2015

Annual Report

In accordance with the ‘Partnerconvenant QuTech’

Foreword

On behalf of all team members I am very proud to present you with the first official annual report of QuTech.

A lot has happened since our start in 2014: we have grown up to 150 scientists, engineers and support staff, delivered groundbreaking scientific results, became a national icon, filed our first patents, welcomed both Microsoft and Intel as industrial partners and contributed to the launch of the European FET flagship programme. All this wouldn't have been possible without the support of our public partners: The ministries of EZ and OCW, TU Delft, TNO, NWO and Holland High Tech.

This report gives you an overview of QuTech activities and output in 2015. It highlights some of our most important scientific and technological milestones, our educational programme, the grants and funding we attracted, new partnerships and an overview of the organization and finance. However, this picture is far from complete. It is a mission impossible to describe the enormous progress that took place at QuTech over the past years.

With the help of QuTech members seconded from TNO, we have made the transition from traditional, university-based science groups to a mission-driven research centre with coherent roadmaps and ambitious goals. And as all physicists know: while a fusion process eventually leads to the release of large amounts of energy, it does take a lot of energy to get started. The same holds for the fusion that is taking place at QuTech. The entanglement of the expertises and cultures of TU Delft and TNO takes a lot of effort, but is now starting to release results in the form of new ideas and approaches.

I am looking forward to everything that will come out of QuTech when the fusion reaches its explosive state in the next years!

Photo credit: Bob Bronshoff

> LEO KOUWENHOVEN

SCIENTIFIC DIRECTOR QUTECH

COLOPHON

Text
TU Delft — TNO

Graphic design
Atelier Pan

QuTech
Lorentzweg 1
2628 CJ Delft
+31 15 27 86 133
QuTech@tudelft.nl

Contents

Executive Summary

QuTech is the advanced research centre for Quantum Computing and Quantum Internet, a collaboration founded in 2014 by Delft University of Technology (TU Delft) and the Netherlands Organization for Applied Scientific Research (TNO). Within TU Delft, both the Faculty of Applied Sciences (AS) and the Faculty of Electrical Engineering, Mathematics and Computer Science (EEMCS) are involved in QuTech. This document presents the most important developments concerning QuTech in the year 2015, with some additional information from 2016.

QuTech is the advanced research centre for Quantum Computing and Quantum Internet, a collaboration founded in 2014 by Delft University of Technology (TU Delft) and the Netherlands Organization for Applied Scientific Research (TNO). Within TU Delft, both the Faculty of Applied Sciences (AS) wand the Faculty of Electrical Engineering, Mathematics and Computer Sciences (EEMCS) are involved in QuTech. This document presents the most important developments concerning QuTech in the year 2015, with some additional information from 2016.

Within each of the three roadmaps 'Fault-Tolerant Quantum Computing', 'Quantum Internet and Networked Computing' and 'Topological Quantum Computing', the QuTech scientists - expertly supported by QuTech's technicians – worked hard on making important research progress. Just one example: The "Loophole-free Bell test: Spooky action is real" was much talked about in 2015. More information about this experiment and the other results can be found in the "Research" section.

These successes did not go unnoticed in the 'outside world'. QuTech researchers received worldwide press attention, were awarded personal research grants (Vidi, Vici, ERC, and so on) and won awards (KNAW, Science Battle). An overview can be found in the "Grants & Outreach" section.

Together with Dutch knowledge institutions, the Dutch government agreed to invest 146 million Euro over the next ten years in QuTech. To this end, a covenant was signed on 1 June 2015. At the same time, QuTech also expanded its successful collaboration with major industrial partners. Next to the ongoing cooperation with Microsoft, QuTech welcomed Intel as a new partner. The company made an investment of USD50 million for a ten-year research collaboration with QuTech. The “Partnerships” section provides an overview of the QuTech cooperation with various Dutch partners, international industry and knowledge institutes.

In 2015, leading QuTech scientists took part in state visits of Their Majesties King Willem-Alexander and Queen Máxima of the Netherlands to Canada and Denmark and joined trade missions led by Prime Minister Mark Rutte and Minister of Economic Affairs Henk Kamp to China and Japan. During some of these visits MoUs were signed regarding cooperation in the field of quantum technologies.

QuTech Academy provides education in quantum technologies via both on-campus and online education. The “Education” section shows that a lot has happened in this area in 2015. Campus activities were established, as was a series of four classes for MSc students after which the students may take on a Master’s thesis project at QuTech. QuTech participated in the IDEA-league summer-school series 2015 on Quantum Science and Technology. In February 2015, the Massive Open Online Course (MOOC) ‘Topology of Condensed Matter: Tying Quantum Knots’ kicked off with as many as 4000 participants.

The “Organization” section offers insight into the governance of QuTech. Furthermore it includes a number of graphs on staffing levels and structure. End of 2015, 110 people worked for QuTech. This number is expected to increase in the coming years to about 250 in 2020.

The “Financial overview and expenses” section provides information on QuTech budgets within the framework of the “partner convenant”. As 2016 is already well underway, we have chosen this information to reflect the current financial situation (September 2016).

Finally, the appendice presents an overview of the QuTech projects.

Research

ROADMAPS

Photo credit:
Ernst de Groot | Haalbeeld

Fault-tolerant Quantum Computing

> ROADMAP LEADERS: **LIEVEN VANDERSYPEN, LEO DICARLO**

Fault-tolerant Quantum Computing (FT) — A major development for QuTech was the signing, in September 2015, of a contract with Intel Corporation to establish a ten-year research collaboration on Fault-Tolerant Quantum Computing.

Intel contributes USD50 million to support research at QuTech, plus a team of about 10 Intel engineers who work closely together with the Delft team. Two of these engineers are stationed in Delft, the others mainly in Portland, OR, USA. From QuTech, both TU Delft and TNO participate in this programme.

The joint collaboration involves:

- electron spin qubits in silicon quantum dots
- superconducting 'transmon' qubits
- cryogenic electronics to control and measure the qubits
- interconnects between the classical control circuitry and the qubits
- quantum computer architecture

The collaboration has gotten off to a very positive start, with weekly exchanges of information and a fruitful joint kick-off meeting in Delft in the Fall of 2015.

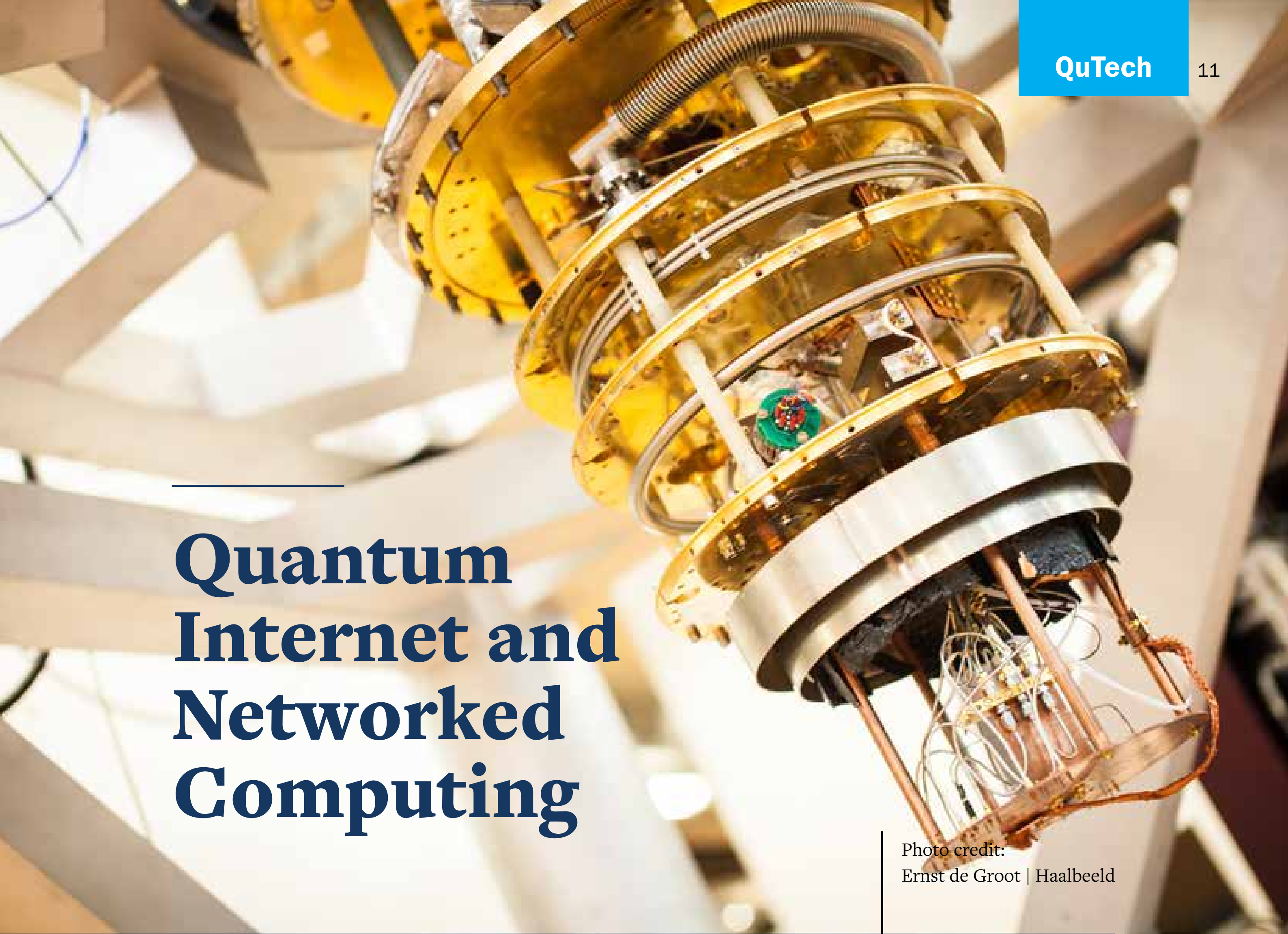
In 2015, experiments on spin qubits have focused on scaling up to arrays of three and four quantum dots. A bottleneck in scaling up is device-to-device variation, which is compensated for by time-consuming tuning. We have completed a first step in automating this tuning process by computer, bringing in concepts from pattern recognition (*Applied Physics Letters* **108**, 213104 (2016)). Furthermore, we have demonstrated spin shuttles, in which an individual electron is moved through a quantum dot array, while preserving the spin projection (*Nature Nanotechnology* **11**, 330-334 (2016)). A second focus was on improving coherence times by moving to silicon instead of GaAs. This has resulted in a 100-fold improvement in the spin dephasing time, and in vastly superior spin manipulation fidelity (*PNAS*, in print, see arxiv:1602.08334). Finally, we have developed initial ideas for creating large 2D arrays of quantum dots based on floating gates for biasing the quantum dots. >>

>> We have started developing a field-programmable gate-array (FPGA) platform to support the readout and control of large arrays of qubits and operating at cryogenic temperatures (*Computing Frontiers*, 282-287 (2016), see arXiv:1602.05786). The platform is compact, thus reducing interconnect from base temperature to room temperature, and enabling reconfiguration of qubit control functionality without expensive warm-up cycles (*Symposium on FPGAs*, 281 (2016)). Several components in the platform have been integrated in deep-submicron CMOS technology and tested at and below 4K (Cryo-CMOS), achieving better than 1K noise temperature over a bandwidth of 1.2GHz. Finally, single-hole transistors and cryo-CMOS models have been created and validated with measurements in collaboration with groups in QuTech, Politecnico di Milano, and Intel (*Applied Physics Express* **9** (1), 014001 (2015), IEDM (2016)).

