical computers, we are currently still in the early stages of the development of quantum computing, and there is no "best way" to build a qubit. But there are many successful approaches, each with their own advantages.

Superconducting Qubits

Superconducting qubits require three ingredients: (1) cold electronic circuits, (2) superconducting material, and (3) so-called "Josephson junctions".

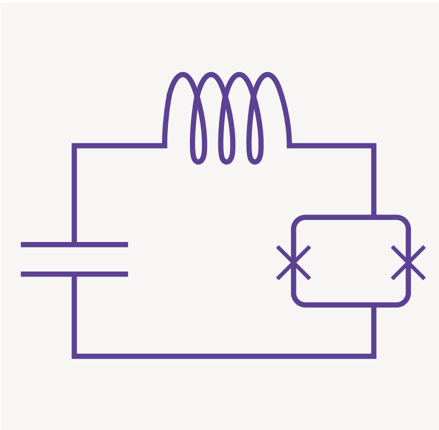
Extremely cold electronic circuits behave quantum mechanically. By constructing these circuits out of a superconducting material – a material with no electrical resistance – the tiny currents in these circuits last long enough that they can be controlled. Small gaps in the circuit called Josephson junctions are required to isolate the two distinct "0" and "1" states used to form a qubit.

There are actually many types of superconducting qubit, the most successful of which has been the "transmon" which was used in Google's famous quantum supremacy experiment in 2019. Devices with 50-100 qubits are currently being prototyped, making them the most commercially advanced qubit to date. Yet, they have a relatively large footprint, and it is not clear if their coherence time can still be significantly improved.

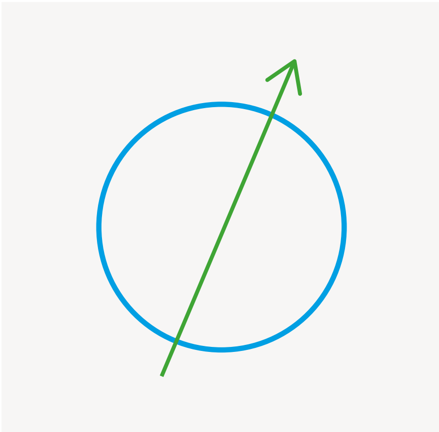
Spin Qubits

The spin of an electron is the quantum property that makes it behave like a tiny magnet. In certain materials, like iron, many of these spins add together to make things like fridge magnets and compasses.

An individual spin is, by several measures, the ideal qubit. When a spin is placed in a magnetic field, it exists in two states: aligned with the field or against the field. The challenge is to trap the individual electrons which hold the spin. One method involves confining electrons in very small semiconductor boxes called quantum dots. This can be done on silicon chips that closely resemble the chips used in classical computers. It is hoped that the advanced fabrication techniques used by the semiconductor industry will be able to manufacture the millions of qubits necessary to build a world-changing quantum computer. It is still a challenge though to connect many spin qubits. Another technique to capture individual spins requires defects such as so-called NV centers in diamond. Despite the name, these defects are quite useful for trapping single electrons in an otherwise perfect crystal and make for high-quality qubits.



Superconducting Qubits
These qubits use extreme refrigeration and superconducting material.

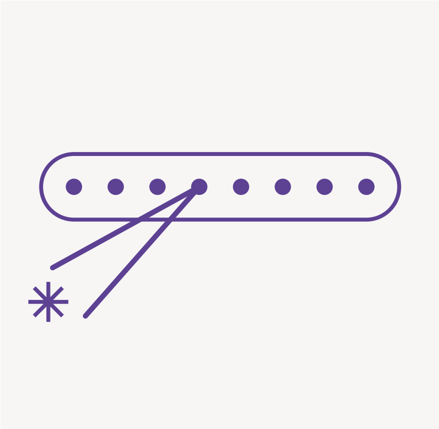


Spin Qubits
These qubits are like tiny magnets, where individual electron spins are added together.

A useful property of the NV center is that it allows a spin qubit to be converted into a photonic qubit, allowing to transfer the qubit over an optical fiber. It remains challenging to scale to very many qubits, though.

Ion Traps

Ions are electrically charged atoms, meaning they are particles found on the periodic table of elements that have lost or gained electrons. All ions of the same element and charge are indistinguishable – a calcium ion in Amsterdam is the same as one on Mars. Since ions are charged, they may be "trapped" using a combination of electric fields which confine a group of ions in a small vacuum chamber. The atoms may then be laser cooled to extremely low temperatures, such that they form a chain of ions. Ions are tiny, and quantum mechanical by nature. To make qubits, ion trappers pick a particular ion, such as Ytterbium-171, that has two high-quality

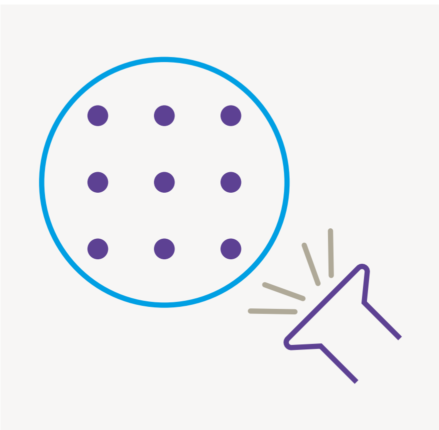


Ion traps
In ion trap qubits, a group of ions is chained together and controlled with laser pulses and vibrations.

quantum states. The qubit formed by these two states can be controlled with precise laser pulses, and qubits can interact with one another through vibrations in the ion chain. Trapped ions have achieved the best-quality logical gates of any qubit type, but again it remains challenging to scale to many qubits.

Neutral Atoms

Neutral atoms share some notable similarities with trapped ions, but show also many key differences. Similar to a trapped ion, a neutral atom can form a qubit by selecting two high-quality quantum states of the atom. Quantum computation can be performed by manipulating the neutral atoms with lasers, just as with trapped ions. However, unlike ions, neutral atoms are not

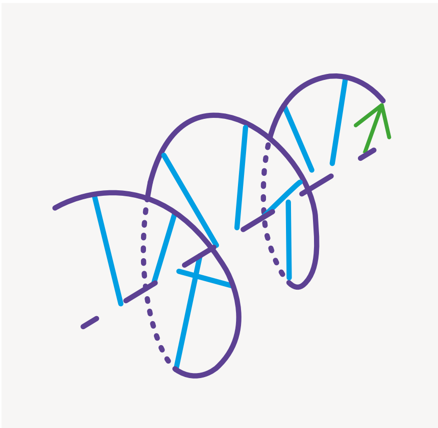


Neutral atoms
Neutral atoms are manipulated using light beams to arrange them in three-dimensional space.

charged, meaning they can't be electrically trapped in the same way as ions. Instead, neutral atoms are trapped using precisely focussed light beams called optical tweezers which can move individual atoms around in a vacuum. Hundreds of neutral atoms can be arranged intricately in three dimensions, making neutral atoms a very versatile platform. The main challenge for this type of qubit is the comparatively low accuracy of gate operations.

Photons

One very important consequence of quantum mechanics is that light comes in discrete packages of energy called photons. Photons, unlike electrical circuits, atoms or spins, are always moving at an incredibly high speed – nearly 300 million meters per second in vacuum. This inspires the name "flying qubits", often associated with photons, and it makes them ideal candidates for moving quantum information around in a network of quantum devices. There are many ways to make a qubit using photons. One common approach is to use the photon's polarization, or orientation, which

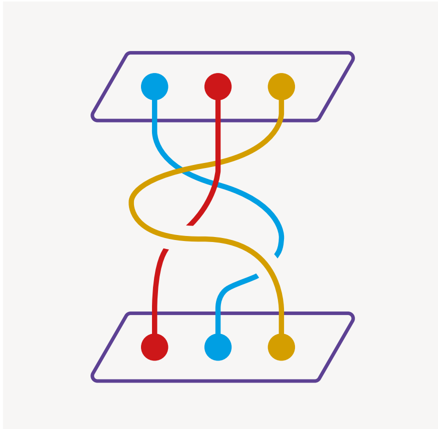


Photons
The polarization of photons, just like in sunglasses, is used to measure different quantum states.

may be in the "horizontal" or "vertical" state. Just like polarizing sunglasses are used to filter out sunlight, photon detectors can be designed to measure only certain polarized quantum states. Other special crystals called wave plates and beam splitters, can be used to "rotate" photon polarization and conditionally manipulate their trajectory. Currently, loss of photons, and thus of qubit states, is most limiting for this technology, making scaling-up an ongoing challenge.

Topological Qubits

Consider an elastic band. Regardless of how you stretch, twist, tie, or scrunch the elastic band, it will always contain a single loop (as long as we don't break it, which isn't allowed). We can call this loop a topological property of the elastic, since it is robust to many types of deformation.



Topological Qubits
This type of qubit is particularly robust and resistant to errors.

Topological qubits strive to take advantage of similar robustness. Imagine you have two special particles on a flat surface. You might reasonably expect that dragging one particle in a loop around the other won't change anything. However, at the quantum scale, braiding one particle around the other results in a measurably different state, and this type of operation can constitute the building blocks of a topological quantum computer. The exact details of the path, – the zigs and zags the particle took on its journey, – don't matter, similar to how scrunching the elastic band doesn't change the fact that it's a loop.

This property makes topological qubits constructed out of these sorts of particles very resistant to errors. In practice, topological qubits are challenging to engineer, and many aspects are still in the stage of fundamental science. However, the allure is tremendous: a quantum processor constructed out of topological qubits would likely require fewer qubits and be more efficient than quantum computers using other qubit technologies.

There are many ways of approaching the building of qubits. The next challenge is combining and preserving them.

Fault-Tolerant Computing

It takes more than just qubits to build a powerful, universal quantum computer.

Decoherence

Qubits are extremely fragile, and this limits how long they are useful for quantum computing. For example, if a quantum calculation is expected to take 5 seconds, but the quantum computer has qubits with a coherence time – the time a qubit can hold its information – of 1 second, the result of the programme will be nonsense. Scientists and engineers call this decay in quality decoherence, and understanding it is essential to evaluate the power of quantum hardware.

Decoherence can be classified into two categories: relaxation and dephasing. Imagine a qubit as a coin spinning on a table. The relaxation time is how long it takes the spinning coin to fall down. The dephasing time is how long it takes us to lose track of how fast the coin is spinning. For real coins, these effects happen because the surface of the table is rough, and air resistance causes the coin to gradually slow down.

Qubits are sensitive to any disturbance, even as small as microscopic vibrations or cosmic rays from outer space. It is for this reason that qubits typically require extremely cold temperatures, which reduce the vibrations of atoms in materials, or high vacuum, which lowers the risk of unwanted particles bumping into the qubits.

Qubit Quality and Quantum Volume

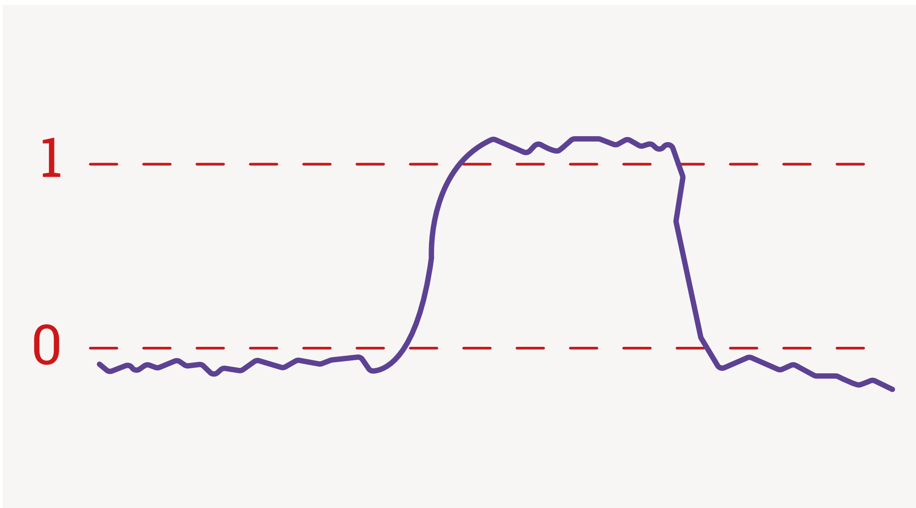
It is tempting to conclude that qubits with a longer coherence time are better than those which decohere faster, but the reality is more nuanced. Qubits may last a long time if they're very well isolated, but they must also be readily initialized, manipulated, and measured in order to build useful quantum computers. Accessibility and isolation are often at odds. Commonly, qubits with long lifetimes are also slow to operate. For this reason, a more meaningful measure of the power of a qubit is its quality factor, the ratio of how long a qubit lasts and how many operations can be performed with it during this time. IBM has encapsulated this idea with their coined term "Quantum Volume", which measures the power of a quantum computer both by how many qubits it has and how many operations can be performed within the coherence time.

Error Correction

Classical computers, the ones we use in our day-to-day lives, rarely make mistakes. Sometimes it feels like they do, when your desktop freezes or a sent email vanishes in the ether. Practically speaking, however, this is because of a mistake in the instructions given to the computer, not because of an error in the semiconductor chips. The bits in a computer, the "0"s and "1"s representing classical information, are digital, and therefore rather insensitive to errors. If a "0" has to change into a "1" in a classical computer, and this is done with a slight mistake, the result still looks mostly like a "1" and is then treated as such.

Let's imagine a computer that is really bad at flipping "0" to "1". How can we prevent errors in our understanding of what this computer is supposed to do? The simplest answer is to let this computer not work on single bits "0" or "1" but on three bits "000" or "111" simultaneously. We can then assume that the computer wants to "0" to a "1" if it does so for at least two "0"s:

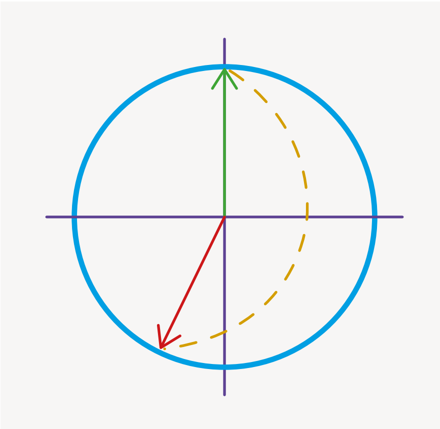
000	→	110	→	1
000	→	011	→	1
000	→	111	→	1
000	→	101	→	1



Error sensitivity
Digital bits, used in computers to represent classical information, are not very sensitive to errors.

Now, even though there are plenty of mistakes, the error could be tolerated because the computer could get it right most of the time. Things aren't so simple in the case of quantum computers for three reasons. First, the possible errors are continuous. For quantum computing, we don't just care about flipping between "0" and "1", we also care about the states in-between. Flipping too much or too little matters a lot.

Second, there is a fundamental law in quantum computing that implies that we can't duplicate qubits (this law is known as the No-Cloning Theorem). This takes away the possibility of copying a qubit multiple times, then trying the operation on each copy, as we showed above.



Single-qubit error
Errors in quantum computing are continuous – flipping too much or too little matters a lot.

Last, there is the difficulty that measuring a qubit destroys superposition. As soon as we look at a qubit, we see exactly "0" or exactly "1". If we suspect an error may have taken place, we can't simply look at the qubit to check without ruining the computation.

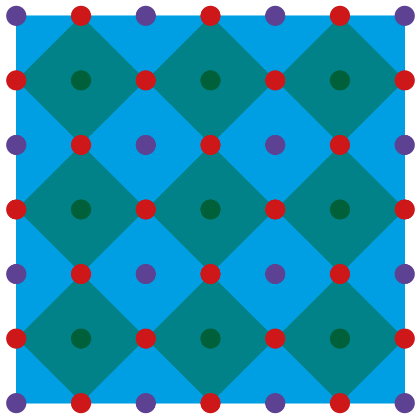
These sound like insurmountable obstacles, but by using the powerful techniques of quantum error correction, inevitable errors can be detected and corrected without running into any of these three roadblocks.

From Physical to Logical Qubits

Quantum error correction uses many imperfect physical qubits to create fewer ideal logical qubits. A quantum computer that operates using logical qubits is called a fault-tolerant quantum computer. One important way to do this is with the surface code, which makes use of a grid of qubits that are all connected to their neighbors.

By encoding quantum information in this way, small errors incurred during initialization, computation, and measurement don't pile up, and can be corrected as the quantum computer runs. The catch is that this requires overhead. A logical qubit may require 10, 1000, or even more physical qubits, depending on how error-prone they are. Because of this, an ideal algorithm requiring a thousand qubits may actually require a quantum computer with millions of qubits. Quantum error correction, however, doesn't always work: the amount of errors in quantum computing it has to deal with should be limited. The surface code can tolerate an error rate of about 1%. To date, superconducting qubits, spin qubits, and trapped ion qubits have all achieved universal control with error rates below 1%.

The most pressing challenge is to increase the number of physical qubits, from the dozens we have today to the thousands (or much more) we need to run the most impactful quantum algorithms. This race to build a so-called fault-tolerant quantum computer is one of the most exciting and technologically demanding pursuits in modern science.



Surface code
Each dot is a qubit: the red ones make up a logical qubit, whilst the green and blue regions represent checks for different types of errors.

Error correction in action

"I can't deny that, although I am a PhD student in superconducting quantum computers, quantum error correction is still counter-intuitive to me. Conceptually, the idea that information can be preserved by encoding it on more faulty (physical) qubits to create a protected (logical) qubit, that is fault-tolerant to certain errors, seems magic!

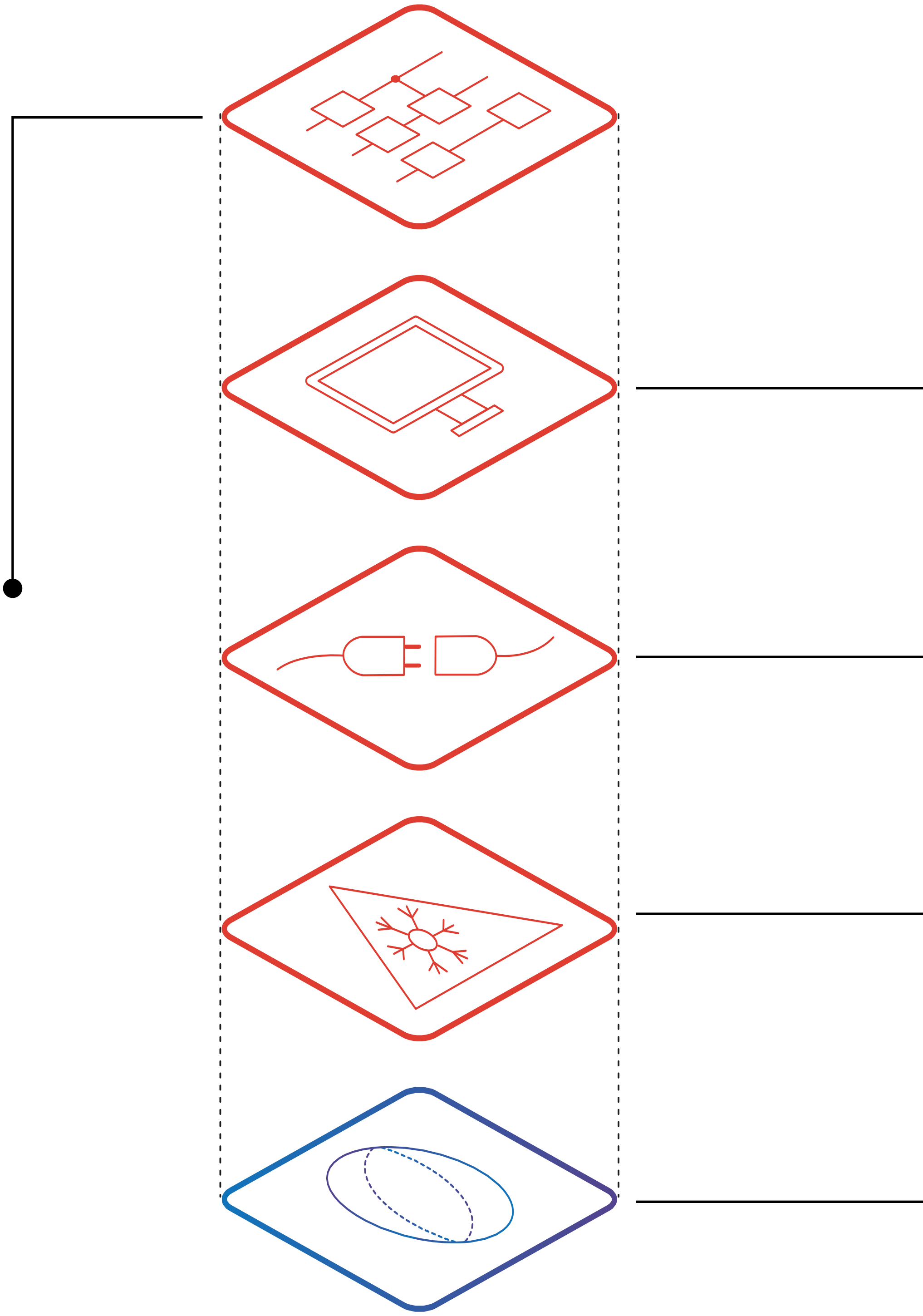
One can classically think of it as creating multiple copies of the information of interest and ensuring the number of copies are subject to errors that are as independent as possible. Now it is not hard to see that if there is any sort of correlated errors impacting these copies (simultaneously and/or spatially) will be a threat to preserving the information. This is one (the biggest in my opinion) of the outstanding challenges to realize quantum error correction at large scale quantum computers. It gives me a great feeling to be one of those who are contributing to that."