In 2015, the superconducting part of FT focused on the extensibility of their superconducting quantum processors and the room-temperature electronics and software required to operate them. On the chip fabrication side, a major focus has been transitioning from processors with lateral input and output ports to ones with fully vertical I/O. This is essential for delivering on the promise of scalability; a necessary step to grow in qubit numbers by copy-pasting a unit cell. The development of vertical I/O involves new fabrication methodologies, including deep etching of silicon substrates, conformal coating of superconductors in 3D structures, and reliable one-step indium-based soldering of chips to multi-layer pc boards (as opposed to conventional wire bonding). These activities constitute a central focus of the new collaboration with Intel and are the subject of a patent application.

On the control side, we have continued developing digital and microwave-analogue electronics for scalable control of superconducting qubits, including a precision pulse multi-caster, an arbitrary waveform generator, power amplifier, I/Q mixers, and a field-programmable-gate-array platform for multiplexed readout and pulse sequencing. We have also developed the essentials of a quantum instruction-set architecture for control of complex processors, achieving a demonstrator at the one-qubit level. We also collaborate closely with Microsoft Research in the development of the new data-acquisition platform QCoDes.

In late 2015, the roadmap secured funding from IARPA to develop an error-corrected 17-qubit superconducting circuit and the electronics and software to control it. This new activity, to be launched in April 2016, is a partnership of QuTech with Zurich Instruments and ETH Zurich. Realizing the 17-qubit logical qubit and an intermediate 7-qubit version will be the main focus going into in 2016 and a complement to the activities with Intel.



Quantum Internet and Networked Computing

Photo credit:
Ernst de Groot | Haalbeeld

> ROADMAP LEADER: **RONALD HANSON**

Quantum Internet and Networked Computing (QINC) — On the quantum network side, the most important result was the loophole-free violation of Bell's inequalities (*Nature* **526**, 682-686 (2015) & Scientific Reports 6, 30289 (2016)).

This experiment has key fundamental importance, but for QuTech's mission it is most relevant that this experiment demonstrates the feasibility of device-independent quantum key distribution – the ultimate security attainable for communication. This experiment also set two technical world records: the longest distance for heralded entanglement (1.3km, was 21m) and the highest quality of remote heralded entanglement (92% state fidelity, was 87%). Also noteworthy is that this experiment benefitted heavily from in-house theory contributions, thus serving as a showcase of the strength of QuTech's broad skillset.

We have also performed theoretical modelling and experimental assessment of nuclear spin qubits as quantum network memories (*Faraday Discuss.* **184**, 173 (2015)). This work unravelled the main limitations and

>>

>> showed a path towards the next generation of experiments in which remote heralded entanglement is combined with local quantum operations (essentially a small quantum computer at each node) for entanglement purification and quantum repeating.

Furthermore, to assess the performance of a future quantum repeater, we have derived new theoretical bounds on the capacity of quantum channels to produce encryption keys. If a repeater design promises to produce more keys than is possible by the capacity of a direct connection, then it is considered to repeat. This forms a guideline for the construction of repeaters (*New Journal of Physics* **18**, 063005 (2016)).

On the quantum computing side, we have implemented quantum error correction on a continuously encoded qubit with real-time feedback (*Nature Communications* **7**, 11526 (2016)). For this work, several critical technical capabilities were implemented for the first time: multi-qubit non-destructive parity measurements, real-time assignment of errors and real-time correction, all the while keeping the quantum information stored. In an experi-

Topological Quantum Computing

> ROADMAP LEADER: **LEO KOUWENHOVEN**

Topological Quantum Computing (TOPO) — In 2015, the Topological Quantum Computation roadmap focused on material science and novel device geometries leading to topological qubits based on Majorana particles.

ment applying multiple rounds of error correction, we could show that the dephasing time of the encoded qubit was improved beyond the dephasing time of the best physical qubit.

The real-time feedback was also put to use to improve the sensitivity of a quantum sensor for magnetic fields (*Nature Nanotechnology* **11**, 247 (2015)).

We have shown that for extremely small devices, such as those in a quantum computer, the second law of thermodynamics takes on a more refined form than was known for large-scale machines. This law puts stringent limits on the efficiency of machines, including those for computation and communication. We derived new second laws that can be used to study the efficiency of even the smallest machines of one qubit (*Proceedings of the National Academy of Sciences* **112** (11), 3275-3279 (2015)).

Combining the appropriate semiconductors and superconducting materials is required to induce a “hard” superconducting gap throughout the structure, a prerequisite of coherent operations on topological qubits. To this end, a novel ultra-high vacuum (UHV) deposition cluster tool has been developed and manufactured. Installation at QuTech started in 2015. The cluster tool will serve to develop and produce nanowire-based devices, with a level of materials integration, design and cleanliness that is not possible with the currently utilized nanofabrication technologies. The cluster tool has been designed to allow the deposition of a variety of pure crystalline materials by means of both Molecular Beam Epitaxy (MBE) and Atomic Layer Deposition (ALD) technology, and to achieve the best epitaxial integration of different material classes (i.e. semiconductor and superconductor) in a single nanodevice without any impact on the material interface cleanliness. The cluster tool installation and run-up phase will continue until the second quarter of 2016. We expect first samples from the third quarter of 2016.

>>

>> A topological qubit stores information as an even or odd parity in the electrical charge within the device, i.e. in whether there is an even or an odd number of electrons. The lifetime of the parity provides an upper bound to the lifetime of the topological qubit. We have fabricated Cooper-pair boxes made out of NbTiN superconducting alloy, commonly used in Majorana devices and measured a parity lifetime exceeding one minute (*Nature Physics* **11**, 547–550 (2015)). This long lifetime was achieved by engineering a spatial dependence of the superconducting gap, creating on-chip traps for quasiparticles.

Majorana states rely crucially on the interplay of superconductivity, spin-orbit interaction, and magnetic fields. Due to the lack of governing symmetry when all these ingredients are present, they have been predicted to give rise to a so-called φ_0 Josephson junction. We have succeeded in measuring this effect using a superconductor-nanowire-superconductor device, where we demonstrated nonzero supercurrent at zero phase difference for the first time (*Nature Physics* **12**, 568-572 (2016)).

In order to drive a nanowire device in the topological phase hosting Majorana states, the chemical potential must be inside the Zeeman gap. All existing theoretical studies use the chemical potential as a parameter. In an experiment, it is however only indirectly controlled through electrostatic gates. In detailed simulations taking into account the electrostatic environment of the nanowire device, we have found that the parametric dependence of Majorana states depends crucially on this environment (*New Journal of Physics* **3**, 033013 (2016)).

A widely investigated platform to induce topological states is based on two-dimensional electron systems, where bandgap engineering may provide an inverted band structure. We pursued this research utilizing InAs/GaSb quantum wells as part of an international collaboration. We could show convincingly for the first time that electrostatic gating drives the system from the normal to the inverted regime (*Physical Review Letters* **115**, 036803 (2015)). We identified the transition by studying the electronic transport in finite magnetic fields. We also showed the presence of trivial edge modes, potentially masking transport signatures of the topologically nontrivial states.

Photo credit:
Ernst de Groot | Haalbeeld

Shared Development

> ROADMAP LEADER: **ROGIER VERBERK**

Shared Development (SD) — Within the roadmap Shared Development several TNO scientist and engineers have contributed to the goals of other roadmaps. Most technologies that were developed in 2015 are incorporated in the most relevant Roadmap. The contribution of the shared development roadmap is described per receiving roadmap.

Topological quantum computing

The interface between the semiconductor and superconductor materials is the most critical and very sensitive to imperfections like oxidation, dangling bonds, chemical residues, or non-homogeneous coverage. To improve this interface, etch recipes were investigated which are more gentle than the current Ar sputtering, resulting in very clean interfaces with minimal damage to the nanowires. High-resolution electron microscopy and know-how of industrial contamination control processes were used to investigate the precise interface coverage.

Deposition of the superconductor material by means of sputtering maybe replaced by other techniques or materials, and existing recipes are optimized. A new deposition tool is designed and installed in the cleanroom of TNO and a new process flow will be developed to ultimately execute all material growth and deposition steps in one system without breaking vacuum. A specialist in MBE deposition technologies, formally working at IBM, was attracted for this purpose.

The device is grown on top of an insulating Si substrate with gate pattern. This 'gate chip' will be improved by better planarization (even CMP seems to result in too rough surfaces), and selection of a dielectric material which is both high quality (no charge noise on timescales of days at low temperatures) and enables a non-reactive and hydrophobic surface to avoid reactivity in ambient conditions. A new process inspired by an industrial 'sacrificial wafer bond and etch process' was tuned to the goals of the Topo Roadmap.

Finally, the shared development roadmap executes simulations on multiscale physics to understand, amongst others, the effects of stress induced in the nanowires by cooling down from room temperature to 15 mK on electron mobility.

Fault- tolerant quantum computing
Important technological developments the roadmap shared development has worked on include the development of electronics architectures for circuits with more than 8 qubits, and FPGA- and RF technology for fast electronic feedback control. The so called Vector Switch Matrix has been built and is now used in the scientific experiments of the DiCarlo group. QuTech has applied for a patent on this concept.

Important technological developments on which the roadmap shared development works on include investigation of computer assisted initiation of spin qubit arrays. The time and effort required to initialize an array of spin qubits scales drastically with the number of qubits in the array. The developed algorithms based on vision recognition and machine learning expertise allow for initialization of spin qubit arrays. This technology may turn out to be a key technology to enable initialization of larger arrays of qubits in the future.