- Hany Ali (PhD candidate, QuTech)

Software and Control

From algorithms to refrigeration, it takes a full stack of components to make a quantum computer.

Although the quantum chip with qubits is what gives a quantum computer its amazing power and properties, it is a very small part of the actual computer. In fact, a quantum computer is mostly made out of "ordinary" classical electronics, which we need to give commands to the quantum chip and read out the results. This complete quantum computer package is often referred to as a full stack quantum computer, and it consists of 5 levels.



1 Applications and algorithms

First, we need to convert our idea for an algorithm into the algorithm itself. We translate our idea of how we can magnify the amplitude of the correct solution, and destroy the amplitude of the wrong solutions onto a concrete sequence of actions which are called quantum gates. These gates can, for example, create a superposition (like the Hadamard [H] gate) or flip a qubit from "0" to "1" (like the X gate). These algorithms can be viewed as the language we speak when instructing a quantum computer what to do.

2 Software

Next, we need to communicate our algorithm to the quantum computer. This is done by expressing it in a quantum programming language on an ordinary computer. Many manufacturers have developed their own programming frameworks, such as Braket, Q# , Qiskit or Forest. Because not all quantum computer users will be experienced programmers, most frameworks offer an interface in which you can simply drag and drop your quantum algorithm – very similar to how you do that on your laptop or PC when you want to let it do a computation but you do not know how to code. The framework itself then handles all the low-level coding, such as communicating with electronics. This will also be where you can retrieve the results of your computation, once it is done.

3 Electronics

Each operation that we perform in our algorithm corresponds to a physical signal going to the qubits. A whole tower of electronics is responsible for sending the correct signals to certain qubits at the right times.

4 Refrigerator and wires

High temperatures can destroy quantum information. For many qubit types, it is therefore essential to keep our qubits at low temperatures – near absolute zero, which is about -273°C. This is why quantum chips are placed inside enormous refrigerators. However, the qubits do need to be connected to the outside world in order to receive our commands and send back their results. A single qubit can already require multiple wires for this – imagine how crammed it would be with thousands or even millions of qubits. This is why a lot of research is going into looking at more efficient ways of sending information over as few wires as possible.

5 Quantum device / processor

This is where the magic happens: when we have programmed our algorithm, the qubits in the quantum processor will do the computations. There exist many different types of quantum chips, discussed earlier in the magazine.

Learn more: quantum hardware

To learn more technical details about the different types of qubits and how to build a complete quantum computer, scan the QR code above.

Qubits and Gates

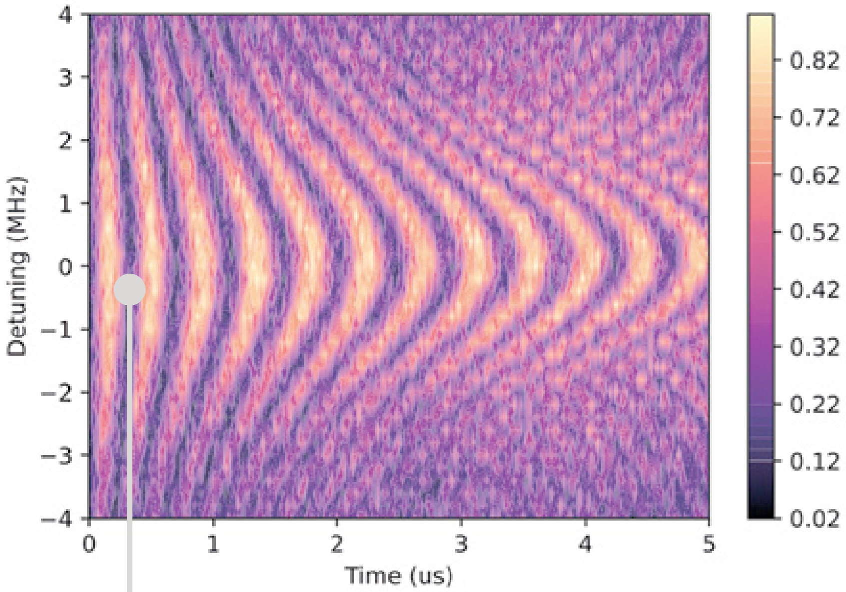
How do quantum gates actually work? Visualizations can help us to understand what's going on inside the box.

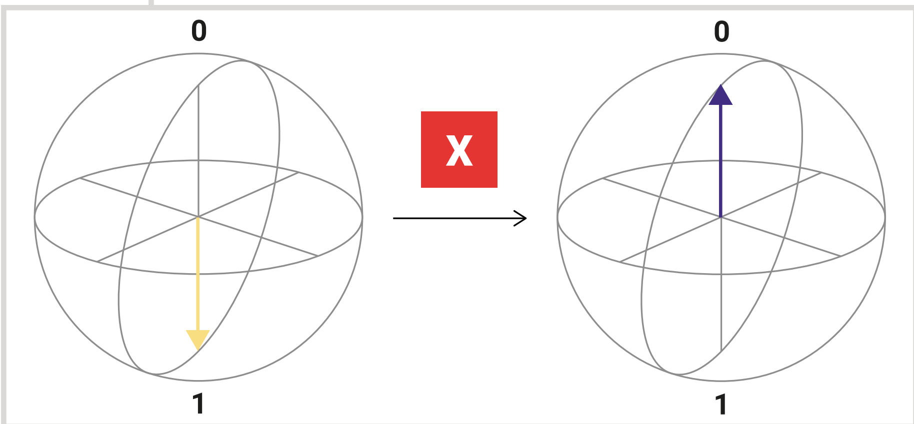
A single-qubit gate

How do scientists and engineers actually perform a quantum operation, such as an X-gate? Let's consider a spin qubit. A spin behaves a bit like a top spinning around its axis. When a top is spinning on a table, it's quite robust against small pokes and prods. Similarly, a spin qubit won't easily flip over. However, if we apply a signal that has the same frequency as the spin qubit, the spin will begin to rotate from its "up" (or "0") state to its "down" (or "1") state. The longer the pulse is applied, the more the spin will rotate. The larger the pulse, the faster the spin will rotate. This spin-flipping phenomenon is known as Rabi oscillation.

The plot on the right shows the state of the spin for various pulse durations and frequencies. We can see that only pulses with exactly the same frequency as the qubit – known as its resonant frequency – will cause perfect flips. To perform an X-gate, for example, this frequency must be tuned for each qubit. Then, the correct pulse duration can be selected such that the spin flips exactly halfway. In this plot, we refer to the difference between the frequency we apply and the qubit's resonant frequency as detuning, shown in the plot on the Y axis.

The colors in the plot represent the probability of the qubit's state being "up" (0), as shown by the legend on the right of the graph. When a point on the plot is dark purple, the qubit's state is most likely to be "up"; likewise, the light yellow points mean the qubit's state is most likely to be "down" (1). The contrast between light and dark is clearest around the center of the Y-axis – so where detuning is zero, and we are applying the qubit's resonant frequency. This shows us how making a qubit resonate results in clear, consistent "flips" between up (light) and down (dark).





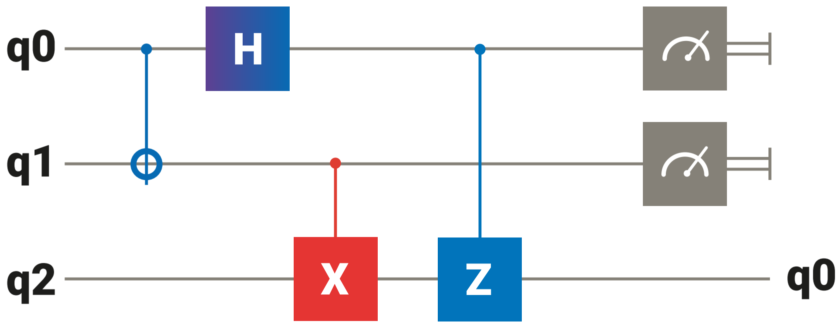
Bloch Spheres

A Bloch sphere (shown above) is a common way of visualizing a single qubit's current state. We do this by showing the state as a vector, starting from the center of the sphere, and pointing to somewhere on its surface. The top and bottom "poles" of the sphere are called basis states – usually "0" and "1", or positive and negative. When we measure a qubit, we find out which of these two states the qubit is in.

A two-qubit gate

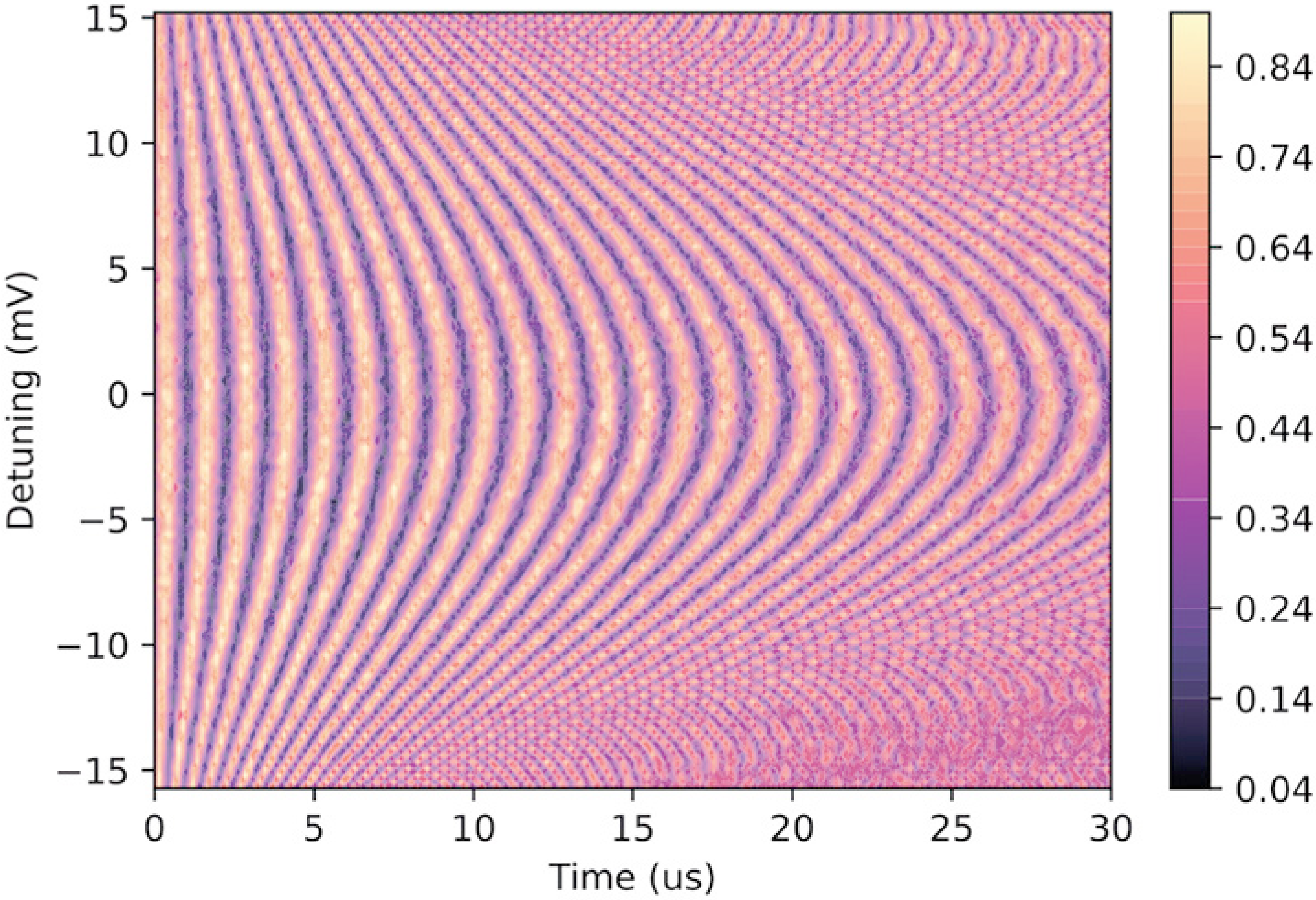
Quantum algorithms are built not only with single-qubit operations, but by using the interactions between multiple qubits as well.

Below is a plot of a two-qubit gate called a CPhase (controlled phase) gate. When two spins are captured in two adjacent wells, or quantum dots, they will exchange information about their state with one another. Unlike in the case of single qubit gates, no high-frequency pulses are needed here. The interaction is "turned on" when the barrier between the two electron spins is decreased such that the electrons move close to one another. Here, the amount of time that the barrier is moved down determines the duration of the two-qubit interaction.



Calibrating circuits
Implementing a particular circuit means tuning the specific qubit hardware and finding the right control pulses.

"Pulses with the exact same frequency as a qubit—known as its resonant frequency—will cause perfect flips."



Resonating Qubits
This graph shows how frequency pulses are used to execute a 2-qubit CPhase (controlled phase) gate.

The Future of Quantum

The near future of quantum computing lays out milestones and obstacles to the ultimate goal: a universal, fault-tolerant quantum computer.

HARDWARE & SOFTWARE

2019 — Quantum Interfaces

Graphical User Interfaces such as QuTech's Quantum Inspire have been developed to enable a diverse range of users to interact with (simulated) qubits and quantum algorithms.

2021 — Prototype Logical Qubit

In 2021, several groups demonstrated the basic building blocks of an error-corrected qubit - though not usable for computation yet.

MILESTONE

2023 — Real Logical Qubit

By 2023, companies aim to produce a *real* logical qubit - with errors smaller than the individual constituents. This would be a major milestone towards building usable quantum computers.

APPLICATIONS

2019

MILESTONE

Theoretical Advantage

Google have demonstrated theoretical quantum advantage: performing complex mathematics with a quantum computer that would take a classical computer many years.

2021 — Molecular Models

Quantum computers have been used to model very small molecules as proof of principle. To show quantum advantage, this has to be scaled up for more complex chemical processes.

The NISQ Era

The Noisy Intermediate-Scale Quantum (NISQ) era is the name given by quantum scientist John Preskill to the near future of quantum computing. It stands for the time in which quantum computers are far from perfect: they are still noisy, without full error correction. Moreover, they consist of a limited number of qubits – the intermediate scale. NISQ computers may have potential applications in chemistry, physics and a few other niche subjects, but do not unlock the full potential of quantum computers – not until we can eliminate errors entirely.

2024

Specialised Computers

The EU Quantum Manifesto places specialised quantum computers (>100 physical qubits) for chemical and mathematical problems as a near-tearm goal.

2024

Quantum Simulations

As specialized computers are built, equally specialized simulations can be run—particular materials or types of conduction, for example.

2025

MILESTONE

Combining Qubits

Logical qubits can be combined to make a larger system capable of simple computations—one of the last barriers to a real, fault tolerant quantum computer.

2027

MILESTONE

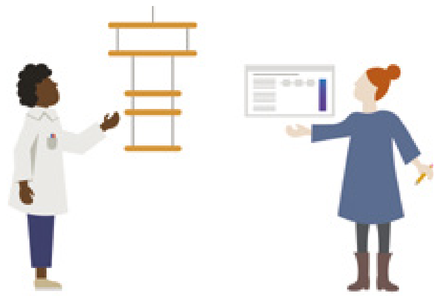
NISQ Applications

Can we find a useful application of a quantum computer before full error correction? Researchers are working hard to find possible algorithms and applications.

2028

Computing Memory

Within the next decade, Quantum Delta predicts the development of quantum computers with a limited memory capacity.



Future applications

Once a fault-tolerant quantum computer has been built, the applications of this technology broaden significantly. Instead of the small-scale, niche applications of the NISQ era, quantum computing could be implemented in many use cases – such as optimization problems, modeling of complex real-world systems, performing searches and factoring. These capabilities can be applied to domains such as cybersecurity, industrial chemistry, material science, and many more.

Distributed Computing

By the end of this decade, distributed and anonymous quantum computing could be developed.

2030

MILESTONE

Universal QC

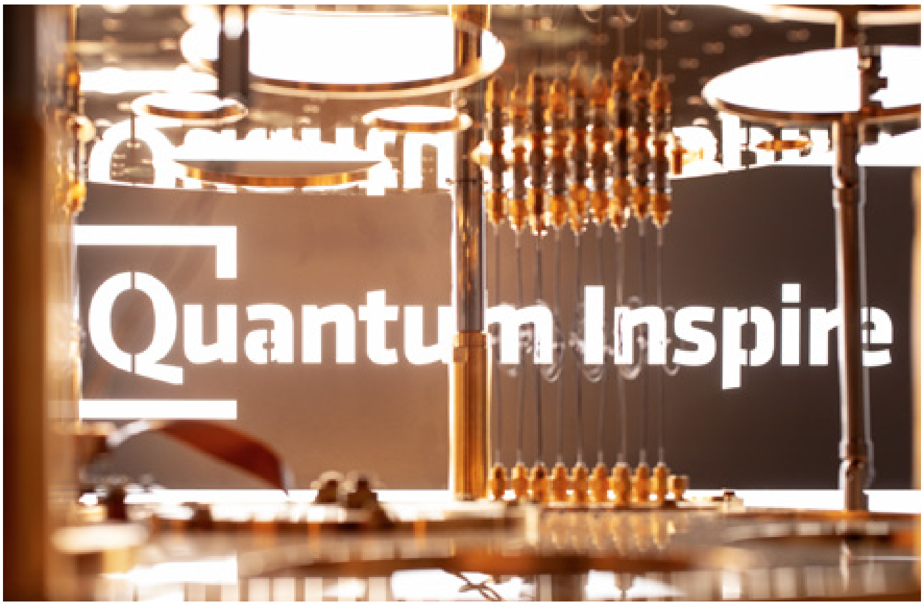
The eventual goal is a universal, fault tolerant quantum computer, with many logical qubits and sufficient memory for computations. This will enable a wide range of new applications!