Quantum Internet and Networked Computing Experiments based, e.g., on entanglement between qubits based on N-V centers are limited by the very low number of photons emitted by qubits. In an effort to boost the detection efficiency of the experimental setups, the setups have been equipped with adaptive optics. These mirrors can be deformed to correct for wavefront errors resulting from imperfect surfaces of the diamond samples. Control of such mirrors is usually based on the signal from a wavefront sensor. The experiments at QuTech do not allow for such sensors, though. New algorithms, based on algorithms developed for astronomy applications before, were therefore developed to control the shape of the mirror based on only an optical intensity signal.

For future experiments and applications, the photons shall travel over distances of kilometers. The photons from N-V centers have a wavelength not very well suited for travelling through optical fibers over long distances. These losses in the optical fibers would be a limitation for such experiments or applications. We have started a project aimed for wavelength conversion by non-linear optical effects. Ultimately this shall enable us to convert single photons to telecom wavelengths.

HIGHLIGHTED PUBLICATIONS

Chip corrects quantum errors

Detecting bit-flip errors in a logical qubit using stabilizer measurements, D. Riste, S. Poletto, L. DiCarlo et al., Nature Communications, 29 April 2015 | doi: 10.1038/ncomms7983

<Delta author Jos Wassink>

Leo DiCarlo and his team have developed a superconducting chip that corrects errors in quantum bits. Quantum data is susceptible to decoherence induced by the environment and to errors in the hardware processing it. Quantum error correctors (QEC) will be essential parts of future quantum computers.

To safeguard one quantum bit (qubit) against errors, start by building five qubits on a chip. That's what researcher Dr. Leo DiCarlo and his team from the Kavli Institute of Nanoscience (Faculty Applied Sciences) and the QuTech Institute have done. They published a photo of their 2 by 7 mm chip in Nature, together with the test results.

The logic behind the manifold is this: three qubits (called top, middle and bottom) are used to encode one qubit's worth of data in special, so-called 'entangled' states of the three. Direct measurement of the state of each qubit would collapse the encoded information. So instead of direct measurements, the researchers perform a parity check between middle and top qubits, and another

Photo credit:
Kim van Dam

between middle and bottom qubit. The parity check produces a '0' when both qubits are in the same state or a '1' when they are in a different state. Each parity check requires one extra qubit, bringing to five the total number of qubits on the chip.

"We can detect flip errors on any one qubit and still preserve the encoded information", DiCarlo explains. Such bit flips are one of three types of disturbances that happen to qubits, the other two types carry even stranger names. To protect one qubit's worth of quantum data against all possible types of error, the goal is to use nine instead of three qubits to store the data, and eight instead of two qubits to perform the parity check. Building and operating the resulting 17 qubits on a chip is the next goal for the team.

Error checking of quantum bits is a subtle game. If you do it too slow, errors will accumulate, and you will no longer be able to reconstruct the original quantum state. If you check too often, the error checking will introduce additional errors.
So will future quantum computers be fickle instruments the output of which can never be trusted? DiCarlo thinks not. He also puts his trust in technological progress to take the quantum computer beyond the threshold of fault tolerance. Improvements in error correction devices and increasing qubit stability are crucial for that progress to happen.

Funded by: This research is supported by funding from the Netherlands Organization for Scientific Research (NWO), the Dutch Organization for Fundamental Research on Matter (FOM), and the EU FP7 project ScaleQIT.

The monopoly of Aluminium is broken

One minute parity lifetime of a NbTiN Cooper-pair transistor, David J. van Woerkom, Attila Geresdi and Leo P. Kouwenhoven, Nature Physics, 25 May 2015 | doi: 10.1038/NPHYS3342

Discovering Majorana's was only the first step, taken by Kouwenhovens group in 2012, but utilizing the Majorana fermion as a quantum bit (qubit) still remains a major challenge. An important enabling step towards this goal has just been taken. Future topological quantum computation with Majorana's relies on so-called parity control and readout of Majorana bound states.

Researchers from TU Delft presented in Nature Physics the first parity modulation of a niobium titanite nitride (NbTiN) Cooper-pair transistor coupled to aluminium (Al) leads. With this device they demonstrated the difference between the even and odd occupation of a superconductor in high magnetic fields. It is an almost thirty years old scientific problem, that has just been resolved. Thus far, this was only possible in aluminium, which is however incompatible with Majorana's. They have shown that the current circuit is compatible with the magnetic field requirements of inducing the topological superconductivity in nanowires, necessary to work with Majorana's. The observed parity lifetime exceeding 1 min is several orders of magnitude higher required for performing future calculating operations (so-called braiding) with Majorana states. This current result opens the road to read out and manipulation of quantum states encoded in prospective Majorana qubits.

Funded by: This work has been supported by the Netherlands Foundation for Fundamental Research on Matter (FOM) and Microsoft Corporation Station Q. Attila Geresdi acknowledges funding from the Netherlands Organization for Scientific Research (NWO) through a Veni grant.

Voltage control for microwave quantum circuits

Realization of Microwave Quantum Circuits Using Hybrid Superconducting-Semiconducting Nanowire Josephson Elements, G. de Lange, B. van Heck, A. Bruno, D.J. van Woerkom, A. Geresdi, S.R. Plissard, E.P.A.M. Bakkers, A.R. Akhmerov and L. DiCarlo, Physical Review Letters 115, 127002 (2015) | doi: 10.1103/PhysRevLett.115.127002

The team demonstrated a novel Josephson junction, consisting of two superconductors bridged by a nanowire, that could help researchers design quantum circuits with more flexibility. Josephson junctions are typically made from aluminium (Al) superconducting wires and an aluminium oxide barrier. These novel electrically tuned nanowire transmons may be operated at higher magnetic fields than conventional qubits. The NbTiN device with an InAs nanowire, can withstand much higher magnetic fields than Al without losing superconductivity. Additionally this may open up the road to realize voltage-tuned superconducting qubits, that would increase scalability towards more numerous qubit numbers on a chip. The current flux-controlled qubit chips require flowing currents that dissipate power. This is an important first step; this line of research will be continued in the future.

Funded by: This research was supported by funding by Microsoft Corporation Station Q, the Dutch Foundation for Fundamental Research on Matter (FOM), the Netherlands Organization for Scientific Research (NWO), and an ERC Synergy Grant.

This publication was selected for an APS Physics Viewpoint on 'Wiring up superconducting qubits'

http://physics.aps.org/articles/v8/87

Yes, Quantum-Chaos increases too

The second laws of quantum thermodynamics, F. Brandão, M. Horodecki, N. Ng, J. Oppenheim, S. Wehner, Proceedings of the National Academy of Sciences 112 (11), 3275-3279 | doi: 10.1073/ pnas.1411728112

Basically, the laws of thermodynamics are the set of rules the universe lives by. They dictate that energy cannot spontaneously appear or disappear. However, the most familiar is the 2nd law, known by many people as: chaos always increases. It tells us that a hot cup of tea in a cold room will cool down rather than heat up; that even the most efficient machines will lose some energy as heat.
The rules of thermodynamics so far only worked for an extremely large amount of particles, such as block tower, a steam engine or a house. New research from UCL and the Universities of Gdansk, Singapore, and Delft has uncovered additional second laws of thermodynamics, also applicable for a small number of particles in the quantum world – in fact, even for just one particle. The result provides a toolbox for quantum physicist wanting to understand the behaviour of tiny systems, such as ‘quantum bits’, and study the efficiency of nanoscale machines. Also, their theory of quantum thermodynamics is a rare and important connection between quantum and classic physics. Stephanie Wehner and co-authors published their work on 9 February 2015 in PNAS.

The rules of thermodynamics date back to the midst of the 19th century, as they - for instance -perfectly explain how a steam engine works. The German scientist Rudolf Clausius stated in 1854 that ‘Heat can never pass from a colder to a warmer body without some other change, connected therewith, occurring at the same time". The law holds fine for machines consisting of a large numbers of particles such as in a steam engine. However, in the world of quantum mechanics - due to these constant interactions between the particles - it is next to impossible to make sure that the requirements ‘without some other change’ is met.

Researchers now used tools from quantum information theory to understand the case of limited numbers of particles. They started with a fully quantum mechanical description and derived rules that apply to machines consisting even of just a single particle. The researchers found additional measures of

Photo credit:
Klapstuk fotografie

disorder, all different to the standard entropy, which quantify different types of disorder. They showed that on nanoscale not only does entropy increase, but other types of disorder also have to increase. Yet, when applied to a very large number of atoms, their description recovers the familiar classical second law.

The results of the study give an improved understanding of how heat and energy is transformed on very small scales. These result paves the way to analyse the efficiency of even the tiniest quantum machines consisting of just a few particles. The work is expected to have wide applications in the design of small systems, including nanoscale devices, biological motors, and quantum technologies such as quantum computers.

Funded by: J. Oppenheim is supported by the Royal Society. M. Horodecki is supported by the Foundation for Polish Science TEAM project co financed by the EU European Regional Development Fund. N. Ng and S. Wehner are supported by the National Research Foundation and Ministry of Education (MOE), Singapore as well as MOE Tier 3 Grant "Random numbers from quantum processes" (MOE2012-T3-1-009). S. Wehner acknowledges support from the Technology Foundation STW.

Loophole-free Bell test: Spooky action is real

In 1935, Einstein asked a profound question about our understanding of Nature: are objects only influenced by their nearby environment? Or could, as predicted by quantum theory, looking at one object sometimes instantaneously affect another far-away object? Einstein did not believe in quantum theory's prediction, famously calling it "spooky action". Exactly 80 years later, a team of scientists led by professor Ronald Hanson from Delft University of Technology finally performed what is seen as the ultimate test against Einstein's worldview: the loophole-free Bell test. The scientists found that two electrons, separated 1.3 km from each other on the Delft University campus, can indeed have an invisible and instantaneous connection: the spooky action is real.

The experiment, published in Nature, breaks the last standing defence of Einstein's iconic 1935 paper: it closes all the loopholes present in earlier experiments. The Delft experiment not only closes a chapter in one of the most intriguing debates in science, it may also enable a radically new form of secure communications that is fundamentally impossible to 'eavesdrop' into.

Photo credit:
Frank Auperlé

Loophole-free Bell inequality violation using electron spins separated by 1.3 kilometres, B. Hensen, H. Bernien, A.E. Dréau, A. Reiserer, N. Kalb, M.S. Blok, J. Ruitenberg, R.F.L. Vermeulen, R.N. Schouten, C. Abellán, W. Amaya, V. Pruneri, M. W. Mitchell, M. Markham, D.J. Twitchen, D. Elkouss, S. Wehner, T.H. Taminiau, R. Hanson, Nature, published online 21 October 2015 | doi: 10.1038/nature.15759

In two places at the same time?
"Quantum mechanics states that a particle such as an electron can be in two different states at the same time, and even in two different places, as long as it is not observed. This is called 'superposition' and it is a very counter-intuitive concept", says lead scientist Professor Ronald Hanson. Hanson's group works with trapped electrons, which have a tiny magnetic effect known as a "spin" that can be pointing up, or down, or - when in superposition - up and down at the same time. "Things get really interesting when two electrons become entangled. Both are then up and down at the same time, but when observed one will always be down and the other one up. They are perfectly correlated, when you observe one, the other one will always be opposite. That effect is instantaneous, even if the other electron is in a rocket at the other end of the galaxy", says Hanson.

Already in 1935, just a few years after the development of quantum theory, this counterintuitive effect was seen as a reason to doubt the new theory. These objections were published in a famous scientific paper, known as 'the EPR-paper' (1935), named after its >>

>> three authors: Einstein, Podolsky and Rosen. They stated there could still be undiscovered properties of particles, so called 'hidden variables', which would provide a more intuitive explanation of the predicted correlations: the two particles were just pre-programmed to be opposite, we just did not know it.

Bell Test

A major step was taken in 1964, when CERN scientist John Stewart Bell devised an experiment that could prove that 'spooky action at a distance' existed - the Bell Test - as it can rule out any 'hidden variable' as an explanation. During the past four decades, many Bell experiments were performed, showing results that conflicted the 'hidden variables' explanation. Nonetheless, the debate didn't just end there: as the opposing scientists stated: the Bell tests performed still contained 'loopholes', or back-doors that could invalidate the proof. Basically, a Bell Test does a measurement on two sides of an entangled pair, choosing randomly between two possible 'questions' at both sides. Depending on which question is asked, a different property of the particle is measured. In a Bell test, quantum mechanics predicts that the outcomes, or 'answers' will be strongly correlated in a way that can't be explained by any 'hidden variable' theory. Nonetheless, as opposing scientists said, alternative explanations could still not be fully excluded. Firstly, it might be possible that the particles or the detectors were 'secretly' communicating to each other in some unknown way that might be beyond our current understanding of nature. By secretly sharing questions or answers between them (the locality loophole), they could be producing the observed correlations in a perfectly local manner. Secondly, if the experiment only detected a subset of prepared entangled pairs, they might not be representative of all of them (the 'detection loophole'). With these loopholes open, the possibility of an alternative explanation cannot be fully excluded.

Loopholes

Over the last decade, advances in nanoscale technology allowed experiments to close these loopholes individually. For the first time, a group of scientists from The Netherlands, Spain and United Kingdom have now managed to close all loopholes simultaneously. The scientists placed two diamonds on opposite sides of the Delft University campus, 1.3 km apart. Each diamond contained a tiny trap for single electrons, which have a magnetic property called a "spin". They managed to entangle the electron spins and perform a Bell Test. "We have two labs, one in the physics building and one on the other end of the campus in the Reactor Institute. The large distance between our detectors ensures that neither the detectors, nor the electrons can exchange information within the time it takes to do the measurement, and so closes the locality loophole. This exchange is limited by the speed of light, and the distance is too far for light to travel in the time it takes us to ask our electron spins a question and get an answer", explains PhD-student Bas Hensen, lead-author of the study. "We also close the detection loophole, because in this experiment we measure all our entangled pairs. This is the first time all loopholes are closed at the same time in a single experiment, and we still find that the invisible bond between the electrons is there: the first loophole-free Bell test".

Secure communications

The experiment in Delft closes a chapter in one of the most intriguing debates in science. "It is one of the few experiments in physics that can directly test and even reject fundamental principles of nature" says Hanson. However, the experiment has practical value as well, as entanglement allows for a form of secure communication. The measurement outcomes can be used as an encryption key: the key is fundamentally impossible to eavesdrop on as it doesn't travel between two points, but is created through the instantaneous entanglement link. However, loopholes are potential backdoors for hackers, so quantum communication will only be inherently secure if all the loopholes are closed.

Funded by: This research is supported by the Dutch Technology Foundation (STW), the Netherlands Organization for Scientific Research (NWO), Dutch Foundation for Fundamental Research on Matter (FOM), the Defense Advanced Research Projects Agency QuASAR programme, the Spanish MINECO project MAGO (Ref. FIS2011-23520) and Explora Ciencia (Ref. FIS2014-62181-EXP), the European Regional Development Fund (FEDER) grant TEC2013-46168-R, Fundacio Privada CELLEX, FET Proactive project QUIC and the European Research Council through projects AQUMET and HYSCORE.

Grants & Outreach

Photo credit:
Frank van der Burg

Vici grant for Lieven Vandersypen

Quantum simulation on a chip

Lieven Vandersypen was awarded a Vici grant by the Netherlands Organization for Scientific Research (NWO). Vici is part of the 'Vernieuwingsimpuls' Scheme of NWO, aimed to give scientists in various stages of their career the opportunity to conduct ground-breaking research. With the Vici grant, worth 1.5 million Euro, Vandersypen will study the possibilities of quantum simulation on a chip. For materials and molecules are often too complicated to be calculated by computers, Vandersypen and his team will reproduce and measure complex materials and molecules in a lab setting, with the help of nanotechnology. They hope to acquire new insights which could lead to improved medication and cleaner technology.

Vidi grants for Stephanie Wehner and Michael Wimmer

Stephanie Wehner and Michael Wimmer were both awarded a Vidi grant by the Netherlands Organization for Scientific Research (NWO). Vidi is part of the 'Vernieuwingsimpuls' Scheme of NWO. With this 800.000 Euro grant, NWO allows excellent researchers who have already spent several years doing post-doctoral research to personally develop new innovative lines of research.

Stephanie Wehner: Large quantum networks from small quantum devices

The internet has transformed the way we live. A future quantum internet will be able to solve problems that are outside the reach of conventional communication networks, such as secure communication guaranteed by natural laws. In this project, Wehner and her team will work on mathematical tools and robust protocols to make a quantum internet based on realistic quantum devices.

Michael Wimmer: Designing robust quantum building blocks

Quantum effects at the nanoscale enable new electronics, such as a quantum computer. However, quantum effects are often too fragile. Wimmer's research will use computer simulations to discover how so-called topological nano building blocks can be built from conventional materials in order to achieve robust quantum characteristics.

Rubicon fellowship for Hannes Bernien

Hannes Bernien won one of the eighteen 2015 Rubicon Fellowships of NWO. With this fellowship, NWO offers postdocs the opportunity to perform their research at universities and institutes outside the Netherlands, to gain experience in international research as a stepping stone to a scientific career. Bernien is using his Rubicon fellowship to conduct research at Harvard University for two years, starting 1 May 2015. In his research he focuses on quantum network nodes. In a quantum network, it is possible to send information which isn't possible to hack. At Harvard, Bernien will develop a fundamental part of a quantum network: the node.

ERC Starting Grant for Stephanie Wehner

In 2015, Stephanie Wehner was also awarded a prestigious ERC Starting Grant by the EU of 1.5 million Euro to fund a five-year innovative research programme. With this grant, Wehner will develop a theoretical framework to take quantum cryptographic security from paper to real world quantum devices.

Quantum networks are still in their infancy, even though quantum communication offers unparalleled advantages over classical communication. Quantum cryptography in particular offers security that is guaranteed by the laws of physics – at least on paper!

To accomplish this, she will investigate new cryptographic building blocks that are directly inspired by and adapted to simple and imperfect quantum devices. Such building blocks can then be stacked together to build complex quantum cryptographic protocols in a quantum network.

Furthermore, she will be developing new procedures to test unknown quantum devices so they can safely be used in quantum protocols. This research will lay the foundations for the safe experimental implementation of general quantum cryptographic protocols in a quantum network.

Fresnel Prize for fundamental aspects awarded to Tim Taminiau

The 2015 Fresnel Prize for fundamental aspects was awarded to Tim Hugo Taminiau. The Fresnel Prize is one of the two EPS/QEOD prizes awarded for outstanding contributions to quantum electronics and optics made by young scientists before the age of 35. One prize is awarded for fundamental aspects and one for applied aspects. Taminiau received the prize for his fundamental contributions to nano-optics and quantum information science through the control of solid-state quantum emitters and spins.

Photo credit:
Ernst de Groot | Haalbeeld

>RONALD HANSON

Ammodo KNAW Award 2015 for Ronald Hanson

Ronald Hanson is one of eight promising Dutch researchers who received the Ammodo KNAW Award. The Ammodo KNAW award is a prize worth 300.000 Euro, to be spent on fundamental scientific research. The award has been established in 2015 to encourage independent, fundamental scientific research and is intended for scientists at Dutch universities and research institutes who received their doctorate less than fifteen years ago. The eight winners in 2015 were selected from 114 nominations. Hanson received the award for his research into the exotic world of quantum entanglement and quantum teleportation.

OUTREACH

Publication of the book ‘Real Quantum’

In 2015 'Real Quantum' was published, a book written by Martijn van Calmthout (chief science editor at the Dutch newspaper ‘De Volkskrant’) that aims to make quantum science understandable to non-specialists. In the Dutch version Leo Kouwenhoven wrote a foreword. In the English version (published in 2016), Minister Henk Kamp of Economic Affairs and EU Commissioner Günther H. Oettinger (Digital Economy and Society) emphasized the importance of quantum computing and quantum internet.

Julia Cramer wins ScienceBattle

In the 2015 ScienceBattles, a series of KNAW/VSNU-supported public outreach events, PhD student Julia Cramer won twice. In each ScienceBattle, four PhD students compete to capture a lay audience's imagination. Who has the best story about his or her research? Does the audience understand what it's about? In a passionate presentation the four PhD students tell about their research that they are doing. They have a ten minutes to share their story. At the end of the performance to the audience selects a winner.

TEDx Amsterdam 2015

On 27 November 2015, Prof. Leo Kouwenhoven shared his findings and passion for the research area of quantum technology with a general audience at the TEDx Amsterdam conference. The talk was recorded and can be watched online.

"Quantum science is ready for engineering," Kouwenhoven explains in the talk. "We're building technology that will forever change and improve our understanding of nature and we can't even begin to imagine the possibilities it will bring us."

Photo credit: Renata Szostek

TEDx Amsterdam
Leo Kouwenhoven
http://tedx.amsterdam/2015/11/can-we-make-quantum-technology-an-interview-with-leo-kouwenhoven/

Partnerships

NATIONAL AND EU GOVERNMENT

Photo credit:
Ernst de Groot | Haalbeeld

The Netherlands invests 146 million Euro in quantum technology

In 2014, the Dutch Government awarded QuTech the status of 'National Icon'. The R&D work towards the quantum computer and its spin-offs is one of the four groundbreaking projects from which the Dutch government expects major societal and economic impact. Icon projects are adopted by Ministers who support them to achieve their goals. For QuTech, this support consisted of base funding with all public partners, participation in several official state visits and economic missions, and commitment of the EU Presidency to launch a European Flagship programme.