2033

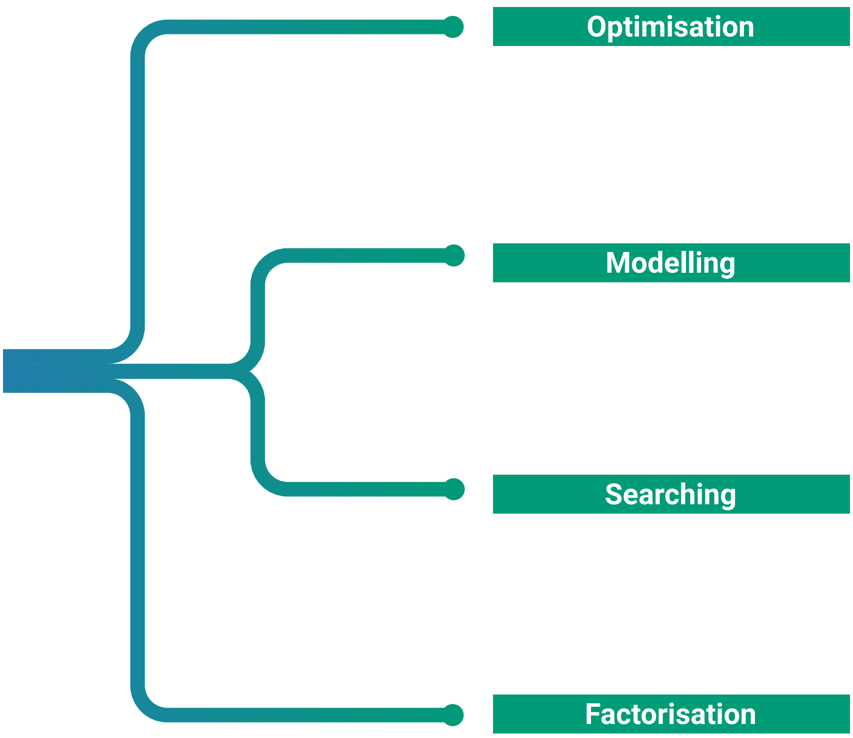
2035

Quantum Internet

Quantum Delta predicts the development of a robust, usable quantum internet in the not-so-far future.



A human touch
Specialized demonstrators (such as QuTech's Quantum Inspire) are being developed as the first point of contact between users and quantum computers.



The Fine Print

Predicting the future is tricky, so many research timelines are cautiously optimistic. Furthermore, many businesses with a stake in quantum computing have an interest in boasting about the rapid progress the field is making. The field of quantum computing is indeed flourishing, but hype alone does not build a fault-tolerant quantum computer. There are many critical engineering challenges to still be overcome, with each promising qubit type coming with its own set of challenges. Critical scientists sometimes compare the field of quantum computing to that of nuclear fusion – which hopes to harness the powerful reactions that occur in stars to make plentiful clean energy on Earth. First conceived in the early 20th century, there is an old joke that it is 20 years away and always will be. Yet with much research, it is often the journey itself that brings the unintended surprises which yield great value to society. Only time will tell what timeline future generations draw when they reflect on the current developments of "Quantum Technology 2.0".

When will we have quantum computers?

Quantum computers already exist! They exist in many university labs, in research divisions of big companies and in Delft there are even two up and running at QuTech that you can try yourself. Quantum Inspire offers a platform which people from all over the world can access to learn quantum computing and test their ideas. Still, it is fair to say these quantum computers are still research prototypes. A full-blown quantum computer with which you can do truly complex calculations, such as breaking encryption with Shor's algorithm, does not yet exist. The challenge to build that full-blown quantum computer is taken up by researchers and engineers all over the world. The next part of this magazine is about this challenge.


OXFORD
INSTRUMENTS

Applications

Future Uses of Quantum

Building quantum computers isn't the only challenge—knowing what to do with them is just as important.

A quantum computer will only be useful if it can solve practical problems – and in particular solve them more efficiently than a classical computer. In fact, a quantum computer has already beaten classical computers. In 2019, Google engineers demonstrated that a quantum processor can solve a certain mathematical problem faster than a state-of-the-art supercomputer. While an important milestone, the mathematical problem solved was especially designed to be hard for a classical computer, and of very limited practical use.

Finding and realizing a useful application of a quantum computer is being heavily researched: programming a quantum computer is very different from programming its classical counterpart. We know that a quantum computer will not solve every problem faster than a classical computer – even as quantum computers become larger, you will most likely continue to use regular computers at home.

Instead, we know of specific (but important!) applications for which a quantum computer promises a speed-up. In this part of the magazine we present a selection of different applications proposed in the scientific literature, ranging from algorithms that will need a universal and error-corrected quantum computer to applications designed for and running on smaller, noisy quantum processors.

Texts and infographics in this section were produced by Brennan Undseth, Timo van Abswoude and Caiseal Beardow.

Looking ahead
Students and researchers at TU Delft are investigating potential real-world applications of quantum computers.

A quantum processor beats classical computers

In 2019, scientists at Google reported using a 53-qubit processor to sample the output of a "random" quantum circuit. By measuring the resulting strings of 0s and 1s, they verified that the output corresponded to random numbers following a quantum probability distribution that is very hard to calculate on a classical computer. On their quantum processor, this task required minutes but may have taken thousands of years on a normal computer with the state of the art of 2019. Since then, more research has also improved the simulations on classical supercomputers, and this has blurred the line as to whether or not their results were truly faster. Nonetheless, this experiment illustrates the ability for quantum processors to out-muscle classical computers.

It's important to ask: is this useful? While there are important applications for random number generation, it's certainly not world-changing. It does show that modern quantum computing sits in a regime near that of the world's best supercomputers, but still shy of the most modest useful quantum algorithms. To span this gap will require both technological advances and algorithmic ingenuity.

Technical challenges
Improvements in both hardware and algorithm development will be needed to realize truly impactful applications of quantum computing.

Quantum Simulation

The properties of quantum computers open up a new world of simulation possibilities.

Since the 1980s researchers have predicted quantum computers will be invaluable tools to study individual molecules, chemical reactions, and special materials like superconductors. Typically, scientists in these fields need to resort to expensive and time-consuming trial and error processes. Think of the pharmaceutical industry, where lengthy studies must be taken to evaluate the performance of new drugs and examine their side-effects on human health. Surely it would be cheaper and easier to simulate the drugs and their effects.

Classical computers can simulate small molecules or chemical processes, but as the number of particles grows, so too does the required computational power. This severely limits the size of the simulations and thus the study of interesting applications. Quantum computers, on the other hand, behave according to the same laws of nature as molecules and materials, namely quantum mechanics! Therefore, it can be much more efficient to use a quantum computer for such simulations.

Here, we introduce some of the leading ideas researchers are using to think about quantum modeling. We also describe one of the "low-hanging fruits" for obtaining a practical quantum advantage, and briefly list some of the big ideas that quantum computers might be able to tackle in the future.

The Fine Print

Much is still uncertain about which quantum algorithms will perform the best when they move from ideas on paper to real quantum hardware. Only very recently have small quantum computers become available for proof-of-concept ideas to be explored. As an example, algorithms that can run on NISQ hardware, like hybrid quantum algorithms, are very exciting due to their near-term usability. However, their ability to achieve quantum advantage is still an open question. Their performance can depend on heuristic guesses, much like classical optimization algorithms. Optimization routines can get stuck or require so much time that any quantum advantage may disappear.

In addition, physics applications that can be implemented soon, such as the Fermi-Hubbard model, and much more complicated tasks envisioned for a universal quantum computer, like investigating chemical reactions in drugs, have vastly different resource requirements. In the short term, quantum computers will therefore be used to study specific problems primarily of interest to small groups of scientists. The world-changing problems require far bigger and better quantum computers, and it will be some time before the opportunity here can be accurately known.

Analog Quantum Simulation

One approach to quantum simulation is to program a quantum computer to behave mathematically equivalent (or extremely close) to how some real system works. Typically, this requires the quantum computer to be built out of components that are similar to what you would like to simulate. For example, magnetism is easier to simulate on computers that are built out of tiny magnets themselves. Analog quantum simulation is attractive, as it generally requires fewer resources than a digital quantum simulation. However, it is less universal and may only extend to studying small and very specific problems.

Simulating complexity
Quantum computers are ideally suited to simulating complex natural systems.

Hybrid Quantum Simulation

In a hybrid quantum-classical algorithm, a quantum processor is used to try to prepare a quantum state for study, such as the state of a small molecule. This is done by guessing an initial quantum circuit that may be adjusted with some parameters. By running, measuring, and analyzing the output of this circuit, the parameters can be optimized on a classical computer. The goal is to obtain an optimal circuit that creates a quantum state out of reach for a classical computer alone. Such hybrid algorithms are heavily researched because they can run on smaller NISQ processors without costly quantum error correction. However, they are still affected by noise, so the extent of their usefulness is limited by the quality of quantum hardware.

Digital Quantum Simulation

Quantum computers can also be digitally programmed to simulate a system by breaking down the simulation into a series of short time-steps – similar to how classical computers solve many interesting problems, like the airflow through an airplane's engine. In digital quantum simulation, it doesn't matter if the quantum computer behaves anything like the system it is simulating – just like a classical computer behaves nothing like a jet engine. Therefore, digital quantum simulation is viewed as more universal, but it also requires more resources including a much larger number of qubits as well as quantum error correction. For the most ambitious quantum simulation problems, including the examples listed here, this kind of approach will be necessary.

High-T_c Superconductors

Quantum computers are expected to provide insight into the behavior of materials that exhibit particularly quantum properties by studying models such as the Fermi-Hubbard model. One example of this are so-called high-temperature superconductors. Many metals will exhibit superconductivity – a phenomenon where electrical resistance vanishes – at extremely low temperatures. Certain materials, however, become superconducting at "high" (or rather, less cold) temperatures that can be achieved more economically, but the physics behind this is not clearly understood. High-temperature superconductors could be used for extremely efficient power transfer over long distances, reducing the cost of moving energy from where it is produced to where it is consumed.

Catalysts

The field of quantum chemistry is concerned with explaining the behavior of molecules using the underlying theory of quantum mechanics. A central concept is that of the electronic structure – the configuration of electrons in a molecule in a given state. The electronic structure determines how different molecules interact, how quickly a reaction takes place, and what products are yielded. Because of their complicated electronic structure, some of the most industrially important molecules are also the most difficult to model with a classical computer. This includes catalysts and enzymes, which facilitate reactions from fertilizer production to photosynthesis.

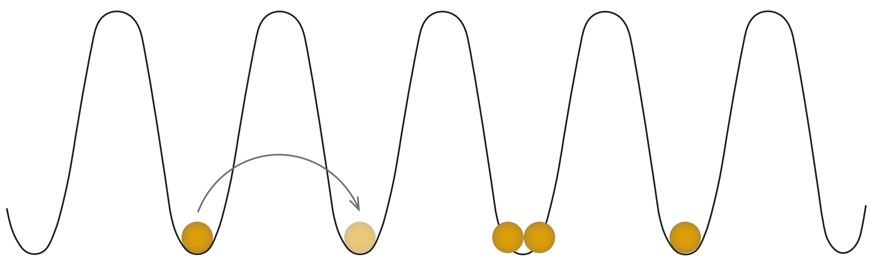
Batteries

As the world transitions away from fossil fuels and towards electric vehicles, the demand for high-quality batteries will continue to surge. The goal is to maximize energy storage and reliability while minimizing cost. In order to do this,

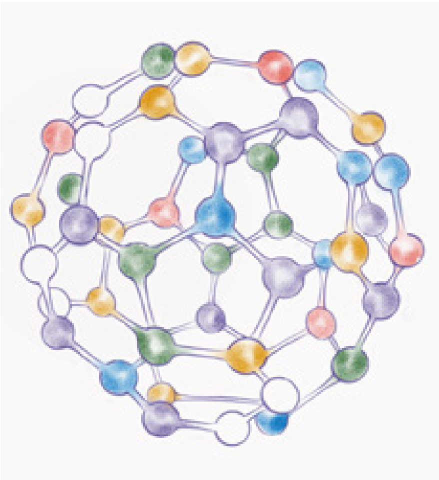
The Fermi-Hubbard Model

The Fermi-Hubbard model is believed to be one of the first practical use cases of a quantum computer, because it is applicable to problems in science that are difficult for classical computers. The Fermi-Hubbard model describes how electrons move in a solid, carrying electricity. They are pulled towards "sites" and may also "hop" between neighboring locations. The quantum nature of electrons means that this simple picture can be challenging to tackle classically, but quantum computers "speak the same language".

This application serves as a good benchmark for how powerful a quantum computer needs to be to achieve a practical quantum advantage. Current estimates suggest that a quantum computer with 50-100 good quality qubits on a NISQ processor could beat a classical computer. However, these qubits must be accurate 99.99% of the time, about 10 times the quality we have today. Furthermore, such an algorithm could require hundreds of quantum computers running at once, with a total computation time of a couple days. Quantum engineers still have much work to do, both improving qubit quality and quantity, but this goal is in sight. It also puts into perspective what "soon" means when discussing the timeline of practical quantum algorithms.



The Fermi-Hubbard Model
The Fermi-Hubbard model could help us to solve difficult scientific problems.



Understanding chemicals
Quantum simulation can help us to better understand the behavior of complex molecules.

researchers try to model the electronic properties of materials as precisely as possible, and this becomes more difficult as the systems become more complex. For instance, many major car companies have taken an interest in the potential of quantum computers, and several exploratory studies are already underway to find out if today's NISQ processors can accurately investigate the industrially relevant chemistry, such as lithium compounds.

Drug Discovery

New pharmaceutical drugs typically cost over a billion dollars and take ten years to reach a commercial market. This is a reflection of the technical complexity required to ensure drug efficacy and safety. Although simulating a drug on a computer is cheaper than running a clinical trial, this is limited by the power of classical computers to accurately model the chemical behavior. Quantum computing has the potential to disrupt the costly drug discovery process by allowing drugs to be thoroughly simulated in less time with less money. Although the general concept is exciting, much more research is needed to understand the applicability of quantum computers to specific problems in this field.

Fertilizer Manufacturing

The industrial process used to create modern fertilizer is called the Haber-Bosch process. It requires high temperatures and energies in order to convert atmospheric nitrogen into a form that is usable by plants. By one estimate, the Haber-Bosch process consumes 2% of the world's total energy consumption. Bacteria, however, can perform this nitrogen fixation process at atmospheric conditions thanks to the use of the enzyme nitrogenase. Due to its difficult electronic structure, many questions about nitrogenase have not been answered, including whether a similar chemical reaction could be used to supplant the Haber-Bosch process with a less energy-intensive procedure. A very large quantum computer would be needed to tackle such a problem, but quantum computational chemistry may help provide scientists with an answer in the long run.

Supporting sustainability
Improving fertilizer manufacturing processes with quantum technology could make significant energy savings.

Quantum Optimization

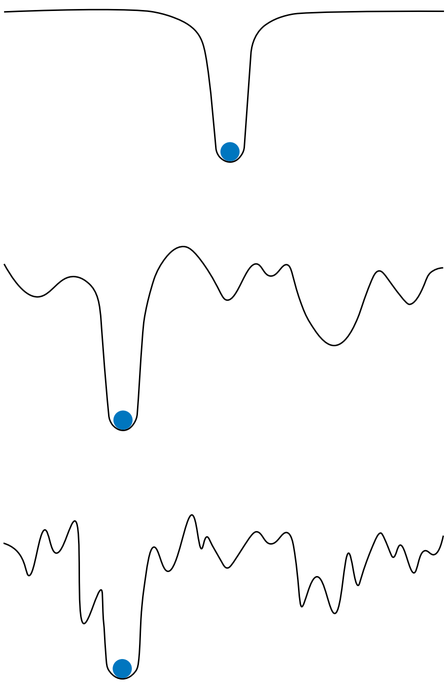
In a world of complex, multi-faceted problems, quantum computing offers a way to find the best path forward.

What is optimization?

Optimization is the art of finding the single best or optimal solution to a problem. In practice this consists of two steps: first find a rule or function for the problem that tells how good a solution is, and then search for the solution with the highest score. The first step is performed by experienced modelers, who are specialized in translating everyday problems into mathematics. They feed these functions into a computer, which then performs the second step for them.

As an example, let's say we want to find the route from Delft to Amsterdam. Our route planner may find the shortest route, or the fastest one. We can make this problem more difficult by imposing additional restraints, such as avoiding highways, stopping at a friend's house along the road who lives in Utrecht and minimizing the number of left turns we take. The more we demand, the more difficult both step 1 and step 2 become.

In the very complex problems that we may encounter in practice, step 2 can take longer than practically feasible on a classical computer. Moreover, although classical computers are good at finding solutions, finding really good solutions is very difficult: how can you be sure that the solution you found cannot be improved anymore? Quantum computers are hoped to improve performance both regarding the speed at which solutions are found, and the quality of the solutions. A specific type of quantum computer tailored to these problems, quantum annealers, are already available for purchase.



Traffic Control

Improving traffic flow is one application for optimization. Traffic jams are not only a nuisance for drivers, they also cost time and money and have a negative impact on the environment. It is easy for a traditional computer to find the optimal route for a single car – any navigation system does this routinely. However, improving the overall traffic flow is a much harder problem: we need to be able to find an optimal route for a myriad of cars driving around simultaneously, or turn traffic lights green at appropriate times – and all of this in real time! This optimization problem has also been proposed to be solved by quantum methods.

In fact, a quantum annealer has already been used to improve traffic flow (albeit only for a few vehicles) in the context of a conference (the WebSummit) in Lisbon in 2019. The increase of visitors to a city during such a conference can cause traffic and public transport congestion. Volkswagen tried to use a quantum computer to optimize the bus service during this conference for nine municipal

Quantum Annealing

The idea behind quantum annealing (also called *adiabatic quantum computation*) is a bit different from the "normal" quantum computer, in which gates are applied to the qubits. Instead, imagine it like rolling a ball in a landscape, which will naturally always roll to the lowest point. We start off with a simple landscape, with just one dip. If we drop a ball in here and wait long enough, we'll know for sure it will end up in this trough. Now, the annealing computer will slowly transform this simple landscape into the system that we'd like to optimize. If we do this slowly enough, the ball will always remain at the lowest point, no matter where this point goes. When the transformation is completed, we only need to look at where the ball is to find the true optimum of the system – the solution of the problem we wanted to solve.

There is skepticism amongst scientists about quantum annealing, as there is no provable quantum speedup in general. Still, there are considerable efforts in this research direction: can quantum annealing beat existing optimization techniques in practice for a specific application?

The Fine Print

The limiting factor of quantum annealing is the "gap" – which can be considered the difference between the best and the second-best solution. This gap typically becomes smaller when the problem size becomes bigger. The gap size determines how fast the quantum annealer can run: the smaller the gap, the slower the annealer needs to transform the landscape and the longer the computation takes. If the annealer runs too fast, it will inevitably end up in a non-optimal solution, as the system will "jump" across the gap from the best solution to worse ones. In other words, the more complicated the problem gets and the more qubits we need to add, the longer we must wait. For this reason, it is believed that quantum annealing offers no quantum speedup in general. There could be specific problems though that can benefit.