Together with knowledge institutions, the Dutch government agreed to invest 146 million Euro over the next ten years in QuTech. To this end, a covenant was signed on 1 June 2015, in Delft by six parties: Minister Henk Kamp (Ministry of Economic Affairs), Minister Jet Bussemaker (Ministry of Education, Culture and Science), the Netherlands Organization for Scientific Research (NWO), also representing FOM and STW, the Top Sector 'Holland High Tech' (formerly 'High Tech Systems and Materials'), Delft University of Technology and the Netherlands Organization for Applied Scientific Research (TNO).

Thanks to the financial support and the governance agreements set out in the covenant, it will be possible for QuTech to attract private investors to invest in laboratories and in the appointment of talented scientists. In June 2015, about 100 employees were working at QuTech in Delft. Over the next five years that number will increase to about 250 employees.

At the occasion of the signing of the covenant, Prof. Leo Kouwenhoven said: "Developing pioneering technology, such as a quantum computer, is a process of trial and error, which requires a great deal of patience. I am delighted that the partners are endorsing the importance of this research by committing themselves to the cause for the next ten years: developing the building blocks for a quantum computer. This commitment puts us in a perfect position to attract top-class scientists and partners from industry."

European FET Flagship programme in the field of quantum technologies

On 20 October 2015, EU Commissioner Oettinger (Digital Economy and Society) and Minister Kamp (Economic Affairs) visited QuTech. They stated that Europe must retain its leading position in the field of quantum technology and face the emerging competition from Asia and the US head-on. To accomplish this, they are working towards a Quantum Manifesto, a joint European strategy for the development of quantum technologies.

Oettinger and Kamp invited all invited parties in science and industry to contribute to the development of this European Quantum Manifesto. During the Dutch Presidency of the European Union in the first half of 2016 the strategy was presented at a 'Quantum Europe' conference on 17 and 18 May 2016 in Amsterdam. Here, the European Commission described its plans to launch a €1 billion European FET Flagship programme in the field of quantum technologies. It is expected to be an initiative similar in size, timescale and ambition to the two ongoing FET flagships, the Graphene flagship and the Human Brain Project.

INDUSTRY

Station Q Microsoft

The Topological Quantum Computing Roadmap of QuTech works in close collaboration with Microsoft Research Station Q, headed by Dr. Michael Freedman.

Station Q is Microsoft's project on quantum physics and quantum computation located at the campus of the University of California, Santa Barbara. It is a collaborative effort between Microsoft and academia directed towards exploring the mathematical theory and physical foundations for quantum computing. The lab combines researchers from mathematics, physics and computer science and collaborates with academic researchers both locally and around the world to understand how topological phases

QuTech enters into collaboration with Intel

On 3 September 2015, QuTech and US-based chip manufacturer Intel Corporation announced a 10-year collaborative relationship to accelerate advancements in quantum computing. With the process technology of the world's largest and highest valued semiconductor chip maker, QuTech can speed up the development of quantum computing. Intel contributes expertise, manpower, facilities and financial support to QuTech, with a planned total amount of $50 million during the ten-year collaboration. Through this partnership, Intel will be able to have access to the long history of expertise in quantum computing of the Delft University of Technology.

Lead scientist Prof. Lieven Vandersypen of QuTech: “The major challenge facing quantum technology development in the coming decades, such as creating a quantum computer, is set to be upscaling: being able to create complex structures with an enormous number of quantum bits. This partnership will enable us to combine our scientific expertise with the best engineering expertise in the computer industry”.

“A fully functioning quantum computer is at least a dozen years away, but the practical and theoretical research efforts we’re announcing today mark an important milestone in the journey to bring it closer to reality,” said Mike Mayberry, Intel vice president and managing director of Intel Labs.

of matter can be used to build a robust, scalable quantum computing architecture. The multi-year cooperation of QuTech and Microsoft was reaffirmed late 2014 by an extension of the Industrial Partnership Programme (IPP) of QuTech, Microsoft and the Dutch Foundation of Fundamental Research on Matter (FOM). In 2015 and subsequent years, the research on topological quantum computation will be continued under the leadership of Prof. Leo Kouwenhoven. In addition to a financial contribution for attracting top researchers in this field, Microsoft also makes a substantial contribution to the research by means of equipment and materials.

INTERNATIONAL KNOWLEDGE INSTITUTIONS

QuTech joins Minster Kamp in official visit to China

QuTech's Prof. Ronald Hanson and Dr. Hannes Bernien joined the Minister of Economic Affairs Henk Kamp on a trip to China in January 2015. In Beijing, they discussed plans and progress on quantum technologies with Prof. Janwei Pan, who leads the quantum efforts on behalf of the Chinese Academy of Sciences. Furthermore, the QuTech delegation visited quantum technology labs in Hefei and Shanghai.

Ronald Hanson: "This trip has taught us a lot about China and the Chinese efforts in the field of quantum technology. Thanks to the Minister and the Dutch Embassy we held valuable discussions, laying an excellent basis for future activities. We expect different QuTech scientists will visit China in the near future. China is a global player in the field of quantum technology with major investments planned.

Delft and Copenhagen join forces to create quantum computer

On 17 March 2015, QuTech and the Centre for Quantum Devices (QDev) of the Danish Niels Bohr Institute signed a Memorandum of Understanding in the presence of the King and Queen of the Netherlands and the Danish prime minister. They are looking to work together more closely and to establish broad-based, international cooperation for the development of the first quantum computer. They aim to create a prominent role for Europe in its development.

“At TU Delft, we work very closely with QDev on a regular basis”, explains QuTech’s Prof. Leo Kouwenhoven. “Together we aim to play a key role in an international network devoted to developing the first quantum computer. We’re already working with major companies such as Microsoft, but we want to expand this network far wider. The next few years are crucial to determining where in the world the development of the first quantum computers will be centred. Together, we’ll be ensuring that Europe will continue to play a prominent role in the years ahead”.

“Now, from the start of the second century of quantum mechanics, we are making formal what much of the scientific community already knows: cooperation, not competition, works best. We also must recognize that scientific ideas and engineering approaches are merging, challenging traditional university boundaries, scale, budget, and training strategies. Removing those boundaries is also a big part of the QuTech-QDev Technical Exchange Programme,” says QDev director Prof. Charles Marcus.

Before the signing ceremony, Bert Koenders, the Dutch Minister of Foreign Affairs, visited the old Niels Bohr building for an explanation of the history of quantum physics in which Niels Bohr played a key role.

QuTech in Japan with Prime Minister Rutte and Minister Kamp

QuTech's scientific director Prof. Leo Kouwenhoven visited Japan on 9 and 10 November 2015. Representing 'National Icon' QuTech, he joined the trade mission led by Prime Minister Mark Rutte and Minister of Economic Affairs Henk Kamp for an official visit to the country. During several meetings with Japanese counterparts from government, science and industry, further cooperation in the field of quantum technology was discussed with the respective ministries. Minister Kamp gave an explanation of the Dutch ambitions in the development of quantum computers and the investment of the Ministry in QuTech. He underlined the importance of (international) cooperation in this area. Interviews were conducted with over a hundred relevant researchers, policy makers and decision makers from the private sector. QuTech is very positive about the many possibilities for cooperation with Japan.

Research and education partnership with University of Waterloo

On 29 May 2015, the University of Waterloo in Canada and Delft University of Technology signed a memorandum of understanding that allows exchange opportunities for students, staff and researchers, collaboration on research projects and the exchange of research publications and reports in quantum information. As a result, Madelaine Liddy is working at QuTech today as one of the Canadian exchange students in Delft.

Feridun Hamdullahpur, president of the University of Waterloo, and Anka Mulder, vice-president for education and operations at TU Delft, signed the memorandum in the presence of Their Majesties King Willem-Alexander and Queen Máxima of the Netherlands during part of an official state visit to Canada.
As part of the visit, the Dutch royal couple also toured a quantum optics laboratory in the Mike & Ophelia Lazaridis Quantum-Nano Centre. The laboratory, led by Prof. Kevin Resch from Waterloo's Institute for Quantum Computing (IQC) and the Department of Physics and Astronomy, is strongly involved in experiments that use light for quantum communication and computing.

The King and Queen also met with Mike Lazaridis, co-founder of Blackberry and major investor in the Quantum ecosystem in Waterloo. Prof. Kouwenhoven accompanied the couple during the visit.

QuTech's ambition is to offer a new style of education to educate scientists in Delft and around the world. The goal is to establish a workforce of 'quantum engineers 2.0', who have in-depth knowledge in the areas of both quantum physics and computer science & engineering. QuTech needs great students with the drive and talent to help build a quantum computer and a large-scale quantum Internet. Additionally, QuTech aims to supply the nascent quantum industry with the necessary human capital possessing an excellent training in quantum technologies.

Education

> STEPHANIE WEHNER

Photo credit:
Martijn Beekman

In order to establish such an educational programme, QuTech has been building QuTech Academy under the leadership of Stephanie Wehner. QuTech Academy @ TU Delft aims to become the first in mainland Europe to offer a targeted programme in the area of Quantum Technology and Quantum Information. In addition to courses at MSc level, QuTech also organises numerous lectures and colloquia for both MSc and PhD students year round, often in collaboration with the NanoFront research programme and the Casimir research school. For example, QuTech Academy hosted Mark Wilde, author of “Quantum Information Theory” (Cambridge University Press) as a guest lecturer of a specialized course series in May 2015.

QuTech Academy provides education in quantum technologies via both on-campus and online education. Campus activities were established in 2015, as was a series of four classes for MSc students after which the students may take on a Master’s thesis project at QuTech. The first of these classes attracted over 140 students completing the class. Subsequent classes were completed by consistent numbers of over 50 students. Online activities presently consist of a so-called Massive Online Open Course (MOOC) on Topology in Condensed Matter, and one of the classes below (Q201) is set to be held as a MOOC in 2016. QuTech Academy aims to expand further into the online domain by developing MOOCs but also shorter video series.

Towards a programme in Quantum Technologies

In 2015, the following programme was created for students from Applied Physics, Electrical Engineering, Computer Science and Mathematics. Many of these students went on to seek a Master’s thesis project at QuTech.

Fundamentals of Quantum Information – An introduction to quantum information, including quantum bits, quantum operations, and essential concepts that distinguish ‘quantum’ from ‘classical’. Students learn basic techniques used in quantum algorithms, and examine basic examples of such algorithms. This class was taught by Leo DiCarlo and Stephanie Wehner in Fall 2015 and attracted over 140 students.

Quantum Communication and Cryptography – In this class, students learn the fundamentals of quantum information theory and quantum cryptography. The goal of quantum information theory is to determine how quantum information can be best protected from errors. It forms a crucial tool for building quantum communication networks. Students also learn the core techniques of

>>

>> quantum cryptography, enabling them to understand and implement quantum key distribution, as well as make an entry into current research in this field. This class was taught by Stephanie Wehner in Fall 2015.

Quantum Hardware – In this class, students learn to understand and appreciate the key challenges in realizing quantum hardware and technology. They get an overview of the state-of-the-art, learn about the most promising approaches to realizing quantum hardware, and critically assess the strengths and weaknesses of each approach. They also get insight in the conceptual similarities and differences between the various technologies. This class was taught by Ronald Hanson and Lieven Vandersypen in Spring 2016.

Electronics for Quantum Computation – This course focuses on the development of hardware for the control of a number of

IDEA League Summer School Series on Quantum Science and Technology

The IDEA League is a collaboration of 4 universities of technology in Europe: RWTH Aachen in Germany, TU Delft in the Netherlands, ETH Zurich in Switzerland and TU Chalmers in Gothenburg, Sweden. In 2015, four week-long graduate schools in quantum information were held at these universities.

The goal of the schools was to provide a comprehensive training programme, targeted to senior Master's and beginning PhD students enrolled at the 4 Universities of the IDEA League. The programme aimed to get these students fully prepared to undertake original research in this area, to get to know their colleagues in Europe and internationally, and to provide the seeds for collaboration, enriching the students' work, both during their PhD and beyond.

The TU Delft part of the programme (29 March – 2 April 2015) centred around the following topics:

qubits. Lab sessions will focus on the simulation, detection, and correction of errors using field- programmable-gate-arrays (FPGAs). Students will get familiar with the concepts of quantum computing while practicing to interface to a quantum computer in real life. This class was taught by Edoardo Charbon and Koen Bertels in Summer 2016.

Targeting a Delft and International education audience, QuTech participated in the IDEA league summer school series 2015 on Quantum Science and Technology, hosting one of the lecture weeks of this 4-week series in Delft. In February 2015, the Massive Open Online Course (MOOC) 'Topology of Condensed Matter: Tying Quantum Knots' kicked off with as many as 4000 participants.

- Spin Qubits
- Quantum Networks
- Single-spin quantum sensors
- Superconducting qubits and circuits
- Majorana qubits
- Systems for Quantum Technologies

Faculty lecturing at the Delft part of the school:

- A. Akhmerov (TU Delft)
- L.P. Kouwenhoven (TU Delft)
- R. Hanson (TU Delft)
- A. Wallraff (ETH Zurich)
- C. Degen (ETH Zurich)
- L. DiCarlo (TU Delft)
- E. Charbon (TU Delft)

Delft faculty lecturing at the other IDEA League Schools:

- L. Vandersypen (at ETH Zurich)
- S. Wehner (at RWTH Aachen)

More information about the schools is available on:

http://qischoolsidea.wikispaces.com/home

MOOC ‘Topology in Condensed Matter: Tying Quantum Knots’

This MOOC by Anton Ahkmerov in collaboration with Maryland University offers a simple and hands-on overview of topological insulators, Majoranas and other topological phenomena. Hosted by MOOC provider edX (an organization founded by Harvard University and MIT), the course is a 12-week online course at an intermediate physics level. It teaches about the variety of subtopics in topological materials, their relation to each other and to the general principles. The course enables participants to follow and critically understand active research on topology, and assists young researchers in acquiring skills required to engage in topology research on their own. The idea behind topological systems is simple: if there exists a quantity, which cannot change in an insulating system where all the particles are localized, then the system must become conducting and obtain propagating particles when the quantity (called a "topological invariant") finally changes. The practical applications of this principle are quite profound, and are highly relevant to topological quantum computing.

Governance

Legend

- Supervise
- Owner
- Perform
- Justify
- Steer
- Executive power
- Partners
- Advise
- Partner Council

Organization

The governance model of QuTech is shown in Figure 1. The colours of the arrows and boxes indicate supervision, ownership, performance, justification, steering, advising and executive power.

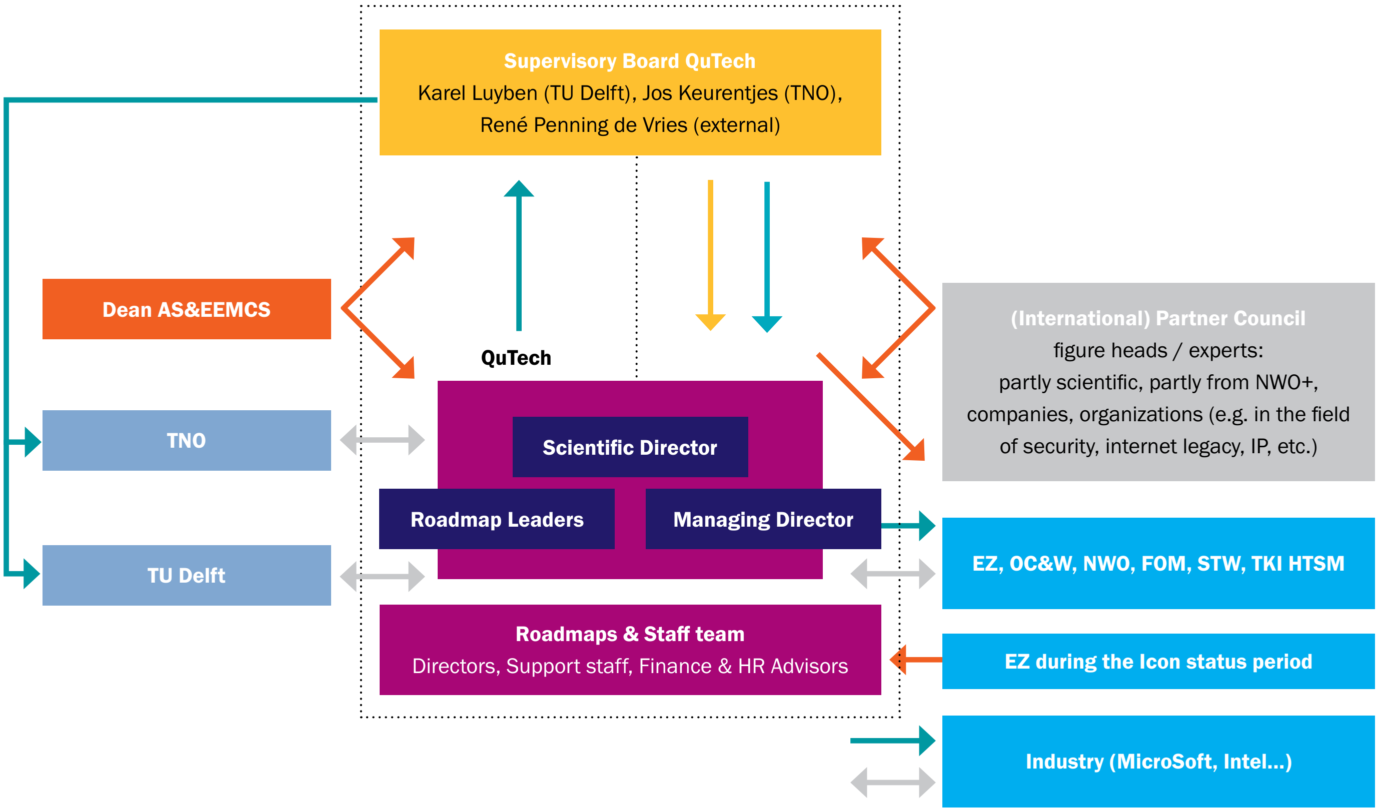


Figure 1. (Right) Governance and stakeholder environment

QuTech is organized along Roadmaps, as shown in Figure 2. A large part of the activities take place within these Roadmaps. General support is organized centrally. Each roadmap has a Roadmap Leader (RL), who is responsible for the principal investigators (PI's, both from TNW and EWI), postdocs, PhD candidates, MSc students, engineers and roadmap-dedicated technicians.

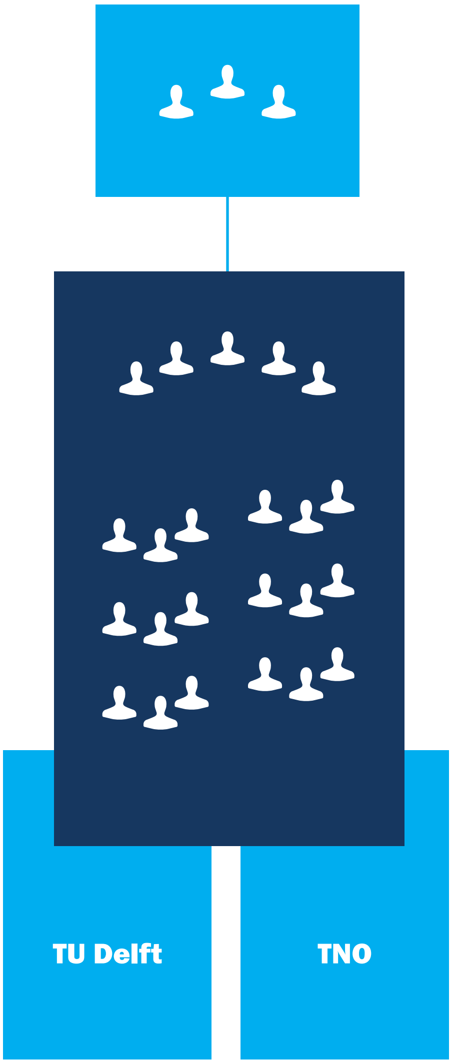


Figure 2. QuTech governance, roadmap leaders, staff and meetings

Supervisory Board: Karel Luyben, chair (Rector Magnificus TU Delft), Jos Keurentjes (Chief Scientific Officer TNO), René Penning de Vries (Figure Head ICT of the Ministry of Economic Affairs)

Roadmap Leaders: Leo DiCarlo, Leo Kouwenhoven, Lieven Vandersypen, Rogier Verberk, Ronald Hanson, Stephanie Wehner

QuTech Faculty: towards ~30 members (scientists)

Management and staff:

- Scientific Director: Leo Kouwenhoven
- Managing Director: Kemo Agovic
- Management Support staff: ~ 10
- Technical staff: ~ 20

Meetings

Supervisory board: long-term and strategic decisions
Management Team: implementations and strategic decisions
QuTech Faculty: strategic discussions
QuTech Tech: technical issues / developments
QuTech Bureau: general (staff) support

Roadmaps are organized as shown by example in Figure 3 where the roadmap exists of an amount (n) of clusters led by a principal investigator (PI). There are two categories of senior scientists: team leaders and group leaders. Group leaders have wider supervision responsibilities.