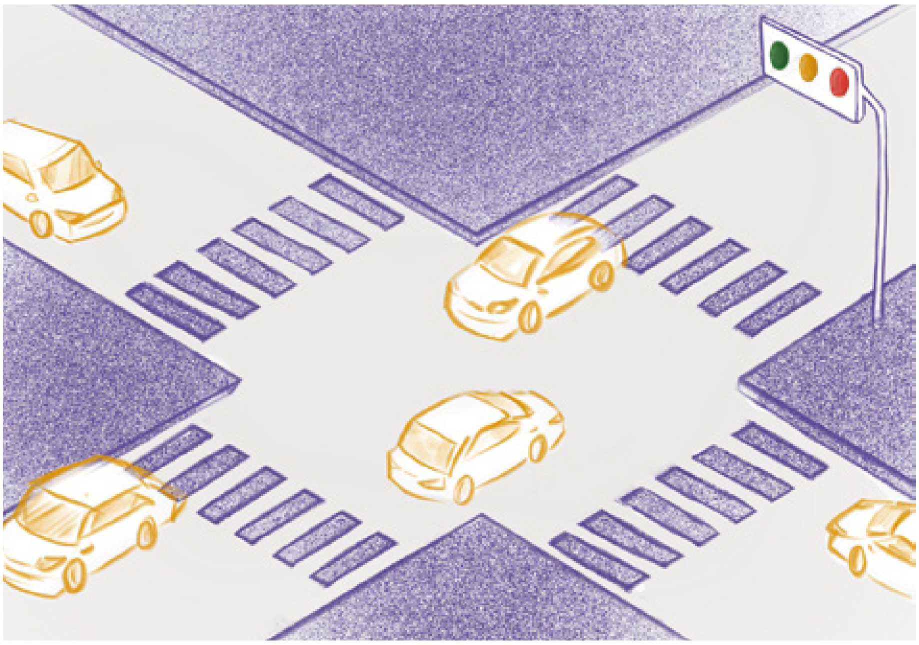
"Optimization problems are ubiquitous in industry... even small improvements in the optimization can lead to significant profit enhancement."

buses called Quantum Shuttles. The two ingredients to be optimized were the route (by avoiding congested places) and the number of passengers on board of the buses, using a prediction algorithm that predicts the most crowded bus stops. Each bus driver was connected to a quantum computer via an app, which recommended an optimal route to the drivers in near real-time. These drivers could then redirect their buses, picking up passengers at the most crowded stops along the way. Clearly, those nine buses could also have been optimized with a traditional computer. Still, it was the application of a quantum computer to a real-life problem.

Industrial Interest

Optimization problems are ubiquitous in industry: finding the most effective way to produce, optimize supply chains, or load cargo. Even small improvements can lead to significant profit enhancement. It is thus not surprising that industry is interested in exploring quantum optimization techniques.

For example, in 2020 aircraft manufacturer Airbus launched the Airbus Quantum Computing Challenge, in which people were challenged to come up with ways for quantum computers to impact the aviation industry. The winning entry used quantum annealing to optimize cargo loading. Ideally, aircraft operators would like to haul as much load as possible, stacking cargo like a giant game of Tetris. This reduces the number of cargo flights, benefiting both profits and the environment. However, you cannot arbitrarily stack all goods in the most tight way. Doing so may result in an off-centered weight distribution, making the aircraft too unstable to fly. There is an optimum for a maximum load with a minimal weight shift, enhancing the fuel efficiency of airplanes and reducing the number of cargo flights. Again, whether a quantum approach outperforms previous methods still needs to be seen also for this problem.



Directing traffic
Finding the shortest route for one car is an easy problem that navigation systems solve routinely. Finding the optimal routes for many cars simultaneously avoiding traffic jams and congestion is a hard problem.

Competition with traditional computers

Optimization problems are typically hard in that there is no feasible procedure that guarantees to find the best solution. Instead, traditional computers usually rely on algorithms that find a "good enough" result. Quantum computing is attractive in that it is a new approach that may find even better solutions. At the same time, this competition has also inspired traditional computer scientists to find improved algorithms. Even better, the understanding why a quantum approach runs faster can sometimes also be used to design better, quantum-inspired algorithms running on traditional computers. For example, recent research has made progress in modeling fluid turbulence using a quantum-inspired approach. In addition, the combination of concepts from quantum computing and traditional computer science has given rise to new research directions, such as quantum machine learning.

Quantum computing has thus already indirectly benefited optimization problems, inspiring and enabling new research directions. The constant competition between traditional computers and quantum computers in this field, however, makes it difficult to say when (or if) quantum computers will be of practical use.

Quantum Searching

Quantum computers deconstruct the haystack to find the needle in record time.

Imagine you're put inside a room with a million drawers. One of the drawers contains the key to unlock the door, and all the others are empty. How long would it take you to find the key? If you're extremely lucky, you will find it on the first try. With a lot of bad luck, you must open all the drawers before finding the key. On average, you will try half of the drawers before finding the key, that is after 500,000 attempts.

A situation like this, where you only have access to unmarked drawers with no additional information, is referred to as "unstructured data" in computer science. It turns out that finding some specific object or value within unstructured data is very difficult to do classically.

Grover's Algorithm

By exploiting the properties of quantum mechanics, we can speed up this search process. The corresponding quantum procedure is called Grover's algorithm. Similar to the visualization with the ant maze example on page 10, the qubits encoding the data are brought into a superposition. Grover's algorithm then shifts the weight of the superposition towards the correct solution. Surprisingly, this requires far fewer iterations than our classical opening of drawers. Even more, mathematicians have proven that the performance of Grover is the best you can do.

Grover's algorithm may sound too good to be true – and indeed it is important to read the fine print. To achieve quantum speed up, certain requirements have to be met. For example, to search through a dataset, we must be able to read it efficiently into a "quantum memory". This is not yet possible. If this obstacle is overcome, one field of interest could be pattern matching, in which small sequences of patterns are found within a large dataset – for example matching genetic sequences in DNA.

The Fine Print

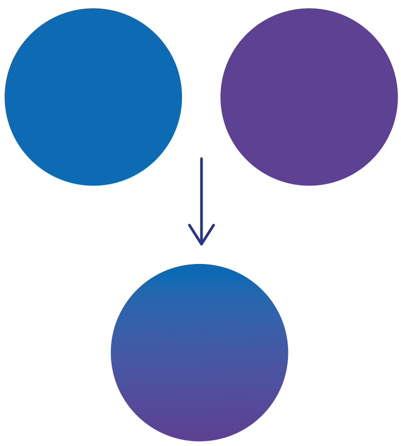
Grover's algorithm is based on a so-called "oracle". The oracle returns a "1" if it recognizes the correct solution, and a "0" otherwise – for example recognizing a key in an opened drawer. The main requirement for quantum speedup is that this oracle can be efficiently applied to a superposition of qubits. For example, if applying the oracle means reading in the whole dataset, any speedup is inevitably lost – we could just as well use reading in the whole data set to find the solution classically.

Grover's algorithm applies the oracle a number of times that is proportional to the square root of what is necessary in a classical algorithm. This is less than the exponential speedup expected in a few other quantum algorithms, but can still be beneficial if the problem size is gigantic.

Solving hard puzzles

Grover can also be used on a different type of problem, which is called a constraint satisfaction problem. Think for example of a sudoku: solving one requires much more effort than checking if your solution is correct. In checking the solution, you look whether the solution satisfies certain constraints (e.g. no double numbers in each row and column) to see if your solution is valid or not. Here, checking your solution is similar to opening a drawer. By using Grover, we would be able to check the correctness of many solutions very quickly, instead of just one by one, only ending up with the ones that are correct. Constraint satisfaction problems are used for example in machine learning and electrical circuit design, and it is believed that future applications of Grover's algorithm may lie there, rather than searching through a dataset.

As you may have noticed, we still lack an example of a "killer application" for Grover. One reason is that many practical problems have additional structure that can be exploited by classical algorithms. For example, a phone book is an alphabetically ordered dataset, and classical algorithms find the desired entry much faster than Grover's algorithm. As such, it is still an open research question for which application quantum searching will give a practical advantage.



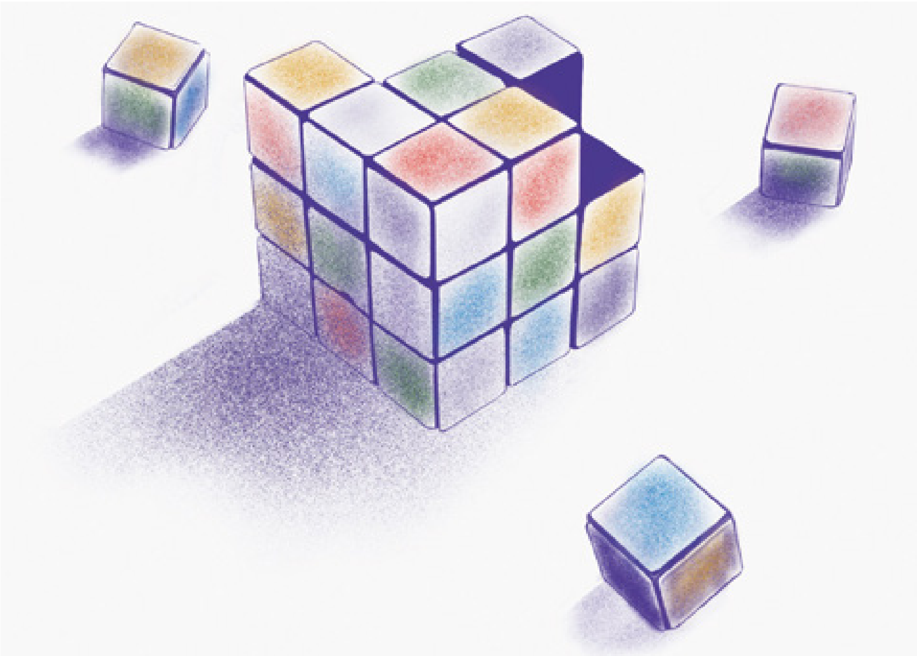
Dealing with data
In order for quantum searching to be truly useful, data will need to be formatted appropriately.

Factorization and Encryption

Quantum computing could revolutionise the way we approach calculations—but can it really break modern encryption?

What is factorization?

Factorization is the process where a number is written as a product of smaller numbers. For instance, consider the number 24. 24 can be represented by 1x24, 2x12, 3x8, or 4x6. 24 is rather a small number, so writing down all possible factorizations is straightforward. But for larger numbers, how can we know that we have found all of the possibilities? One option is to continue factoring until all of the factors are prime. That is, each number has no factors other than 1 and itself. In our case, 24=2x2x2x3. All possible factorizations can be constructed from this list of prime numbers. For example, 24 = (2x2)x(2x3) = 4x6. The prime factorization of a number is like its fingerprint – it is unique to each one.



The factorizing process
Finding the prime factors of large number is a very hard problem for a traditional computer, but could be solved much easier on a quantum computer.

A one-way function
Computing the result from a given input is easy, but inferring the input from the result is virtually impossible!

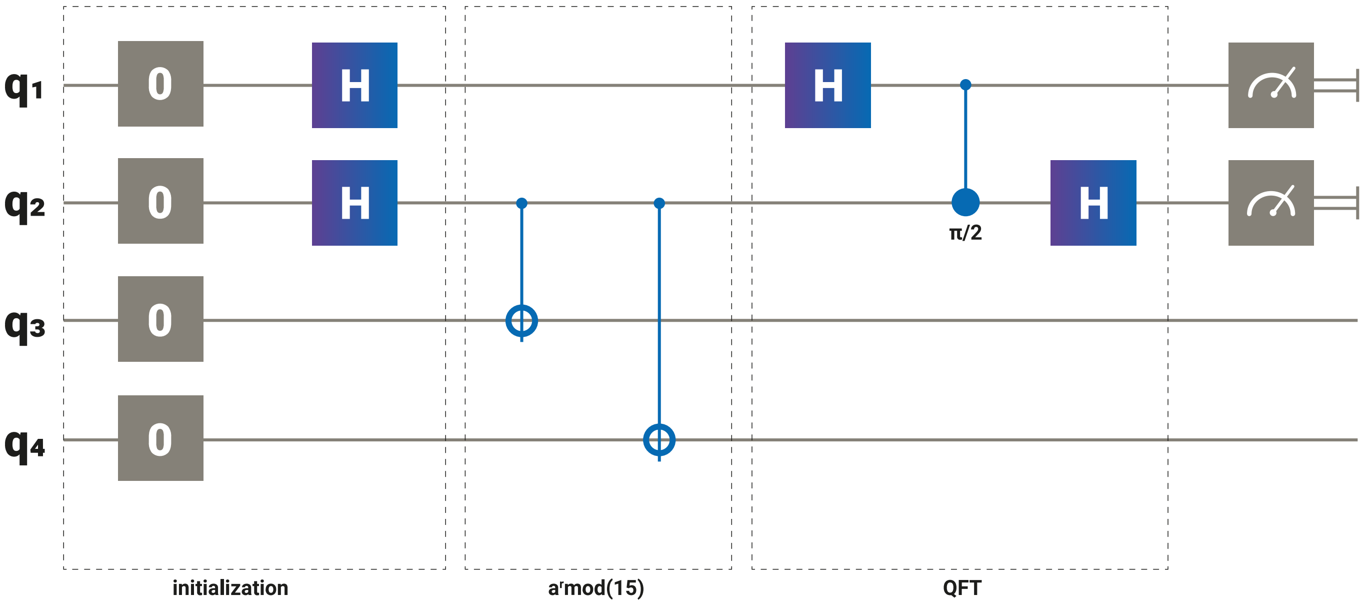
A difficult problem

What if we wanted to factor 49,189,447? This might take some time, because it can only be written as a product of two prime numbers: 6221x7907. Surely, a classical computer would be able to tackle this problem by trying a list of possibilities: 2, 3, 5, 7, and so on, until it found the correct numbers. But there are infinite prime numbers! The largest found to date (in 2018) has 24,862,048 digits when written down. If someone were to multiply this prime number with another massive one, even modern supercomputers wouldn't be able to find the 2 factors.

There's something peculiar about the asymmetry of this problem. Multiplying the numbers is easy, even for very large numbers, but factorization seems to be incredibly difficult. This is an instance of a one-way function, a mathematical problem that's easy to proceed in one direction but hard to reverse. One-way functions are incredibly useful for keeping digital secrets. If you've ever made an online payment or sent a WhatsApp message, a one-way function has been used to secure your data. The most common example, RSA encryption, directly relies on the idea that factorization is computationally inefficient.

Shor's Algorithm

This is where quantum computing comes in: a quantum computer can *efficiently* factor large numbers. For example, factoring a 600 digit number with the state-of-the-art classical techniques would require about a billion years. A large quantum computer may take a few hours. Why is this so? The answer, in a nutshell, is that the mathematics that describes how quantum computers work is also very good at describing the periodicity of complicated functions. This fortunate coincidence means that quantum computers can tackle certain mathemati-



Constructing Shor's Algorithm
Like all quantum algorithms, Shor's Algorithm is built using a series of gate operations.

cal problems that contemporary classical computers aren't able to grapple with. Factorization is the most famous of these mathematical problems, and the quantum program which solves the problem is called Shor's algorithm, named after its inventor in 1994.

Perspective

Shor's algorithm has become the crown jewel of quantum computing for two reasons. First, factorization is notoriously difficult, and the ability of quantum computers to excel at this problem over their classical counterparts has become symbolic of the supposed power of quantum information. Second, the existence of a quantum computer large enough to break RSA encryption would have profound implications for modern technology. This latter point raises an important ethical issue: why should society desire to build a device that would threaten to hack valuable personal, financial, and military data? For one thing, as with all powerful technologies, it's not something that you want to let your adversary have exclusive access to. More importantly, there is a lot more societal good that quantum technology could do – as described in this magazine – including enabling a generation of even more informationally-secure devices and communication strategies.

The threat of quantum computers with respect to modern encryption is often overstated in popular science. In order to factor meaningfully large numbers, a very large number of physical qubits is required – present estimates place this in the range of several million. This is still far ahead of present quantum processors which operate with fewer than 100 qubits. This gives plenty of time for cryptographers to devise new post-quantum encryption schemes which are secure against large-scale quantum computers.

Shor's algorithm serves as the most striking example of the potential for quantum technology when complemented with human ingenuity. It is one of the few problems where we know with certainty that a quantum computer can outperform the best classical algorithm at present. However, it will take a large, error-corrected quantum computer to be able to execute Shor's algorithm in the long term.

The future of encryption
Current encryption of communication (such as using a website starting with "https://") is vulnerable to Shor's method. Scientists work on alternative encryption schemes resistant to quantum methods.

The Fine Print

Shor's algorithm requires a quantum computer with a large number of qubits. The main reason is the need for error correction. It has been estimated that to break typical RSA encryption a quantum computer with 20 million qubits would be needed. This greatly exceeds today's quantum machines.

"Why should society desire to build a device that would threaten to hack valuable personal, financial and militaristic data?"

Learn more: quantum algorithms
To learn more about the algorithms in this section and why they work, scan the QR code above.

The near-term future of quantum computers

An interview with Barbara Terhal

Barbara Terhal (Professor of Quantum Computing, TU Delft/QuTech), interviewed by Michael Wimmer

You are a professor at the electrical and computer science department and QuTech. What are your main research interests?

I am interested in quantum error correction and its physical realizations, in particular the use of superconducting qubits. I also find the theory behind superconducting qubits, called circuit-QED, fascinating, as it is a novel, emerging, theory of quantized electric circuits. I have a long-standing interest in the power of quantum computers, that is, what you can and cannot do with them.

What are near-term applications of a quantum computer? Often the near-term future is called the "NISQ (noisy intermediate-scale quantum) era". What does that mean and what kind of applications might be possible?

NISQ means that the current chips have a limited number of qubits (say 10-100 qubits), and logical operations on these qubits are inaccurate. This means that we can only do a limited number of operations on these qubits before the outcome of these operations becomes unreliable and therefore useless. One can program different types of quantum dynamics on these devices, for example aimed at simulating some small physical or chemical system, or solving a small quantum or classical optimization problem.

What role does the recent Google supremacy experiment play in this regard?

The Google supremacy experiment and follow-up experiments has shown that we are entering an era where the classical simulation of quantum experiments on NISQ devices becomes very costly and time-consuming. This by itself does not mean that the quantum device is solving an important or interesting problem, it just means that its different capability, which was theoretically understood previously, is starting to become an experimental reality.

What role can small-scale quantum computer prototypes play in this endeavour (such as Quantum Inspire)?

I believe that a device like Quantum Inspire is useful in giving researchers who are not experimental quantum physicists themselves access to quantum chips, allowing them to familiarize themselves with how they function and what limitations or possibilities they have.

Most of the known promising quantum algorithms require very small errors when doing qubit operations. To this end error correction is essential (one of your main research topics). What is the current status of quantum computers in this regard? What are the main obstacles to achieve quantum error correction?

Quantum error correction experiments with 4-20 qubits are taking place and in these experiments one is looking at how well errors can be corrected. Quantum error correction works by adding redundancy. Nine physical qubits are used, say, to make one, better, so-called logical qubit. If error rates are low enough, then adding more redundancy helps, so one uses, say, 25 qubits to make an even better logical qubit. So the challenges are: first, are error rates low enough. And second, can we handle the redundancy, that is, can we build and control bigger chips with many more qubits (and still keep error rates low).

What is your personal expectation: what will be the first useful application of a quantum computer and when would it happen?

I expect that quantum computing will be useful for understanding a novel and common property of the dynamics of many-body correlated quantum systems that may have eluded us because of limitations of classical algorithms. Such application is not necessarily useful for society-at-large. Let's hope we can achieve this goal in the NISQ area, say in the next 10 years, by simply building bigger chips without requiring the full realization of quantum error correction.

"...Quantum Inspire is useful in giving researchers who are not quantum physicists access to quantum chips, allowing them to familiarize themselves with how they function."

Ditching the Quantum Hype

Despite its potential, some claims about quantum computing should be taken with a pinch of salt.

Many articles about quantum computing make claims that are speculative and sometimes outright incorrect. For becoming quantum streetwise we discuss three important misconceptions about quantum computing:

1 Quantum computers will replace classical computers

Classical computers, like your laptop and smartphone, are extremely fast, reliable, and cheap relative to the wide range of tasks they can perform. Quantum computers are, for some time to come, very large, fragile, and expensive. They will be used in specialized computing centers to which users can send problems remotely (perhaps using a quantum internet) and receive answers back once the computation has finished. So be wary of anyone trying to sell you a "quantum desktop"!

2 Quantum computers will be able to solve all problems faster

The quantum algorithms that exist at present solve useful, but quite specific, problems. There is no magical black box that lets us take any difficult problem and solve it using a quantum computer. Also, there is not yet a simple rule that tells us what problems a quantum computer can definitely solve faster than a classical computer. For example, we know Shor's quantum algorithm can factor numbers efficiently, while the best classical algorithm invented so far is inefficient. However, we can't rule out that an even more efficient classical algorithm still exists. It is possible that the "quantum advantage" in factoring numbers may disappear by old-fashioned human ingenuity.

3 Quantum computers are faster because they can try all possibilities at the same time

A common oversimplification of quantum algorithms is that they are faster because "they try all of the solutions at once". Although it would be very convenient if this alone gave us a quantum advantage, nature doesn't seem to work like that. What's the catch? Well, the incorrect answers need to interfere in such a way that only the correct solution remains to be measured, and this is difficult to implement for an arbitrary problem. Typically, there must still be some "hidden" structure in a problem that a quantum computer can take advantage of, such as in the case of factoring numbers. For many "hard" problems (as computer scientists like to call them) this structure is not easy to uncover. Achieving quantum speedup doesn't just require a quantum computer, but a lot of creativity too.

Impact

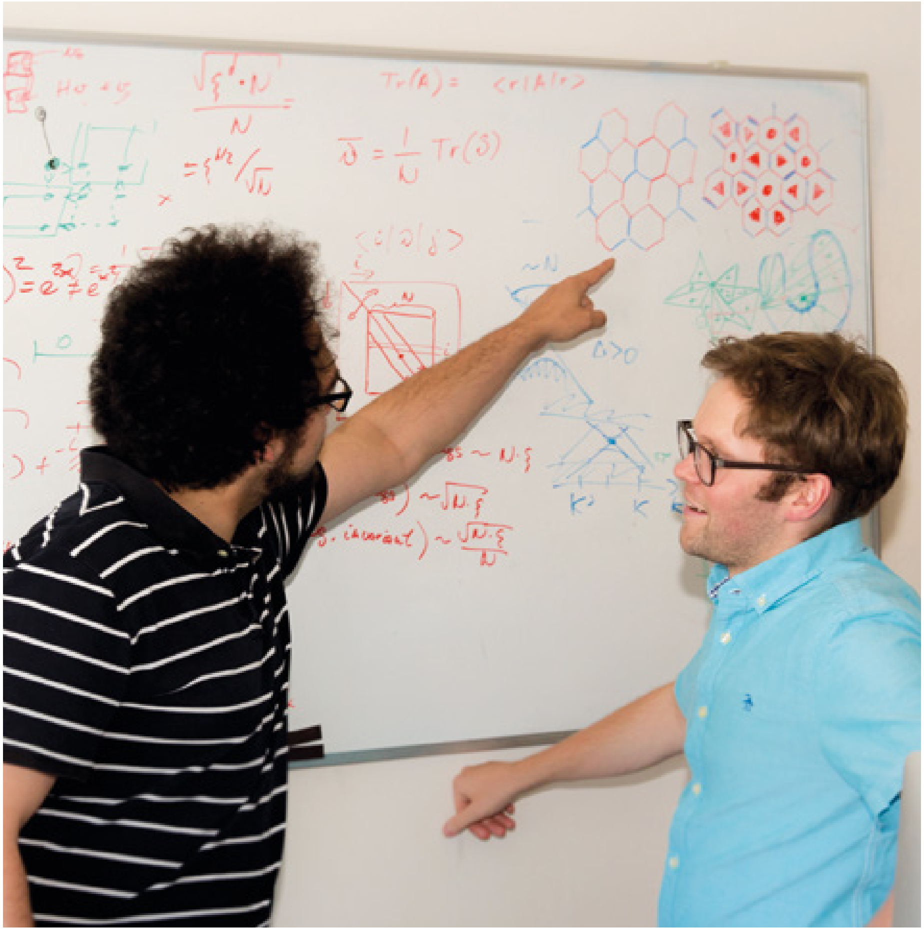
What's Coming Next?

Gathering perspectives from experts, other disciplines and groups in society can help us to build an inclusive future for quantum computing.

Having a sense of what quantum computing is and what applications it may have, already gives a perspective on what quantum computing can bring. Transport companies may improve their logistics, hospitals can scan DNA faster, academia may discover useful new materials, and everyone has to change the encryption of their data and communication. Quantum computing may also bring more systematic changes to society. The superconducting materials and better solar panels that may be discovered may revolutionize the generation, storage and transport of energy. And changing encryption may lead to new infrastructure for data storage and transmission. So what is the larger impact of quantum computing on society?

To address this broader question we organized a number of meetings of people in society. These people will be the first to be confronted with quantum computing and can be taken as experts on what this new technology will bring society. We had meetings with industry, with the Dutch government, with national security experts, with scientists using computing, with educators, with designers, and with secondary school students. We discussed with them how people look at quantum computing, what they see as the benefits and challenges of its applications, and how the emergence of quantum computing can bring change.

In the next few pages you can find the lessons we learned during these meetings. Because of the Covid-19 pandemic most meetings were online, introducing the threat of more passive exchanges. We were happily surprised by the engagement of all, and by the knowledge people had of quantum computing and its applications. The meetings were lively ones, leading to rewarding insights.



Quantum community
The efforts to build a quantum computer require interactions between scientists of different fields and external stakeholders.

Finally, we asked students - the future experts on quantum computing - to give their vision of what quantum computing can bring. We organized a contest among all TU Delft students to imagine the year of 2040 and envisage how quantum computing has found its place in society. We end this Impact part with two of those visions.

A global perspective
Countries all over the world are developing quantum technologies.

The Netherlands and Quantum

The Netherlands has a front row seat in the development of quantum computing research and industry.

Pieter Vermaas

A Faraway Promise

The Dutch state is actively anticipating the emergence of quantum computing. It has taken a front row seat: it has a Quantum Innovation Hub Rijksoverheid that explores what quantum computing can mean for the country, and it is funding research on quantum technologies with 615 million euros through a programme called Quantum Delta NL. The Dutch government is including quantum computing in its technology governance policies, and should enable that Dutch science and industry to make optimal use of it. And the Dutch state may use quantum computing itself.

For the governance part it does make sense to take a front row seat, since that will give a head start to Dutch research and industry in the scientific and economic competition. It also gives the government enough time to update its digital communication and data encryption for ensuring digital security when in the future quantum computers may decipher existing encryption methods.

Plans for the Future

For its own uses of quantum computing it may however be somewhat frustrating to have a front row seat. Lots of applications could be possible. Quantum computing might add benefits to modeling, and governmental agencies are engaged in this application. They model, for instance, the development of the climate and its impact on the Netherlands. And agencies could model the currents in the North sea, for finding shipping routes that are more sustainable. Dutch agencies are also monitoring and controlling such things as financial streams for detecting oddities that may indicate fraud and other illegal behavior. And eventually traffic control becomes a mega computational challenge when we will drive in autonomous vehicles. Numerous potentially useful applications, but full-blown quantum computers cannot be ordered yet from their manufacturer. What is coming is rather a phase in which only a few parties – say, institutes or big tech companies in the US, Europe, China – will have full-blown quantum computers, making computation time a rare and strategic commodity. Maybe the Dutch state can then run an incidental climate model, but it may not expect to do daily weather forecasting or continuous analysis of financial streams. And even an incidental scan of financial streams will be problematic: the Dutch government is obliged by law to carefully store and process privacy sensitive data of its citizens, which sits uncomfortably with sending that data over internet to a quantum computer possessed by a third party. The opportunities of quantum computing only come in a second phase when full-blown quantum computers become systems that can be ordered against feasible prices. When the Dutch government can have its own quantum computer, only then many potential use cases may be in reach.

	Incidental	Continuous
In-house	• Scans of private data	• Fraud detection through financial stream analysis • Traffic guidance
In the Cloud	• Climate modelling	• Weather forecasting

Potential applications of quantum computing for the Dutch State

Dutch Innovation
The Dutch State is at the forefront of developing quantum technologies.

Who

We spoke with representatives from the **Dutch government**.

What

We asked the government representatives to describe the opportunities and challenges they see for quantum computing.

Takeways

There is a significant amount of **investment and innovation** around quantum computing in the Netherlands.

The Dutch government sees applications for quantum computers in **modeling**.

Quantum Delta NL: The Dutch Community for Developing Quantum Technologies

An interview with Freeke Heijman

Freeke Heijman (Director of Quantum Delta NL), interviewed by Pieter Vermaas

You are a founding director of Quantum Delta NL. What is Quantum Delta NL?

Quantum Delta NL is a foundation aimed at accelerating the development of quantum technologies in the Netherlands, and executing a programme for this development that the Dutch government funds with 615 million euro for 7 years. Quantum Delta NL is also the community of all people in the Netherlands working on quantum technologies. We call it an ecosystem.

What are your main tasks in Quantum Delta NL?

I am one of the directors of Quantum Delta NL. We have an executive board with Ronald Hanson from science, myself, Jesse Roberts from industry, and a vacancy for a 4^{th} person. We are formally responsible for the Foundation and the execution of the Quantum Delta NL program. Also I am responsible for Action Line 2, as we call it. That part of the programme focuses on the ecosystem development. It supports startups and SME, makes sure that there is venture capital for them, and it builds a new House of Quantum, a space where the community can come together.

Quantum Delta NL aims at building by 2028 a quantum computer with more than 100 qubits. Is that a computer that can be bought by industry and people?

We don't foresee it to be a commercially available product. Our aim is to bring demonstrators to the market for educational and precompetitive purposes: the quantum computer will be a test bed for demonstrating the maturity of the technologies we develop. This quantum computer is, so to say, a step from scientific research to commercial activity.

Will it be a Dutch computer?

Yes, the funds come for a large part from the Netherlands and the hardware is developed in NL. A lot of the research is carried out in the Netherlands, but there are also components that come from suppliers. And we work together with European research institutes, with Grenoble in France for instance, and also with American companies. It is a consortium effort, so to say, with of course an emphasis on the Netherlands. I would call it a European quantum computer.

Is it going to stand in the Netherlands?

It will be physically touchable in Delft!

One of the insights in this magazine is that developing quantum computing is not only a matter of creating new technologies but also of bringing different groups together. What groups are part of Quantum Delta NL?

It is a broad mix: we have scientists, entrepreneurs, students, end-users, policy makers, teachers and investors. And we have disciplines such as physics, material science, computer science, systems engineering, innovation management and policy analysis. Quantum Delta NL has an ecosystem approach, for research and industrialization, but also for educating people about quantum technologies, in universities and at secondary schools, polytechnics, and for small and medium-sized enterprises. We engage with governments because quantum has very strategic applications, such as securing critical infrastructure and cyber security. The earlier you engage with end users, the better you can raise awareness of all the ethical, legal and societal aspects.

To zoom in on one group of the ecosystem: a key goal of Quantum Delta NL is to get more startups out of the research at universities and also attract them from other places. We have startups in Delft and Amsterdam building components of quantum computers. For instance, QBLOX develops electronic hardware needed to control qubits, Delft Circuits produces the wires for connecting quantum computers, and Qu&Co makes algorithms that run on quantum computers. These startups join forces in Quantum Delta NL, and we help them with funding. Also we have scouts who scan if PhD researchers have a really good idea that may lead to new patents or startups.

How is Quantum Delta NL achieving that all these groups can talk with each other and collaborate?

It is challenging because it is a very complex and abstract technology that you cannot see because it lives on the nanoscale. The language of scientists is hard to grasp for policy makers or end users. For bridging that gap you need translators: people who know enough of the technology and can translate it to others. Also between the different disciplines this is a thing. A computer scientist has deep knowledge of software and algorithms, but does not understand electronics, and the other way round. So on all levels you need translation, development of a joint language, and also of a joint culture. Industry runs projects and steers tech development in a very different way than academics. And the culture in the public domain is different to the one of startups. It is a challenging adventure, because when you put these cultures together, you can learn new things. You can get the best of both, or even more. So it is very exciting to be part of it!

And Quantum Delta NL has those translators?

We try to. And we organize lots of events to help an open flow of conversation. Everyone should feel proud and happy to be part of this ecosystem, so that we don't have to work hard on letting people talk to each other, but that they like to do that. That it is fun.

The Dutch Quantum Computing Startup Ecosystem

An interview with Ton van 't Noordende

Ton van 't Noordende (Quantum Delta NL Resident Investor), interviewed by Deborah Nas

You initiated the Infinity program at Quantum Delta NL. What is it, and how is it different from startup accelerators?

Infinity is a stage and TRL level agnostic program that can connect Dutch quantum technology startups with 20 billion euro in investment capital, managed by European and U.S. funds. Our goal is to make the Netherlands the number one quantum tech startup ecosystem in the world. We give startups tailored assistance to scale their businesses and optimize their attractiveness to investors. Dutch quantum startups in all phases can apply, ranging from pre-foundation to consecutive stages of venture capital financing and everything in between. Unlike startup accelerators, we prefer to keep startups in stealth mode while closing a serious investment round. Because of our network and personal approach, investors are highly interested in the startups we introduce them to. After closing their investment round, the startup actively engages in communication and PR.

For very early quantum tech startups we built a dedicated microfund of 2 million euro that can deploy 50 thousand euro SAFE note tickets (Simple Agreement for Future Equity). We adopted the SAFE note as it's an instrument that is straightforward, founder-friendly and fills the gap in the earliest stage for quantum startups. This approach gives early startups the maximum flexibility needed, particularly in the quantum technology space as development timelines and roads to profitability extend far beyond that of classic startups. The investment does not have to be repaid, as with a traditional convertible loan or note, if a startup fails to advance. Our goal is to fund 35 to 40 new quantum startups in the next couple of years with this microfund.

After this first step, capital raising can grow substantially. QuantWare, a spinoff of QuTech and member of the Quantum Delft ecosystem that develops high-performance quantum processors, is the first startup to tap into the program. In total, QuantWare raised 1.15 million euro, right out of stealth with support from the Infinity program and the initial SAFE note investment. Infinity has also supported and guided the Delft-based startup QphoX in their fundraising round, which raised 2 million euro to bring its Quantum Modem to the market. QuantWare and QphoX are just two examples that signal the potential we have in The Netherlands if we are willing to look further than the classical path to acceleration. Utilizing the full potential of directly available and well-curated, primarily European venture capital funds means that we can both make early bets and double down on our Dutch ventures when the capital is needed to scale up further.

How is the quantum startup landscape developing?

The number of startups is rapidly growing, as is the capital available to them. In the past three years, investments in quantum startups have increased almost eightfold. In the first half of 2021 alone, 1.3 billion US dollars were invested in startups globally. In the Netherlands, capital invested in quantum startups has doubled in the past nine months. This trend will continue; the quantum ecosystem develops at an unprecedented speed. Having said that, we remain aware that capital might become a constraint in the future, for European quantum startups and Dutch ones in particular, as many European funds are still not diving into foundational technology. We'll need to engage with both local and international sovereign wealth funds, institutional investors and family offices to ensure that our later-stage quantum startups can attract large sums of capital (100+ million euro rounds), so that we can hopefully look back in eight years and see how we've helped to create a new and incredibly important quantum scale-up ecosystem that can stand on its own.

What are key themes within the start-up domain?

Right now, there is more focus on developing hardware and software as opposed to applications. Startups tend to provide limited information about applications; the ones that do mention usually higher-level applications, like healthcare or material design. This makes sense considering the current state of quantum technologies.

What types of investors show interest in quantum technologies?

There are three types of investors. First, more general investment funds that recognize the potential of quantum technologies but are risk-sensitive; they will limit their investments to one startup per fund. Second, we see deeptech funds, i.e. funds that invest in early-stage technologies. Some funds that used to be technology-agnostic are now specializing in quantum technologies. Third, there are niche funds with a strong focus on quantum technologies. Overall, interest from investors is growing. As a result, valuations go up, and there is a bit more flexibility in deal terms, which further accelerates the development of startup ecosystems. We are still in the beginning though – overall valuations are relatively low.

What characterizes quantum startups?

Teams are highly knowledgeable; most of them were scientists before. Contrary to what people often say, I observe that many scientists can become successful entrepreneurs. The insecurities and risks that come with entrepreneurship are usually a bit scary for them, but they are eager to make things happen, and seem to be more responsive than non-scientist startup founders I work with.

Quantum and Sovereignty

From science for sustainability to sovereignty struggles, the national and global future of quantum computing is complex.

Pieter Vermaas

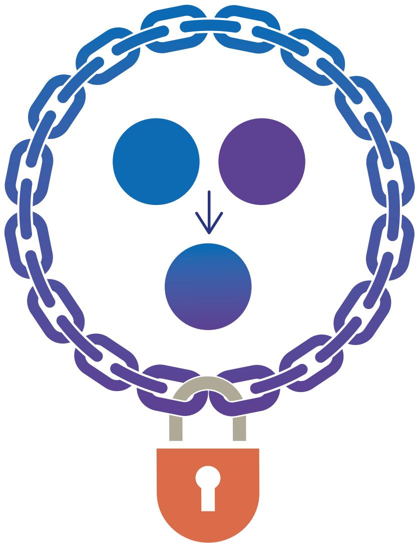
A Global View

Whereas quantum computers are typically presented as new powerful tools in facing our global challenges, it is sometimes also promoted as a technology you need to have to defend the country. Let's start with the global aims. Quantum computing can help find new materials and new chemical processes that are less polluting, require less energy resources or help enable the transition to new energy resources. Quantum computing may also help in better modeling the climate and its changes, guiding us to better ways to mitigate the effects of these changes. These are all laudable opportunities, fitting the 21st century approach of facing global efforts together in an open international way by developing quantum computers and creating applications that benefit us all.

This perspective contrasts with a more grim one of states and even big tech companies competing with each other to have the benefits first. The US, China and Europe are the big blocks, and they are complemented by individual countries that take their own shot at quantum computing. Collaboration is then replaced by secrecy and export bans on key technologies, leading to a technological rat race with states defending their digital sovereignty.

Digital Sovereignity

Having a full-blown quantum computer does give a country quite some strategic advantages. With the famous Shor algorithm running on a multi-million qubit quantum computer you can start decrypting the secret files of other countries. These other countries may have switched to "Shor-proof" post-quantum encryption of their latest documents, yet some older documents may lack that new encryption, and could still be quite interesting. The other countries may also quickly hide their older documents, yet if you are smart as a country, you are already storing all interesting documents from the other countries. And when your quantum computer becomes powerful, you have all the time to decrypt the documents of your fellow countries. And what holds for countries and their competitions may hold for industry as well.



Public versus private
Should governments keep quantum technologies under wraps or share their knowledge?

Having a powerful quantum computer available has additional advantages for a country. It gives your institutes and industry clear advantages over their competitors in other countries in finding new materials and processes. And using quantum search algorithms, such as the one to get out of a maze (see page 10), allows you to analyze and collect information about other countries that those countries themselves do not even know. Quantum computing then seems to bring us back to the uncertain times of the mid 20th century where in the Cold War the US and the Soviet Union had to constantly guess what the other knew and could do.