In practice a person can work in several roadmaps. The colored dots show the (current) contributions over the boundaries of the roadmaps.

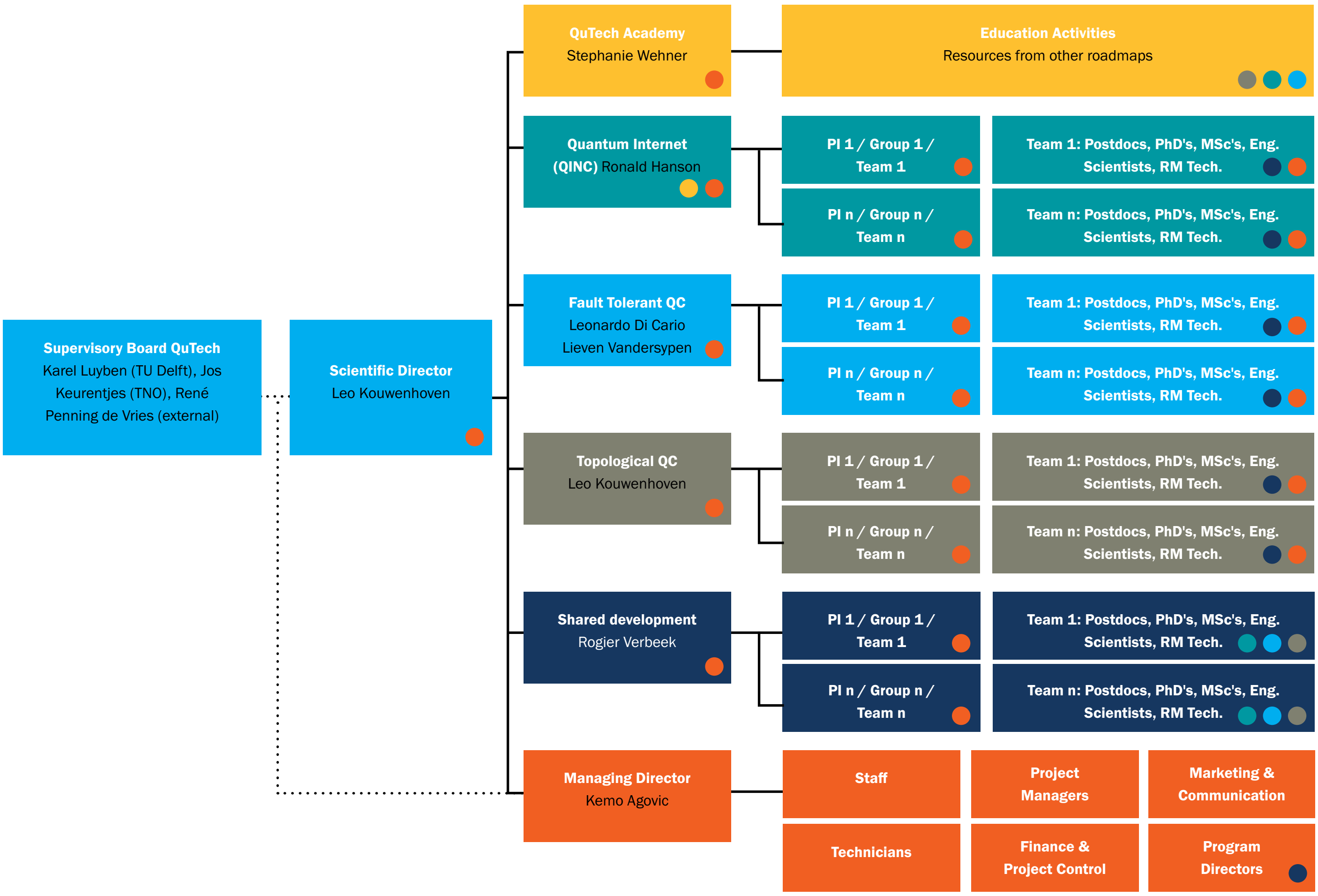
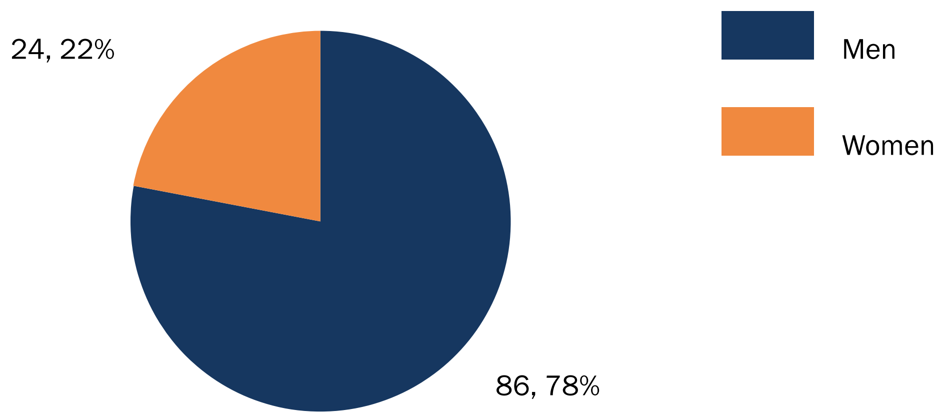


Figure 3: Organogram QuTech

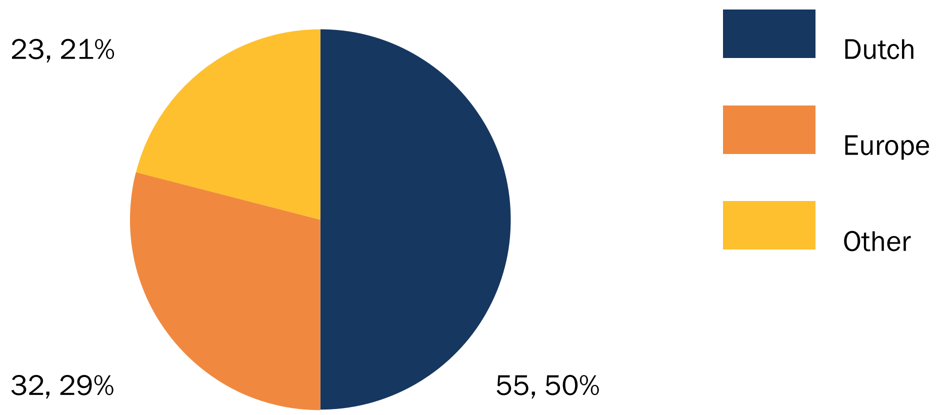
Statistics/graphics

End of 2015, 110 people worked for QuTech. This number is expected to increase in the coming years to about 250 in 2020.

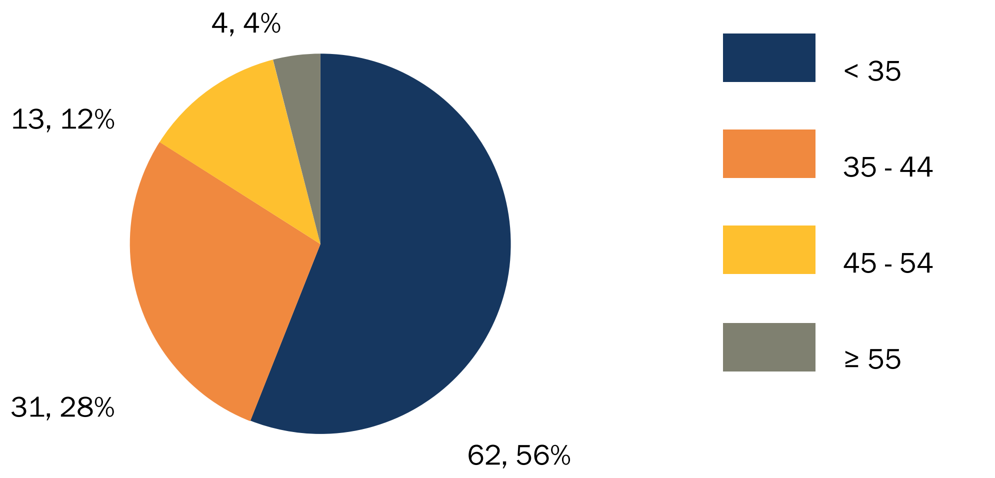
Gender



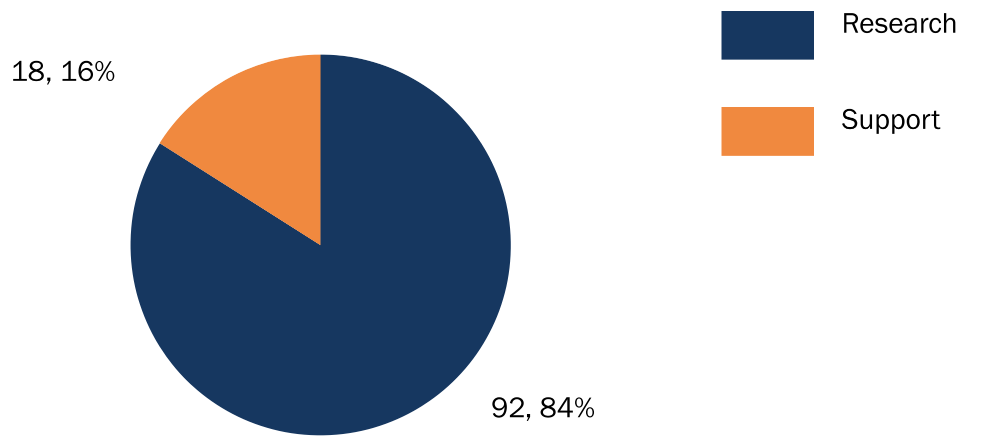
Nationality



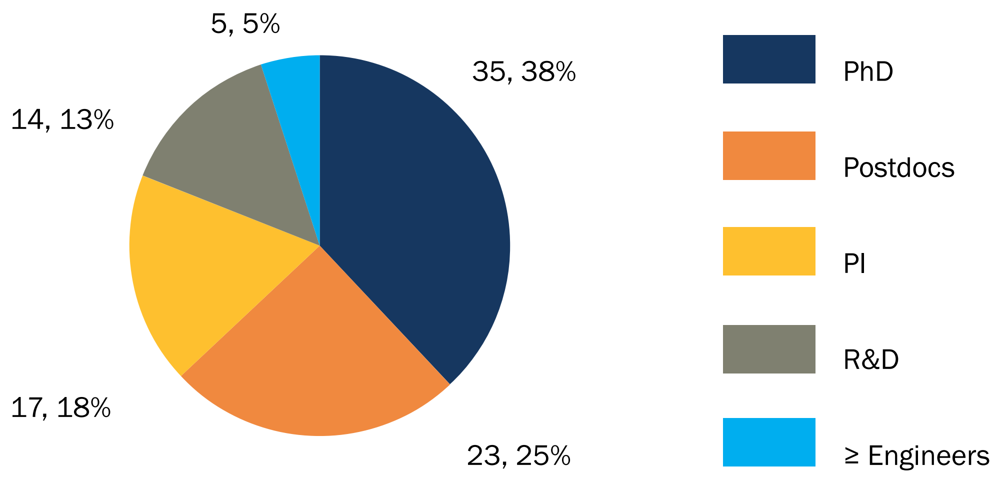
Age structure



Ratio Research / Support staff



Research activities



Financial overview

FUNDING AND EXPENSES

Photo credit:
Kim van Dam

QuTech started in 2014 with scientific staff, engineering and support staff. Both types of staff as well as the operating budget and the investments are funded from four main contribution sources: 1) TU Delft, 2) TNO, 3) Industry funding and 4) EZ, HTSM, NWO, FOM and STW.