"Having a full-blown quantum computer gives quite some strategic advantages for a country."

How will this competition work out? Probably, we will face a period where for a few years one of the parties has a serious head start in the development of quantum computing. But who? The US? A US-based tech company? Or will it be the Netherlands? Whomever it will be: it will be relevant for the geo-political and of course the economic balance in the world.

Who
We spoke with **national security experts** from the Netherlands.

What
We asked the experts to outline their vision for the global and national future of quantum.

Takeaways
Quantum technology can offer countries a **strategic advantage**, which could cause a race to the top.

The more holistic benefits of quantum computing could be better achieved with an **international, collaborative** approach.

Quantum computing, national security and geopolitical competition

An interview with Patrick de Graaf

Patrick de Graaf (Business Director of Cybersecurity & Quantum Technology, TNO), interviewed by Pieter Vermaas

You work at TNO, the Dutch Organisation of Applied Research, as Business Director of Cybersecurity & Quantum Technology. What are your main functions at TNO?

My main role is to make sure TNO does the right research & development projects for the defense sector on quantum technology and cybersecurity. Besides that I coordinate TNO's overall cybersecurity R&D portfolio.

TNO and TU Delft have created QuTech, the organization that develops quantum computing. TNO also brings new technologies to industry. Is industry already interested in quantum computing?

For starters we see a growing number of quantum technology startups, slowly but surely building an industry base. And we've seen in industry some initial experiments, for instance, internationally in Big Tech, automotive & traffic, defense, aviation & space, financial institutes and pharmaceuticals. Explorations are usually about the applicability of quantum algorithms and learning the pros and cons. What are the opportunities, what is the business case?

Also the threat of quantum computing is on the radar. Focus here is on making cryptography of stored and communicated data safe for future decryption techniques enabled by quantum computers. The National Institute for Technology and Standardization in the US runs an international competition for new post quantum crypto algorithms. Final results are expected in 2024 and then implementation of quantum safe algorithms in systems and networks can start, which may take another couple of years.

Another approach to quantum-safe cryptography is Quantum Key Distribution over a quantum internet. Here some early solutions are already available on the market and multiple industries have shown interest in this approach, though a lot of work is still to be done.

Quantum computing was, for a long time, a topic of only research institutes and some early adopters in industry. Currently we see also interest by national security agencies and the military. What are their main thoughts or worries about quantum computing?

The key concern in the security community is of course the threat to current encryption. With the foresight of quantum computing available in the cloud, every cybercriminal could potentially break the security of, say, financial transactions or e-government facilities. That is a major risk. In the military a two-edged approach can be seen. What is the advantage if we have quantum technology and our opponent does not? Can we break their crypto? Can we process large quantities of data much faster? On the other hand: what is the threat if our opponent does have quantum technology and we don't (or less)?

The development of quantum computing was initially mainly open science: findings are published and prototype quantum computers are shared globally. Will that open character be changed by the interest of security agencies and the military?

I don't think major changes will take place here. Fundamental research was and will be transparent. However, when you get close to military or security operations in your research, things become more secluded. Informing the scientific community is one thing, informing your opponent on specific military capabilities is another.

With the geo-political competition between the US, China and EU the main question seems to become who will have the first powerful quantum computer. Is this the right question? Are there other factors relevant in this global competition?

Interesting question! For sure quantum computing has become a geopolitical issue. Large and smaller geopolitical players invest, like the US, Japan, Russia, China, Canada, Denmark et cetera. The Netherlands does also and punches with the Quantum Delta NL investment above its weight. I think both security and economic growth are at stake here. Quantum technology also fits quite well in discussions at the EU and Dutch level on strategic (digital) autonomy. The main question seems to be how much control we strive for on quantum computing. Is it okay to invest in R&D and leave selling quantum computers to the Americans? Should we focus on algorithms and applications too? My answers would be: no, yes.

My personal key concern is: who will build and deliver future Dutch or European quantum computers? Currently investments in Europe are mainly public and, as far as I can see, no big European industry player is substantially engaged in developing a quantum computer. In the US Big Tech is in the driver seat and I guess they are also well positioned to win the market for quantum computing. Where does that leave us?

My call to action is therefore to form a consortium of major industry players and startups to reap the benefits of quantum computing R&D. Quantum Delta NL can be the perfect platform to kickstart that consortium!

"We see a growing number of quantum technology start-ups, slowly but surely building an industry base."

Quantum in Industry

The quantum computing industry is a superposition of viewpoints, from start-ups to global corporations.

Michael Wimmer & Giordano Scappucci

The present and future industry around quantum computers involves a variety of business stakeholders, from small startups and spin-offs to global corporations. Scratching below the surface of the media feeding frenzy, we learn that quantum computing is seen by different stakeholders from different viewpoints. In our stakeholder discussions, we have asked for analogies to understand how quantum computing is expected to impact the world around us.

Understanding value
Economic value is generated on different levels.

What is a quantum computer like?

Differently from the portrait we find in the popular press, quantum computing has little to do with a moon-landing effort, but is rather a continuous progress. On the one hand, a quantum computer could be considered like an iPhone: although designed as a mobile phone, we are now using it almost exclusively for other tasks. In the same spirit, a quantum computer will enable use cases we cannot imagine now. On the other hand, we could think of a future quantum computer as a quantum processing unit (QPU), a specialized tool designed to solve specific problems, just like a graphic processing unit (GPU) today. As GPUs became more affordable, new use cases were implemented, for example Artificial Intelligence (AI). The same might happen with quantum computers if they become more affordable. Also from a business perspective, there is a similarity between AI and quantum computing: The goal should be to search for testbed pockets where quantum algorithms provide a huge advantage.

Compared to traditional computers, a quantum computer is very different: It was known for a long time how to program a digital computer, even before computers were available. Programming a quantum computer is still in its very early stages and far less obvious. Furthermore, unlike in the semiconductor industry, there is no standard hardware platform yet. However, a quantum computer is also very similar to a traditional computer: we need to build a value chain now. Economically, it might be less relevant to be able to build a quantum computer completely, but rather where the most value is generated. Like in classical computers, most likely breakthroughs will be identified later in a reflection phase.

A Growing Industry

As the efforts towards quantum computing unfold, interesting relationships are emerging between different stakeholders such as big companies and small startups mainly originating from academia. Several big players have entered the quantum computing arena, perhaps also for the fear of missing out. The academic roots of quantum computing are still strong in the quantum groups at big companies, since even the bigger players are still operating like a university research lab in terms of work culture. Furthermore, quantum computing programs are also a way to attract talent to big companies. In the current phase, startup companies are service providers with their specialized knowledge, while being more reliable and IP-aware than a university. Startups need the contact to both academia and industry to become the leader in their expertise. As a convincing use case for the quantum computer is still needed, more expertise than what a single company can provide is required. Looking more into the future, it is expected that for startups there will be a time of consolidation for example when big players stop certain directions or startups are being bought within the next decade.

Who

We spoke with representatives of big **companies** as well as small **startups**.

What

We asked them how they expect the commercial exploitation of quantum computing will develop.

Takeways

A quantum computer will be **specialized** computing hardware and solve particular problems.

Likely, the first practical use case will be an application not thought of yet.

It is important to **build up a value chain now**: even without producing a complete quantum computer, significant value can be generated in lower parts of the chain.

Starting a Company in the Quantum Tech Market

An interview with Sal Bosman

Sal Bosman (Founder & CEO of Delft Circuits), interviewed by Giordano Scappucci

You are CEO and founder at Delft Circuits. How did you end up starting your own company?

As a teenager I always dreamt of building my own electronics factory, did a BSc in Industrial Design Engineering in the Eindhoven high-tech region, and then founded a startup working on wireless sensor networks – nowadays called internet of things. This startup was way too ahead of the curve and was shut down. From there I went into physics, even theoretical.

Then I discovered that qubits could be built using processes from the semiconductor industry. So, I commenced a PhD on superconducting circuits at the TU Delft with Prof. Gary Steele. The final result was the vacuum-gap (capacitor) transmon qubit, of which recently the patent was granted. As I started Delft Circuits already during my PhD – I do not recommend that! – I never had the time to hand in my thesis…

During my PhD research the industry started to get seriously interested in quantum computing and with my entrepreneurial design/engineering background I started to wonder: is there any opportunity here?

What does Delft Circuits make? What specific problem are you tackling? What is your unique solution?

We focus on solving the cabling (i/o) problem for quantum-computing, quantum internet and quantum sensing. As most quantum systems reside in a cryogenic system and need to be controlled from the outside, this problem is common for various systems. We solve this by making lithographic defined circuits on multi-layer flex, called Cri/oFlex®. We integrate many components, like filters, couplers and attenuators. By doing so, we greatly improve the heat load, reliability, size, and eventually costs. Especially for systems requiring hundreds or more channels this works better as the standard coax solution. Our now 30 person team specializes in quantum, cleanroom fabrication, micro-wave engineering and cryogenics.

Quantum computers and their applications are still projected in the future. Why does Delft Circuits already step into this quantum tech market?

With the experience of an earlier startup, which failed due to bad timing, this was also my biggest concern. As our problem already solves a current problem in cryogenics, our business success is not entirely dependent on the achieved timelines in quantum computing. Another advantage is that we supply cabling solutions to customers for four out of the five main architectures for quantum computers. Next to that we also address the other quantum fields, aerospace and biological/medical markets.

Quantum computing is a multi-disciplinary effort. How is it to work in a quantum ecosystem with academic groups and other startups?

From our network in various fields in quantum, we have set up collaborations with a few labs. With them we can validate our products in an early stage to identify problems and refine requirements. Next to very interesting data, this helps to understand our technology and customers much better and accelerates our progress. Also we can cross-fertilize between sometimes very different requirements.

Regarding the startups, in the ecosystem in Delft a group of startups has evolved that almost forms a complete quantum computer value chain. This year we formed a consortium, impaQt, where we explore building a quantum computing demonstrator in this value chain oriented way.

Interest in industry around quantum computing is booming. What is the role of startups in the current phase? What kind of relationships are emerging between startups and large corporations?

Startups have an advantage: they can really focus on a specific problem, whether it's a software framework, algorithm development or cabling, such as in our case. We can spread the investment costs over multiple customers, which in the end is beneficial for the large corporates. They are just focused on getting to useful applications in short timelines. Since a few years, customers see the benefit of what startups bring to the table. Our experience with various corporates is very positive, as most of the engineers come from the same academic field.

Make it or break it. Will there be such a moment for quantum computing technology?

I like to call this the Omaha Beach moment. Like in Normandy, where for the first time you reach a so-called beach head. The process is far from over, but the end is in sight. Arguably, the Google Quantum AI paper from 2019 is already such a moment. To demonstrate that with even 50 noisy qubits you can seriously outperform a supercomputer is quite tantalizing. Imagine what we can do with a kQbit processor? I think we should get such hardware as soon as possible online for the quantum-algorithm and -application developer to tinker with. Of course the road to a full-fledged industry that has a serious impact on the global economy is still far away, but I would say the Normandy beachhead is there.

Quantum for Science

Quantum computing has major implications for the future of scientific research and engineering.

Matthias Möller & Boyang Chen

A Problem of Scale

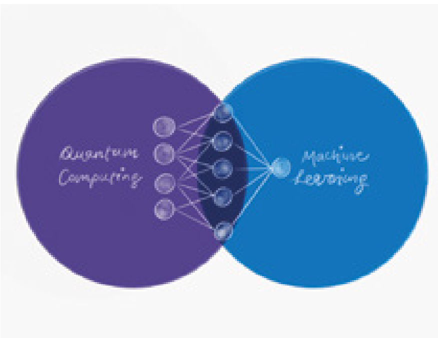
A recent study by the U.S. Sandia National Laboratories revealed that "system performance at scale on computational problems that arise in mission, commercial, or scientific work is below 20% of peak floating-point performance" with the "efficiency for even well-tuned codes [...] be[ing] just a fraction of a percentage point in some critically important cases, particularly if multiple scales and multiple physical regimes must be addressed" [Leland 2016].

This summarizes what experts in weather forecast from renowned institutions in Europe – ECMWF, the European Centre for Medium-Range Weather Forecast and KNMI, the Royal Netherlands Meteorological Institute – have reported independently when asked about today's major bottlenecks in their computational workloads. Despite the enormous effort of their in-house scalability teams that constantly improve the performance of simulation models, they "are still struggling to make good use of the hardware […] and are only able to harvest a couple of percent of peak performance from supercomputers". Our interview partners are moreover pessimistic that this situation will change in the near future. "The percentage of peak performance has been reducing over the past decades getting smaller and smaller" says one of them.

Learning from AI

Weather prediction stands as representative for a wide range of challenging computational problems that involve big data (about 40 million data sets per day), multi-scale and multi-physics models with complex nonlinear and even chaotic interactions, and the need to produce results in a limited amount of time, e.g. forecasts for the next couple of days no later than the prime-time news. As the problem is too large to be solved directly, simulation models must make compromises and adopt simplifications like the truncation of scales, which leads to a lot of uncertainties that need to be modeled rather than resolved. A recent trend that is not only seen in weather forecast but in many computational science domains is the use of machine learning techniques, also known as artificial intelligence (AI), to deal with uncertainties.

Experts from TU Delft who are at the forefront of developing novel super-compressible meta materials shared with us their experience with using AI as a key enabling technology to overcome key enabling technology to overcome the limitations of classical computing. In their experience, "it is not that difficult to switch from a neural network to parameterized quantum circuits" at least for certain types of neural network architectures since "quantum computers can be seen as a special case of a tensor network". Their suggested approach to move away from classical computing to quantum computing by adopting machine learning as the vehicle might turn out to become a general strategy to make quantum computing accessible to a broader community of scientists without background in quantum physics.



Dealing with uncertainty
Lessons can be learned from aritificial intelligence to deal with uncertainty in quantum computing.

An Expert Opinion

Accessibility of the quantum literature is considered another major challenge that stands in the way of an early adoption of this emerging computing technology through academia and industry. While new programming languages and compute paradigms like GPU-computing can be learned on the job, the development of quantum-accelerated scientific applications requires profound expert knowledge "that is not something you can do next to your normal work". And that's the core of the problem. It needs a certain technology readiness level (TRL) before industry and academia gets interested

Who

We spoke with **scientists and engineers** who work with quantum computing in their research.

What

We asked the scientists and engineers to describe the impact of quantum computing on engineering and the computational sciences.

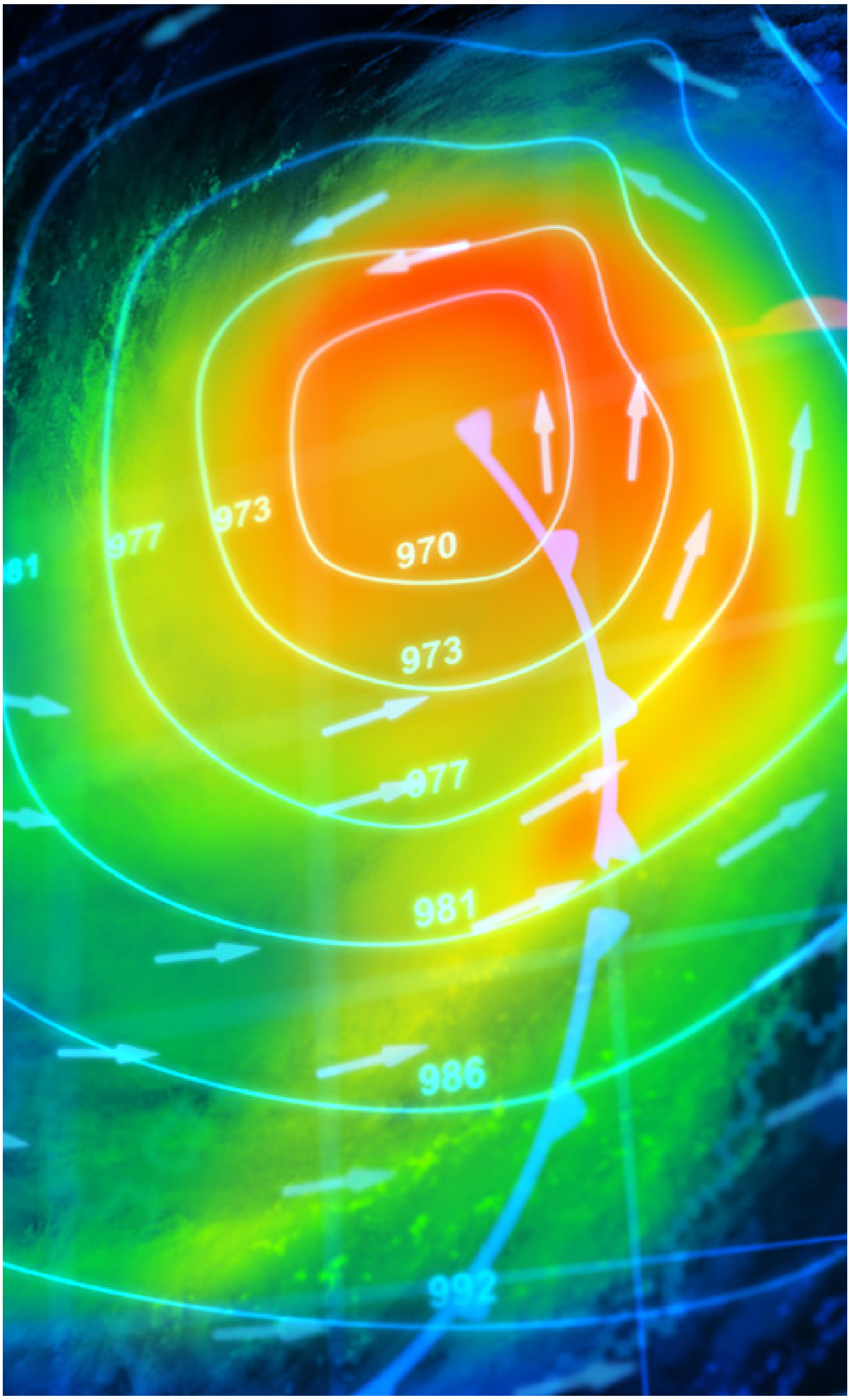
Takeways

Scalability is a major concern for the future of quantum computing.

We can learn from **machine learning** when dealing with **uncertainty and accessibility** in quantum computing.

in adopting quantum computers as their work horse.

This not only applies to the TRL of the hardware and software tools but especially to the quantum algorithms and computational building blocks that will enable the creation of real-world quantum-accelerated applications. What would be very much appreciated by domain experts who are not yet working in the field of quantum computing but eager to not miss this new trend is interdisciplinary communication. “Every now and then there is a new highlight article. I would rather see communication in terms of what is feasible today and where are we and where are we going to be” says one of our interview partners. The time has come to open up the quantum computing community and involve researchers from the different computational sciences and engineering disciplines to turn quantum computing into an impactful technology for the future.



Looking into the future
Quantum computers could prove particularly useful for forecasting.

Weather Forecasting: an unexplored field for Quantum Computing

An interview with Peter Dueben

Peter Dueben (Machine Learning & AI coordinator at the European Centre for Medium Range Weather Forecasts), interviewed by Matthias Möller

“Quantum computing is very promising, but we don’t know how to use it yet” says Dr. Peter Dueben, coordinator of machine learning and AI activities at the European Centre for Medium Range Weather Forecasts (ECMWF). Peter is one of ECMWF’s 390 staff members and works at the headquarter in Reading, UK. Established in 1975 as an independent intergovernmental organization with sites in Bologna, Italy, and Bonn, Germany, ECMWF is supported by 34 states in producing different types of numerical weather predictions ranging from global multi-day to seasonal predictions.

”To make good predictions of the weather, you need to represent the atmosphere but also many other components like ocean and land surfaces, cloud-physics, atmospheric chemistry, sea ice, land ice, etcetera” says Peter. This all is combined in a very complex multi-physics numerical forecast model that is run on ECMWF’s in-house supercomputer, one of the biggest machines in Europe and among the top 100 worldwide, multiple times per day. But that’s not the end of the story. The numerical forecast models need to be fed with initial and boundary conditions and that is where observations from weather stations and balloons but also planes and ships crossing the ocean and satellites come into play. For weather predictions of a single day, tens of millions of observations are assimilated into the numerical forecast model which itself is producing data that easily fills tens of terabytes.

For the efficient pre- and post-processing of this vast amount of data, ECMWF is using different types of statistical data analysis tools, among them machine learning, which is one of Peter’s areas of expertise. When asked about the opportunities for quantum computers to speed-up numerical weather forecasting in the future, Peter is not so sure. “The deep learning wave hit us some two to three years ago” he says. Today, AI-based tools that have been developed in collaboration with international research consortia partly funded by the European Commission, are investigated across the computational workflows at ECMWF. But the situation with quantum computing is different. When ECMWF got interested in machine learning, the technology already was at a rather high technology readiness level with ready-to-use hardware and software libraries that allowed researchers to quickly explore application opportunities. This is clearly not the case in quantum computing yet.

According to Peter, it’s not necessary to have the quantum computing hardware ready to make decision-makers interested in this topic. What would be more important is to have proof-of-concept emulations of quantum algorithms for practical applications such as solving global minimization problems, finding the solution to differential equations, or data assimilation. ECMWF is pursuing a lot of in-house research on AI, simulation technologies, and high-performance computing but building up all required expertise in quantum computing and algorithm development from scratch would be a long-term investment. Peter envisions collaborations between quantum computing experts from outside ECMWF and domain experts inside the organization as the most realistic way to go forward.

He sees collaboration as a win-win situation for both parties. “At ECMWF we have a lot of experience in dealing with uncertainties” he says. Numerical weather prediction is based on so-called ensemble models in which multiple weather model simulations are run with slightly different initial conditions. This helps the experts at ECMWF to forecast trends in temperature, winds, and rainfall with good accuracy. But there is more to it. When a tornado is approaching the U.S. west coast it is very difficult to predict long in advance if, where, and how strongly it will hit. In this case, safety measures need to be taken based on a probability analysis of the different scenarios to prepare the region for the most likely event. Whether the probabilistic nature of quantum computing can be of any help is not clear yet, says Peter. However, he sees the other way around, opportunities for ECMWF helping the quantum computing community in dealing with inaccuracies that might occur during computations. ECMWF has recently switched from double precision to single precision arithmetic in forecast simulations and is also exploring the use of half precision for certain parts of the computations. Dealing with inaccuracies in computation, and uncertainties in predictions is therefore not a new topic for ECMWF.

When asked about NP-hard problems in numerical weather forecasting, Peter surprised me by saying “Yes!”. A huge challenge in developing numerical weather prediction codes is the optimal placement and movement of data, which is the major bottleneck today. With high-performance computers becoming more and more heterogeneous this NP-hard problem will become more and more important and difficult to solve at the same time. Using quantum computers for it seems to be plausible for Peter with a big impact on all big-data applications.

Quantum Education

Quantum technologies are set to continue to grow—but is our future workforce ready to embrace them?

Carmina Almudever & Aletta Meinsma

A Need for Knowledge

Quantum computing has been a very promising topic in recent years as quantum computers hold the promise to efficiently solve some kind of hard problems that cannot be inherently solved by even current and future classical supercomputers. Thanks to the efforts of quantum computing experts from both companies and academia, quantum technologies have become more mature despite their youth. With the advent of the first functional quantum processors in the form of full-stack quantum computing systems, and with the prospect that larger quantum devices integrating hundreds or even thousands of qubits will be delivered in the next 5 to 10 years, the need for quantum computing training is becoming crucial, not only in its physics-oriented aspects but also in its more engineering-oriented ones.

This need for offering training and education on quantum engineering and technologies has also been identified by the European Quantum Flagship programme, which in 2019 launched a call on "Training and Education on Quantum Technologies" (FETFLAG-07-2020). As mentioned in the call, "the expected impacts of this initiative are: i) the development of a European quantum education community and education research agenda towards modern, quality-controlled education in quantum technologies and engineering; ii) the establishment of high quality quantum engineering programmes across the union addressing industry needs; and iii) create the first generation on joint MsC students connected to industry and more broadly preparing a skilled young future workforce in quantum technologies and engineering ready to be employed by the European industry". In addition, the quantum community in their Strategic Agenda called for Coordination and Support Action (CSA) to

Quantum audiences
There are very different target groups interested in quantum education.

fulfill an intermediate need to coordinate all efforts on public education and outreach and at all levels including schools, universities, industry and general public. As a result, a project for Quantum Technology Education (QTEdu) was launched in September 2020, whose goal is to assist the European Quantum Flagship with the creation of the learning ecosystem required to inform and educate society about quantum technologies.

The Role of Academia

Currently, several universities in Europe and around the world already offer Master and Minor programmes, tracks and specializations in quantum science, engineering and technology to train physicists, mathematicians, computer scientists and engineers in the multidisciplinary field of quantum computing. Note that developing a universal large-scale quantum computer requires contributions from several fields of study. Universities try to cover all layers of the quantum computing system in their education: from quantum materials and quantum devices, through classical control electronics, and up to quantum compilers, quantum programming languages, quantum algorithms, quantum applications as well as other related quantum fields such as quantum communication and cryptography and quantum metrology and sensing.

At this stage, it would make sense to make the education on quantum computing a joint effort. For instance, with the coordination of a national master programme combining forces from different universities – including ethical, legal and societal (ELSA) aspects that are currently missing – to create a strong and potentially broad and multidisciplinary master program. Furthermore, if the demand continues like this, a completely new and more specialized and focused programme could arise (e.g. a quantum technologist). In addition, most of the educational programmes target master levels but it is expected that in the next years programmes in quantum computing for bachelor students are developed.

What about educating other audiences? Several universities in the Netherlands have already been organizing outreach activities aimed at secondary school students, and the subject of quantum mechanics is included in the Dutch secondary school's educational programmes. With this kind of initiatives students might be more open to the field of quantum mechanics because they become familiar with its counterintuitive laws at a younger age. Focusing on another group, we need people who have gained practical skills throughout their education for actually building quantum devices. This could be an opportunity for Universities of Applied Sciences (hbo) to offer practical quantum specializations to their students. And finally, we envision that in the future, there will also be a need for training end users (i.e. companies) as they should be able to use quantum computers for solving

Quantum curriculum
New courses will have to be developed from scratch.

their problems. In this specific case, the involvement and support of academia is debatable. Should academia offer this kind of courses and, as a return, gain input from the industrial sector on possible use cases? Or should this need be covered by a different sector?

An Emerging Challenge

Quantum computing, in its more practical or experimental form, is an emerging field of research. Similar to other topics such as artificial intelligence (AI) or neuromorphic computing, this requires academia to move and adapt fast to the increasing need of educating and training students that get these crucial new skills.

This means that although some "conventional" courses (i.e. courses taught in other engineering/physics/mathematics programmes) can be included in quantum computing education from different disciplines, and some books already exist for teaching the fundamentals of quantum information and computation, completely new courses need to be developed from scratch based on the research activity and progress. Therefore, having enough critical mass to fulfill the increasing demand might be the first challenge the quantum community will be facing.

As any multidisciplinary field, quantum computing requires researchers from different areas of expertise to work together. The challenge here is to find a common language so that they can easily understand each other. What are effective ways to teach quantum mechanics to engineers, such that they'll be able to speak effectively with their physics colleagues? Or the other way around, how to teach engineering or computer science courses to physicists? Or even, what are the boundaries between the different disciplines? That is, how much should an engineer learn about quantum physics? Or how much should a physicist know about quantum algorithms?

In addition, as quantum computing is still in its infancy, education on quantum computing will be certainly affected by the progress in this topic. (Re-)designing and creating new teaching materials for even different target audiences (e.g. industry) will also probably be a difficult task.

We don't have the answers yet but would like to predict the following: that the next couple of years will prove to be very interesting times for the field of quantum education.

"Developing a universal, large-scale quantum computer requires contributions from several fields of study."

An international effort
Universities all over Europe are offering master and minor programs on quantum topics.

Who

We spoke with **educational stakeholders** from academia and industry.

What

We asked the stakeholders to outline **future opportunities and challenges** in quantum education.

Takeways

Quantum education can be improved by making it **collective**: a joint effort between institutions.

A **common language of quantum principles** is needed for different disciplines to effectively work together.

The Public's Perspective

As science and industry propel quantum technology forward, it's important to keep society involved in the process.

Kamiel Dankers

Quantum and Society

This magazine focuses on the select group of people around the world that work with quantum technology in their daily lives. However, they account for only a tiny fraction of the world population. The majority of people worldwide have never worked with quantum technology and might not even have heard of the concept. Even though these people do not have a direct influence on the development of the technology, they play an essential role in the future of quantum technology. For quantum technology to reach its full potential, it has to be accepted and supported by society.

The mysteries of quantum theory have always intrigued millions of people and have been used as an inspiration for several publications in popular culture. An example of this is the 1990s bestseller written by Gary Zukav named *The dancing Wu Li masters*. This book describes parallels between quantum theory and "modern psychology and metaphorical abstractions to Buddhism and Taoism." A more recent example is the Marvel superhero *Ant-Man*, who will be starring in the upcoming movie (2023) *Ant-Man and the Wasp: Quantumania*. In a previous movie *Ant-Man* unknowingly became "quantumly entangled" with his friend in the "quantum realm", later he has to build a "quantum tunnel" to save one of his friends. Even though most appearances of quantum theory in popular culture are far from physically correct, they can be important to incite enthusiasm and interest in quantum theory.

The Quantum Classroom

During our time in a high school class the curiosity for quantum mechanics in society was very clear. A presentation was prepared to engage the class and

Schrödinger's cat
The thought experiment of a cat in a box is tantalizing for everyone with a curious mind.

hopefully get some of their views and a few questions on the topic. Above all expectations, it took a single minute before the first hand was raised with an interesting question. From that moment onwards, the hands did not stop reaching for the ceiling for the rest of the hour. After a very intense and interesting 45 minutes the presentation was only one-third finished due to all the questions.

This enthusiasm has to be used by the quantum community to get a broader public engaged in quantum mechanics and technology. At the moment, the community is actively working to get an increasing number of people in society interested in quantum technology. On YouTube, videos that correctly explain quantum computing have tens of millions of views, newspapers publish regularly on the latest breakthroughs and quantum screen time on national television is growing. Another great example of building quantum awareness in society is Quantum Inspire, allowing everyone, quantum expert or layperson, to execute their own quantum algorithms on an actual quantum computer. Those engaging efforts have to be intensified to prepare society for the implementation of quantum technology.

Back to Basics

The most famous quantum related quote is attributed to Richard Feynman: "If you think you understand quantum mechanics, you don't understand quantum mechanics." This view of quantum mechanics being incomprehensible, harms the endeavor to create a bigger quantum knowledge among laypersons. However, it does summarize the tension for someone that wants to explain quantum theory. Because actually there are many things that we do not intuitively understand, think of the wavefunction collapse, the measurement problem and non-locality. In recent years, the number of statements similar to this quote has been decreasing. The focus shifts to trying to understand and discuss the fundamental issues that quantum theory exposes.

In this struggle for more quantum engagement and understanding, quantum theory is blessed with the Schrödinger's cat thought experiment. This eyebrow raising experiment perfectly catches the strangeness of quantum mechanics and is therefore used regularly to explain quantum mechanics to laypersons.

In conclusion, it is essential for the future of quantum technology that society is involved in quantum technology. Quantum technology has the advantage of an immense inherent interest in its mysteries. However, the challenge for the quantum community is to keep away from the idea of quantum being incomprehensible and teach the basics to the broader public. The tools needed to do so, such as the Schrödinger's cat thought experiment and Quantum Inspire, are present. By intensifying their efforts, the quantum community can get society in shape for the quantum era.

Quantum at school
Quantum is part of the curriculum at high schools. Additional outreach activities can help to foster curiosity.

"The challenge for the quantum community is to keep away from the idea of quantum being incomprehensible and teach the basics to the broader public."

Who

We spoke with **14-15 year old students in a HAVO/VWO high school.**

What

We explained to them the basics of quantum technology, and asked for their views on its future.

Takeways

Quantum technology generates an enormous amount of **interest from the general public**.

The quantum community has to use this enthusiasm to **prepare society for the quantum era**.

Designing the Future of Quantum

Communication is key for the future of quantum computing. Luckily, designers are ready to lend a hand.

Derek Lomas & Caiseal Beardow

A Social Challenge

Building a quantum computer is not purely a technical challenge, but a social and human one too. Quantum computing is unlikely to have the desired positive impact on society if societal stakeholders do not know how or for what purposes it can be used. Communicating this knowledge, however, remains a challenge: quantum computing can appear inscrutable for people outside the expert community.

The emerging field of Quantum Human-Computer Interaction (QHCI) seeks to address this issue by studying the needs of various societal groups who interact with quantum systems, and creating principles for designing such interactions. It is inherently multidisciplinary and requires engagement from both quantum computer scientists and designers (amongst others). In order for this engagement to be fruitful, however, common goals and vocabulary need to be established.

Creative Collaboration

Together with quantum computing experts from QuTech and designers from TU Delft's Industrial Design Engineering (IDE) Faculty, we explored these topics through a collaborative workshop. Our explorations were centered around two topics: opportunities for design in the development of quantum computers, and knowledge gaps to be addressed in the process. We began the workshop by asking the participants to share free associations about quantum computing, followed by a short 15-minute lecture that covered basic principles of the field (such as qubits and superposition). The participants were then split into their respective professional domains (i.e. quantum computing or design) and asked to prepare questions for each other about the nature of their field. Next, mixed-profession groups were formed and the participants discussed both their prepared questions and other topics, such as challenges and design opportunities in quantum computing. Finally, we reconvened for a plenary session in which to reflect on our findings.

First impressions
The participants shared their thoughts on quantum computing with us in a free association acitivty.

The results of the workshop provide some valuable insights into the way quantum computing, both currently and in the hypothetical future, is perceived. We noticed that quantum computing experts were more focused on known applications of the technology and its technical properties, whereas designers seemed to take a more general view, looking at wider (potential) application domains and characteristics. Additionally, the designers used words such as "inaccessible", "buzzword" and "opaque" to describe their immediate thoughts on quantum computing. We saw that quantum computing can appear inscrutable, even intimidating, without good communication strategies. This is a clear barrier to the interdisciplinary work that is key to the future of quantum computing.

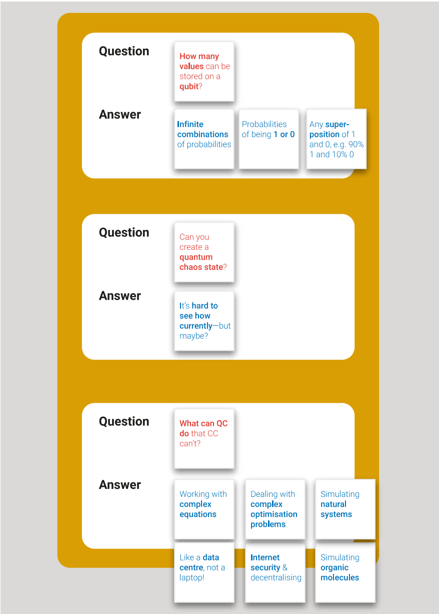
Communicating Value

The mixed-profession discussions we held revealed further barriers to such work. The designers frequently raised the issue of value: what is quantum computing good for, and how does this relate to society? In contrast, the quantum computing experts were unsure of not only the value of design to quantum computing, but what kinds of skills and tools designers actually use in their work. Again, the topic of communication was central – in particular, sharing knowledge between disciplines and creating a common vocabulary of quantum principles in order to do this.

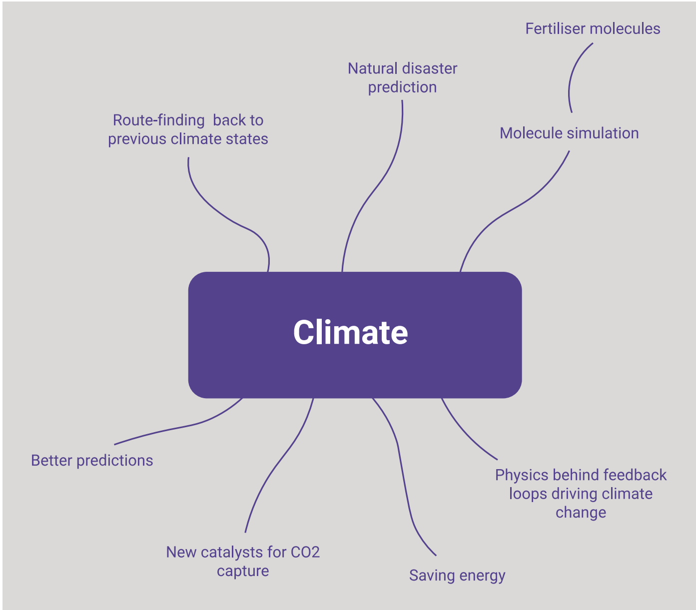
It became increasingly clear that, although quantum computing experts are keen to work with other disciplines and learn from each other, they are unsure of how to share information in the right way for different audiences. This is partly due to the sheer complexity of their field, but also due to its nascence: we simply cannot say for sure how the technology will develop in the future. We have good predictions (as shown in the Hardware & Software part in this magazine), but as of yet the use cases we do have are relatively niche. This makes it difficult for other disciplines to imagine how they might meaningfully engage with quantum computing.

Designing the Future

Luckily, designers are experts in communication and may have much to offer quantum computing in this respect. In particular, the workshop participants identified



Questions and answers
Both the quantum computing experts and designers had knowledge to share with each other.



Collaborative thinking
Together, the designers and quantum computing experts imagined future uses of quantum computing.

visualizing quantum systems as a key opportunity for designers to contribute. Quantum behaviours can be quite unintuitive for those outside the field; better visual abstractions of these behaviours can help to build a level of 'quantum intuition'. Based on the findings of our workshop, we expect that further collaboration between designers and quantum computing experts can help to generate such abstractions. In this way, a 'middle level' between visual accessibility and scientific accuracy can be created.

Who

We spoke with **designers** and **quantum computing experts**.

What

We asked the participants to explore the future of quantum computing and identify opportunities for design to contribute.

Takeaways

Communication is key to interdisciplinary work. Designers can help to facilitate this.

Better **visualisations** and **abstractions** of quantum principles are needed to make the field more accessible.

"Quantum computing can appear inscrutable, even intimidating, without good communication strategies...Luckily, designers are experts in communication."

Interdisciplinarity
Communication is key in an interdisciplinary field such as quantum computing.