This paragraph provides more information on QuTech financials which are based on “partner convenant”. In this document, the “partners”, being the Ministry of Economic Affairs (EZ) and the Ministry of Education, Culture and Science (OCW), The Netherlands Organization for Applied Scientific Research (TNO), Delft University of Technology (TU Delft), The Netherlands Organization for Scientific Research (NWO), technology foundation STW and the Foundation TKI High Tech Systems and Materials (HTSM), agree to financially support QuTech, as strategic partnership, for the period June 2015 – June 2025. They do so to develop the knowledge and the technology for quantum computers and quantum internet and to build up a multiform ecosystem in The Netherlands together with national and international partners.

The budget includes both in-kind and in-cash contribution by the partners:

TU Delft in-kind	29	M€
TU Delft in-cash	20	M€
TNO in-cash*	50.75	M€
NWO/FOM*	36.18	M€
STW in-cash	9.6	M€
Total	**145.53**	**M€**

*The HTSM TKI allowance is included in the budgets of TNO and NWO/FOM.
The budgets per year are shown in Table 1.

TU Delft budget

The 10-year commitment of TU Delft includes:

- In-kind contribution (29 M€)
  - housing, energy, cleanroom, infrastructure and the professors/researchers/personnel from the faculties TNW and EWI.
- In-cash contribution (20 M€)
  - provided from the TU Delft strategy funds.

TNO budget

The TNO budget consists of:

- TNO strategic funds (29.75 million Euro)
  - SMO (Samenwerkings Middelen Onderzoek) from the High Tech Systems and Materials roadmap and ICT roadmap
  - Early Research Programme
- EZ via TNO (11.75 million Euro)
  - This is the EZ fund allocated for TNO for QuTech purposes
- TKI-allowance via TNO (9.25 million Euro)
  - This is based on the contribution of 1 million Euro/year of private companies

TKIs explained

Within the Top Consortium for Knowledge and Innovation (TKI) 'Holland High Tech' (formerly 'High Tech Systems and Materials'), knowledge institutions and industry collaborate on a public-private funded multi annual TKI programme. A TKI programme includes fundamental research, industrial research, experimental development, or a combination of these types of research. With TKI-allowance the Ministry of Economic Affairs stimulates private-public collaboration between research organizations and industry. The basic principle is simple: for every euro the private sector invests in R&D at a knowledge institute, the Top Consortium for Knowledge and Innovation receives € 0.25. The TKI uses these revenues again for new public-private research.

NWO/FOM budget

The contribution of the FOM budget (NWO FOM, TKI-allowance via NWO/FOM, NWO/FOM IPP, Private Contribution) for 2015 is not fully spent yet.

In order to facilitate the research and development and the growth of the QuTech organization (250 FTE in 2020, labs, facilities etc.) in the upcoming years, QuTech dedicated some of this budget for new initiatives, attracting new scientists, new labs (equipment) and personnel. The other part of the budget is dedicated for the QINC roadmap.

QuTech and NWO/FOM agreed that TKI-allowance should go directly to QuTech (via TU Delft). Agreement from HTSM TKI is needed, the request for this pending.

The private contribution budget is allocated for research in the roadmap Topological quantum computing (scientific staff, postdocs, PhD's, technicians, equipment).

The NWO/FOM budget consists of:

- NWO FOM (7.5 million Euro);
- NWO FOM IPP (7.5 million Euro)
  - Industrial Partnership Programme with Microsoft
  - This IPP was explicitly included in the partner convenant according to the wish of EZ and HTSM partners for private contribution exceeding 2 million Euro/year in order to participate in QuTech.
- Private contribution
  - Private contribution
- TKI-allowance via NWO/FOM
  - TKI-allowance generated from collaboration Microsoft-TU Delft-FOM

STW budget

For the period 2014-2017 STW has granted 2.6 million Euro. The budgeted costs of 1.6 million Euro (PhD's, materials, equipment, cleanroom, engineers) are partially spent.

The remaining budget will be spent according the plan.

Appendices

OVERVIEW

RESEARCH PROJECTS

Photo credit:
Frank van der Burg

QuTech — Projects active in 2015

FT - Fault-tolerant Quantum Computing
QINC - Quantum Internet and Networked Computing
TOPO - Topological Quantum Computing
SD - Shared Development

ERC Synergy Grant QC-Lab
Vandersypen
Roadmap: FT
Funding: EU

Intel collaboration
Vandersypen
Roadmap: FT
Funding: INTEL

FOM project
Spin squeezing in quantum dots
Vandersypen
Roadmap: FT
Funding: FOM

FP7 project
SIQS
Vandersypen
Roadmap: FT
Funding: EU

TKI Intel
Vandersypen
Roadmap: FT
Funding: TKI HTSM

Vici grant Vandersypen
Vandersypen
Roadmap: FT
Funding: NWO

Nanofront/Casimir project
A spin qubit network coupled via a microwave resonator
Vandersypen
Roadmap: FT
Funding: NWO
Granted in 2015, started in 2016

ARO subaward
Solid State Quantum Computing Using Spin Qubits in Silicon Quantum Dots
Vandersypen
Roadmap: FT
Funding: ARO via University of Wisconsin

FP7 project
Graphine
Vandersypen
Roadmap: FT
Funding: EU

Nanofront/Casimir project
Quantum Simulation of Gauge Theories in Circuit QED
DiCarlo
Roadmap: FT
Funding: NWO

FP7 project
Scaleqit
DiCarlo
Roadmap: FT
Funding: EU

Nanofront project
Quantum-Entangled Electronic Networks
DiCarlo
Roadmap: FT
Funding: NWO

TKI Intel
Vandersypen
Roadmap: FT
Funding: TKI HTSM

STW start-up funds QuTech
Kouwenhoven
Roadmap: Algemeen
Funding: STW

Marie Curie
Career Integration Grant Di Carlo
DiCarlo
Roadmap: FT
Funding: EU

FOM project
An electric-spin-ensemble memory for the superconducting quantum processor
DiCarlo
Roadmap: FT
Funding: FOM

FOM project
Planar CQED
DiCarlo
Roadmap: FT
Funding: FOM

FOM project
FOM project SPN NV centres at mK temperatures
Hanson
Roadmap: QINC
Funding: FOM

ERC Starting Grant Hanson
Hanson
Roadmap: QINC
Funding: EU

NAW Ammodo grant Hanson
Hanson
Roadmap: QINC
Funding: KNAW

Marie Curie ITN
Spin-Nano
Hanson
Roadmap: QINC
Funding: EU
Granted in 2015, started in 2016

FOM project
Dynamic decoupling of single and entangled spins from solid state decoherence
Hanson
Roadmap: QINC
Funding: FOM

ERC Starting Grant Wehner
Wehner
Roadmap: QINC
Funding: EU
Granted in 2015, started in 2016

Veni grant Taminiau
Taminiau
Roadmap: QINC
Funding: NWO

Nanofront project
Nano-scale tomography with single-proton resolution using a single-spin quantum sensor
Hanson
Roadmap: QINC
Funding: NWO
Granted in 2015, started in 2016

FOM project
Cooperative and nonlinear optical processes at the nanoscale
Hanson
Roadmap: QINC
Funding: FOM

Marie Curie ITN
Hanson
Roadmap: QINC
Funding: EU

Vidi grant Wehner
Wehner
Roadmap: QINC
Funding: NWO

Veni grant Geresdi
Geresdi
Roadmap: TOPO
Funding: NWO

Nanofront project
4n interferometry using Majorana bound states
Kouwenhoven
Roadmap: TOPO
Funding: NWO

ERC Consolidator Grant Bakker
Bakkers
Roadmap: TOPO
Funding: EU

FOM project
Cooperative and nonlinear optical processes at the nanoscale
Kouwenhoven
Roadmap: TOPO
Funding: FOM

Spinoza Prize Kouwenhoven
Kouwenhoven
Roadmap: TOPO
Funding: NWO

ONR subaward - *Majorana Fermions in Superconductor-Semiconductor Nanowire Systems*
Kouwenhoven
Roadmap: TOPO
Funding: ONR via Pittsburgh

Vidi grant Wimmer
Wimmer
Roadmap: TOPO
Funding: NWO

FP7 project
Sispin
Bakkers
Roadmap: TOPO
Funding: EU

FOM project
Nanoscale electric devices for 2D and 3D TI's
Kouwenhoven
Roadmap: TOPO
Funding: FOM

Nanofront project
Improved nanowire materials for Majoranas
Kouwenhoven
Roadmap: TOPO
Funding: NWO

FOM IPP Microsoft i26
Kouwenhoven
Roadmap: TOPO
Funding: FOM/Microsoft

FOM IPP Microsoft i39
Kouwenhoven
Roadmap: TOPO
Funding: FOM

Marie Curie Individual Fellowship De Lange
Kouwenhoven
Roadmap: TOPO
Funding: EU

FOM project *Quantum Nanotubes*
Kouwenhoven
Roadmap: TOPO
Funding: FOM

SMO (Samenwerkings Middelen Onderzoek)
Verberk
Roadmap: Shared Development
Funding: TNO

ERP (Early Research Programme)
Verberk
Roadmap: Shared Development
Funding: TNO

KNAW Visiting Professor grant Eriksson
Kouwenhoven
Roadmap: TOPO
Funding: KNAW

ONR subaward - *New Directions in Quantum Transport Algorithms*
Wimmer
Roadmap: TOPO
Funding: ONR via CEA
Granted in 2015, started in 2016

NWO FOM start-up funds QuTech
Kouwenhoven
Roadmap: General
Funding: FOM

STW start-up funds QuTech
Kouwenhoven
Roadmap: General
Funding: STW

QUTech