Projective Measurements

Tracing out the impact of Quantum Technology in 2040

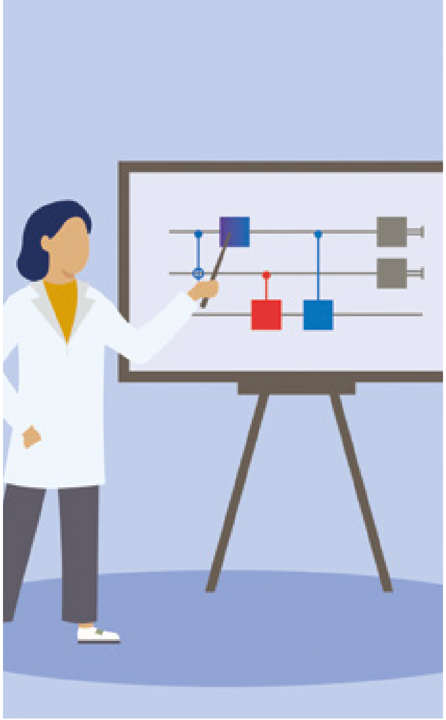
Scarlett Gauthier and Brennan Undseth (MSc. Applied Physics, TU Delft)

Presently, the field of quantum computing is rapidly growing and is the subject of an intensive effort of engineering, design and innovation. Yet, the field is still in the early stages – will there be a powerful quantum computer advancing science, technology and society in 2040? Or will the scientists of 2040 look back on the efforts of today as a naïve dream that was doomed to fail?

We believe that the path of quantum technological development will have a lasting positive impact on society – regardless of whether or not disruptive quantum computation is achieved by 2040. In the next two decades, we expect that quantum technology will remove divisions in science, inspire a new generation of students, and incubate a new era of innovation.

Already today, quantum computing has raised interest in many scientific disciplines due to its potential to advance progress in myriad fields. For example, molecular modeling by a quantum computer may be a boon to pharmacology, advanced quantum machine learning might detect patterns in scattering events from particle colliders, and a quantum network could improve the sensitivity of astronomers' telescopes. The breadth of applications offers an incentive for specialists to not only be aware of quantum computing, but to speak its language. As a result, scientific problems of many flavors will be distilled into a common framework, intelligible to scientists across different disciplines. By interconnecting people and their expertise, the benefits to humanity will extend beyond unlocking computational power.

In fact, there is a precedent of a similar development in the second half of the 20th century: the space race motivated an entire generation of young people to strive towards technical pursuits. Today, discussion of quantum technology pervades popular culture and a similar opportunity to recruit young minds exists. Embracing of this opportunity can be seen in the forging of industrial partnerships, global press coverage of developments in quantum technology, and an active dialogue between the research community and governments around the world. The large pool of researchers attracted by these initiatives will bring the fresh perspectives needed to examine enduring problems from new and creative angles. As teams working within the field expand, there is impetus to address and combat existing inequalities in social issues such as gender balance and cultural diversity. To this end, it is important that community leaders from under-represented groups remain visible and initiatives such as mentorship programmes are taken seriously.



Future impact
Quantum technologies could have a lasting positive impact on society.

Forecasting the impact of technology is often foolhardy. With the space race came not only an increased focus on technology, but also the expectation of humanity expanding to the stars. Yet more than 60 years later we do not inhabit other planets or cohabitate with sentient AI. However, technological progress manifests in ways we least suspect. If the COVID-19 pandemic occurred 30 years ago, a socially-distanced society would have had to sustain itself on telephone, fax, and mail. Yet in 2020, the world surprised itself by embracing a digitized lifestyle – not even a far cry from the sci-fi-esque predictions of the 1950s. The science fiction author William Gibson says "the future is already here – it's just unevenly distributed". So perhaps the allure of Shor's algorithm suddenly breaking RSA encryption of communication is never realized, or perhaps it occurs and the post-quantum-cryptographic future collectively shrugs. In 2040 "quantum" – whichever form it takes – will have happened. And it will be the legacy of how it came to be that defines the quantum future.

These pieces were produced by their authors for a student writing competition on the topic of quantum technologies, in which they were awarded joint first prize.

Our Quantum World with Jim Murray

Every Thursday 19:30-20:30 on the Discovery Channel!

Alexander Ivlev (MSc. Applied Physics, TU Delft)

"First of all, thanks for inviting me to your show, Jim! And that's an interesting question. Would today's 12-year-old be able to design a quantum computer? Surely not! But is that same 12-year-old better in using quantum computers than its inventor? Most definitely, given their intuitive understanding of quantum mechanics already at an early age. It's funny, how my grandchildren react when I tell them how we experienced life before anyone could see quantum. I guess it's like when blind people tell us how they view the world. I remember watching vlogs by a blind woman 50 years ago, on a platform called YouTube. I could somewhat imagine what kind of impairment it was for her, but she barely grasped our experience. That blind person, that's who we are to kids these days, blind to the principles that govern the whole universe."

"You said that we were blind, as if the inability to see the quantum world is an impairment. Yet, society was able to function perfectly without. Humans have done so for millennia. Why is it so essential?"

"Well, the short answer is that we believed this was the way to progress in quantum technology, or honestly technology in general: medicine, material-science, logistics, simulations, all of it depends on quantum tech nowadays. But back then, say 2039, apart from some breakthroughs every few years, there was no progress, surely no stable one, and the field seemed doomed to a slow death. Some concluded that the big problem was fundamental: there was not enough intuitive understanding of the principles of quantum mechanics. There were a few geniuses here and there that brought the field forward, but in slow and non-consistent steps. We were in dire need of more quantum talent."

"Looking back, what do you feel was the turning point in that?"

"To me it was when Jason Flamming came with a new idea of visualizing quantum-mechanical phenomena on one of his visits to Delft. We didn't think much of it at first, but then he came with a demo, utilizing VR technology. We could walk through a virtual classroom at TU Delft, and tweak some of the fundamental constants. 'What would happen if Planck's constant was higher?', we asked. And we'd of course see wave-particle duality emerging, but also phase-changes in materials, changes in electrical conductance; Jason had programmed in a few things. It was quite an experience to see all the physical phenomena we had been working on for decades right in front of our eyes. During that demo, I saw middle-aged, grumpy CTO's, professors and investors suddenly turn into children. Myself, of course, included." (laughing)

A quantum revolution
The question is not if scientists will use quantum computers, but when.

"And was that also suited for daily use, like anyone can do today?"

"Well, at that point, we could just about sustain a single user. We took baby steps. With the help of AI and AR progress, we could integrate the software in a set of glasses, which later would be replaced with the neural interface we now use. The data would be sent to the quantum processor in the cloud, which simulated the material behavior under parameter changes made by the user. That was, say summer 2040 when the first prototype was in use."

"And when did you realize that this would reignite the quantum revolution?"

"For me, the big, 'wow, we actually hit gold' moment, was when one of my postdoc researchers called me up after a few hours on the simulator. He thought of a novel way to reduce some noise that we had struggled with for decades. As a result, we decided to make this technique widely available for any researcher: people could reserve time on the simulator, running on a dedicated quantum computer. It was in essence an educational tool, as it still is today, which enabled such in-depth knowledge that the productivity of its users was unparalleled. The step to introducing it to high schools quickly followed. As a result, technological progress escalated, and to accelerate that further the UN Education Commission founded QSight in 2051, which you all know about. But that's an entirely different story."

"Amazing, I'd love to hear about that some other time. Thanks a lot for being here, Dr Philip Hay!"

Reflections

Towards a TU Delft Vision on Quantum Computing

Concluding remarks

Pieter Vermaas (chair), Michael Wimmer, Derek Lomas, Carmen G. Almudever, Giordano Scappucci

Quantum computing is scaling up

The development of quantum computing is scaling up, and this manifests itself technically as well as socially. The technical scaling-up has received significant coverage in the news and scientific articles, and is observable in rapid progress: functional qubits have been achieved in many different physical systems, and quantum processors are containing an ever increasing number of better qubits. This progress poses grand technological challenges, such as how to control higher numbers of qubits. On the other hand, the social scaling-up concerns the broadening of stakeholders driving the development of quantum computing, from quantum physicists and computer scientists, to engineers, industrialists, governments and ultimately society at large. This second scaling-up involves incorporating knowledge and practices from different disciplines and reconciling divergent interests. It is this second development we focus on in summing up the findings of the Vision Team and in proposing a TU Delft vision on quantum computing: a constructive collaboration between all the stakeholders leads to challenging tasks and to meaningful choices about what quantum computing can eventually bring to society.

TU Delft stands in the forefront of both developments of quantum computing. It is home to seminal research on quantum computing. In 2014 TU Delft brought together physicists, computer scientists and engineers by co-founding QuTech, a collaboration of TU Delft and TNO, the Netherlands Organization for Applied Scientific Research. A result of this collaboration is Quantum Inspire, providing experimental quantum computers for exploration to researchers and other interested parties all over the world.

Our meetings with stakeholders confirmed that a multidisciplinary approach is indeed essential for successfully overcoming the challenges of developing quantum computing, and TU Delft should embrace this approach for the years to come.

A common language across disciplines

The initial driver of quantum computing was the technical development of qubits. This development was physics-driven and put the language of quantum physics with its enigmatic concepts of superposition and entanglement central in our understanding of quantum computing. Yet, this understanding is not intuitive, as pointedly stated by the famous Richard Feynman: Nobody understands quantum mechanics. Quantum computing has however become a multidisciplinary endeavor. The accompanying language must evolve accordingly and outgrow its pure quantum physics origins.

The broadening of the understanding of quantum computing beyond physics is a crucial challenge according to many of the stakeholders we have spoken to, and also was the main topic of the winning student contributions. Building a prototype of a quantum computer relied on close collaboration between physicists, engineers and computer scientists. Developing applications of quantum computing requires that even more stakeholders can understand quantum computing. We spoke for instance with scientists and software developers who are eager to explore how quantum computing can be used for problems in their fields, yet have difficulty grasping quantum physics. To include these new stakeholders, each with their own disciplinary tradition, it is necessary that a common understanding of quantum computing is emerging with concepts and language that all can master.

Moreover, the development of quantum computing depends on educating future generations of quantum computer experts who master the different disciplines for further development and who can operate quantum computers for their applications. This education again requires making quantum computing accessible and understandable more broadly. At the same time, we witnessed across all people we spoke with a natural curiosity towards the puzzling quantum phenomena such as Schrödinger's cat being in a dead-and-alive superposition. Future quantum education should build on this curiosity but step away from a Feynman-style warning that nobody understands quantum.

Finding a common language for understanding quantum computing and interacting efficiently with quantum computers is still an open research topic. Solving this problem will require involving additional disciplines such as mathematics, design and philosophy.

TU Delft should contribute to creating this common and multidisciplinary language for quantum computing, through its research programs and in its education development.

Beyond the funnel of first use cases

Quantum computing comes with dreams of solving important scientific and societal problems, ranging from creating new materials to reducing energy consumption of industrial processes. And it comes with the more nightmarish possibility of breaking existing encryption of our digital data and communication. For this reason the social scaling of quantum computing has drawn in external stakeholders such as industry and the government for exploring and assessing applications. Yet, in our discussions there was no consensus on what the first use case will actually be – it may very well be an application not thought of yet!

We observed that the interests of industry and governments introduce the danger of funneling the search for applications into narrow domains. For industry to invest in quantum computing, it has to find commercially viable applications. This focus may introduce a bias towards only a few specific applications at the cost of others. Governments amplify this focus on commercial applications with arguments that investments in quantum computing should lead to national economic growth. Governments also increasingly acknowledge risks and opportunities of quantum computing for national and international issues such as cyber security and geopolitical balances. This focus is meaningful yet introduces the limiting perspective of seeing quantum computing as a technology controlled by the larger power blocks in the world for their economic and security interests.

To escape the funnel and unlock the full potential of quantum computing for all stakeholders and for all countries in the world, academic institutions should not only focus on the applications brought forward by industry and government. In fact, it is very likely that first use cases also arise in the science domain. Many research fields rely on high-performance computers, and quantum computing may overcome existing limitations. Such scientific applications of quantum computing might not be profitable, yet be relevant to society. If for instance quantum computing can lead to breakthroughs in pharmacy for the search for treatments to diseases in developing countries, and industry is not taking it up, we should develop these applications nevertheless.

We advise TU Delft to engage in the exploration of applications of a quantum computer in a broad range of fields, to contribute to our global society in a meaningful way. This includes interacting with industry and creating economic value, but also with academic researchers from any interested field.

Openness for science, education and society

The idea of having open access to research results and data has grown in the past years, and TU Delft is committed to this principle. This vision team believes that open access can play an important role in quantum computing. At the moment quantum computing is in the ramp-up phase, and most research can be open, whereas it may close as the technology becomes more proprietary. Yet, it should be acknowledged that quantum computing will stay for the next few years in its ramp-up phase. Hence, shifting now to a more closed mode of research out of geoeconomic or geopolitical motives will actually hamper development. Also in later phases open access can be beneficial to quantum computing: it can support the search for socially relevant applications, help industry with finding technological standards, and promote TU Delft's research and education. For instance, in the absence of a settled curriculum, openly sharing education materials will lead to beneficial interactions with other universities, and can help to promote and advance the Delft education program.

Openness also has the meaning of being accessible and trustworthy. There is a significant outreach effort ranging from informing people about quantum computing to attempts to express the value of its applications in general (layperson) terms. Still, with the media mostly focusing on a few overly hopeful results – quantum computing curbing climate change – or extreme threats – quantum computing eliminating digital security – it can be hard to get a faithful picture of quantum computing. Hence, it is essential to provide industry, scientists, policymakers and the public with honest information about the development of quantum computing and about what applications it realistically can bring.

TU Delft should harness openness: it will be essential for quantum computing to be a successful research field, and should be used to promote our efforts in research and education. At the same time, we find it important that TU Delft provides balanced information in an open and active way.

The end point of social scaling is the inclusion of society as a whole into quantum computing. Developed with industry and governments in an (inter)nationally secure way and in with an open and trustful dialogue with societal stakeholders, quantum computing has the promise of becoming an exciting technology that brings economic prosperity and societally meaningful applications.

Response by the Rector Magnificus, Tim van der Hagen

Our Rector Magnificus reflects on the future of quantum computing at TU Delft.

Tim van der Hagen, Rector Magnificus and President of the Executive Board, TU Delft

At TU Delft, quantum technology is one of our strategic priorities.

Together with TNO, we have established QuTech as our mission-driven institute for quantum computing and quantum internet. We are committed to combining excellent research and engineering to advance quantum technology. We help deliver this technology to the market by supporting startups and connecting to industry, and we've set up innovation ecosystem Quantum Delft to accelerate this process. We actively support the national initiative Quantum Delta NL, and we will soon welcome the House of Quantum to our campus as a nationwide meeting place for researchers, industry and society to discuss and develop quantum technologies.

We are convinced quantum is the future. For us to keep fulfilling our mission of educating future generations of engineers and performing innovative research in physics and other fields, quantum computing should become a comprehensible and applicable technology. That is why we are committed to the development of a common and multidisciplinary language for quantum computing. We're also setting up an interdisciplinary Master's programme on Quantum Information Science and Technology, and members of various faculties have teamed up with quantum scientists to work on the interface between user and quantum computer.

As TU Delft, we value open science and open education wherever possible, though geopolitical issues or agreements with partners can set limits to what we may or should disclose. An emerging technology such as quantum computing will benefit from open access to research results and education materials, enabling the scientific community as a whole to make the most of our advances. TU Delft is also committed to honest and truthful communication about the reality of technological progress to academia and to society as a whole.

At TU Delft, we are helping to develop and deliver technology-driven, innovative solutions to societal problems. We explore potential applications of quantum computers in a broad range of fields in industry, science and society. We align our research and education to the Sustainable Development Goals of the United Nations, and quantum computing could contribute to realizing those goals as well. How this contribution can take shape is a research question in itself, and I invite scientists and engineers at TU Delft to take up this question. In this regard, our vision teams are also an essential part of our responsibility of interacting with society and exploring how the technologies we work on can have a meaningful impact on society. I hope you have enjoyed the contents of this magazine and had an informative and inspiring look into quantum computing!

"We are convinced quantum is the future...quantum computing should become a comprehensible and applicable technology."

Special thanks

This magazine is the result of a joint effort of the Vision Team Quantum Computing and all the experts with whom we have spoken to understand what quantum computer is about and explore what impact it can have on science, industry and society.

The vision team was installed by the Executive Board of TU Delft. We want to thank Tim van der Hagen, Rector Magnificus and President of the Executive Board, for his invitation to explore the impact of quantum computing. And we want to thank all experts for their contributions.

The work of the vision team was disrupted by the covid-19 pandemic. Early 2020 the TU Delft had to redesign within weeks its core activities of education and research, and all planned meetings with experts transformed from visits to the TU Delft campus to "distant" online meetings. We are impressed by the joint effort and shared commitment to continue under these challenging conditions.

A special mention goes to the students who participated in the vision team: Caiseal Beardow, Kamiel Dankers, Merel Schalkers, Brennan Undseth and Timo van Abswoude. Their researching, writing and designing forms the core of this magazine.

Pieter Vermaas (chair)
Michael Wimmer
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Carmen G. Almudever
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List of Stakeholder Meetings

Industry
Delft Circuits
Microsoft
Orange Quantum Systems
Frank Ruess, author of Boston Consulting Group's *The next decade in quantum computing*
QBlox

Education
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Lay persons
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The TA Team

Brennan completed his MSc Applied Physics thesis at QuTech while working on silicon spin qubit devices in the Vandersypen lab. He is currently pursuing his PhD thesis in the same lab, working to bring silicon-based quantum computing a step closer to reality.

Caiseal is a PhD candidate at the Faculty of Industrial Design Engineering, TU Delft. In her research she is developing theories of and interfaces for interacting with quantum computers, as part of QuTech's Quantum Inspire project, with a focus on accessibility and outreach.

Kamiel has followed the Physics for Quantum Devices and Quantum Computing track of the master Applied Physics. During his thesis he has performed research in Ronald Hanson's group, focusing on the Quantum Internet.

Merel wrote her master thesis on circuit generation for quantum computers. Currently she is working on the same subject as a PhD student at the Faculty of Electrical Engineering, Mathematics and Computer Science at the TU Delft.

Timo first came into contact with quantum computing in his bachelor's thesis, where he worked with superconducting qubits. During his master's Applied Physics at TU Delft he followed the Physics for Quantum Devices and Quantum Computing track, which he currently finishes with a thesis about spin qubits at QuTech.

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TU Delft

Top education and research are at the heart of the oldest and largest technical university in the Netherlands. Our 8 faculties offer 16 bachelor's and more than 30 master's programmes. Our more than 25,000 students and 6,000 employees share a fascination for science, design and technology. Our common mission: impact for a better society.
www.tudelft.nl

QuTech

QuTech is the advanced research center for quantum computing and quantum internet, a collaboration founded in 2014 by TU Delft and the Netherlands Organization for Applied Research (TNO).
www.qutech.nl

QuTech Academy

To build the first quantum computer and quantum internet, QuTech works together with talented students with in-depth knowledge in the areas of quantum physics, computer science & engineering.
www.qutech.nl/academy
QuTech and the TU Delft offer several free online courses on quantum computing:
https://www.edx.org/course/hardware-of-quantum-computer
https://www.edx.org/course/architecture-algorithms-quantum-computer-internet

Quantum Delta NL

A partnership of Dutch research centers, compagnies and government agencies with the aim of positioning the Netherlands as a leading ecosystem in quantum technology.
www.quantumdelta.nl

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The UK National Quantum Technologies Programme

This site contains various reports and resources about quantum technologies as part of the United Kingdom efforts on quantum technologies.
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TU Delft regularly launches vision teams to learn about perspectives on technologies that exist in society. TU Delft is at the foreground of developing technologies and is informing society about these technologies and their uses. With vision teams we want to understand concerns about the impact of technologies and explore how they can be made of better use to society.
www.tudelft.nl/en/about-tu-delft/strategy/vision-teams/

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Quantum Computing

From Hardware to Society

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