CWI

Strategic Plan **2022-2027**

“We are laying foundations for the digital society”

Preface

In 2018, CWI published its Strategic Plan 2019-2024, outlining its ambitions, strategic research themes and planned activities. Towards the end of 2019, the NWO Executive Board commissioned a study of the role and position of CWI as a national institute for mathematics and computer science in the Netherlands. This study was completed in February 2020 and contained several valuable findings and recommendations for the future of CWI. We have taken these findings and recommendations to heart by discussing our new vision of CWI's national role with the NWO Executive Board and with representatives of nine university departments of mathematics and computer science. The results of these discussions have been incorporated into this new Strategic Plan 2022-2027.

In formulating our strategy, we were asked to emphasize our uniqueness. What is unique at CWI, is that computer scientists and mathematicians work closely together. Since its foundation in 1946, just after the end of World War II, when the word 'computer scientist' didn't even exist, scientists at our institute took up the challenges and exploited the opportunities that the digitization of society began to bring more and more. The automation of tasks and the development of new applications are making ever greater demands on computing power and memory, exceeding Moore's law on hardware speed. Mathematically rigorous and efficient algorithms offer solutions for this. It is this uniqueness of a close connection between mathematics and computer science that forms the basis of our strategy.

The ubiquity of information and communication technology has also created new societal requirements on the fairness and transparency of algorithms. Translating such requirements into mathematical concepts is a prerequisite for ensuring that large-scale applications of algorithms can be trusted and benefit each individual and society.

In this context, and with our uniqueness established over many years, we will take on our role as a national institute for the mathematics and computer science communities in the Netherlands more prominently than before. I am convinced that CWI, with its track record of international scientific excellence, societal impact and providing a breeding ground for talent in the Dutch mathematics and computer science communities, will enter an inspiring new phase in the next five years. We will do so in close cooperation with researchers from these communities, and we will inspire each other during workshops, meetings and sabbaticals at CWI.

I welcome everyone to CWI to help laying the foundations of our digital society and thus contribute to solving major societal challenges.

Ton de Kok
Director CWI

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CWI at a glance

CWI

Centrum Wiskunde & Informatica.
CWI is part of the Institutes Organisation of NWO (NWO-I) and is located at Amsterdam Science Park.

CWI
Research institute for mathematics & computer science in the Netherlands

Short history

- Founded in1946
- CWI built the first Dutch computer in 1952
- Calculated the dike heights for the Delta Works
- Invented a globally used algorithm for route navigation
- Was the birthplace of the European internet in 1988
- Kick-started the development of the popular programming language Python in the 1990s
- Created the knowledge and tools in the 2000s that made column-stores the current practice for today's databases
- A few years ago developed software that rapidly calculates the ideal radiotherapy plans for prostate cancer patients
- Since 1946 over 230 CWI researchers have become full professors at thirteen Dutch universities

75 Years CWI

Staff

46 permanent researchers

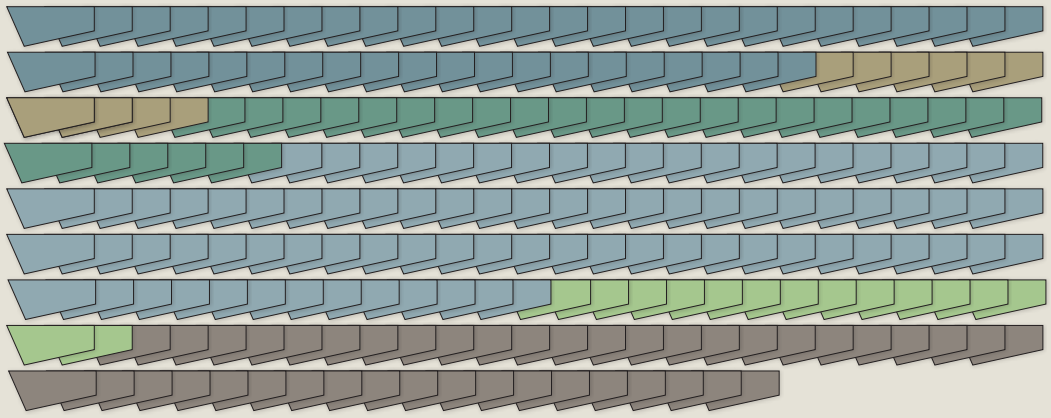
10 tenure track researchers

28 postdocs

85 PhD candidates

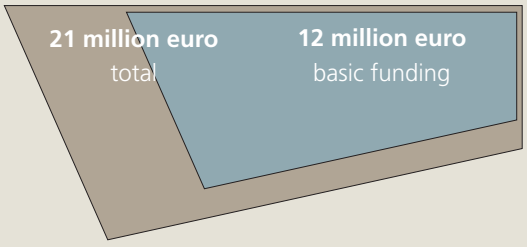
15 scientific support staff

43 other support staff



In total 227 people (with 32 nationalities)

Annual budget



(numbers are from February 2022)

Summary

Statutory Mission

CWI conducts pioneering research in mathematics and computer science, generates new knowledge in these fields and conveys it to society at large, and to industry in particular.

Vision

CWI advances the scientific foundations of our digital society and supports the national mathematics and computer science communities. CWI wants to be a connector for these communities, a breeding ground for talent and a place of scientific interaction.

The strategy to realize CWI's vision has two pillars:

RESEARCH

To align with the needs of science and society, CWI will focus in the coming years on four areas of fundamental research

1 Algorithms
The digitalization of society and the omnipresence of computers bring new challenges and opportunities for algorithms.

2 Data and Intelligent Systems
The growth of data and increasingly complex processes require advances in data management and intelligent autonomous systems.

3 Cryptography and Security
The more society digitalizes, the more important it becomes to guarantee the security and privacy of all digital information and its processing.

4 Quantum Computing
The development of quantum computer hardware simultaneously requires the development of quantum computing algorithms and software.

The four research focus areas are the basis for steering all research investments, in refocusing research staff and in creating new connections between researchers with different expertise.

NATIONAL ROLE

In the coming years, CWI will strengthen its role in the national mathematics and computer science communities in three ways

1 Being a meeting place for research and cooperation
hosting joint research activities and providing opportunities for researchers to attend national seminars, participate in semester programmes, spend sabbaticals at CWI, and meet with national and international colleagues and with partners in industry.

2 Contributing to academic teaching
CWI researchers will spend on average ten percent of their working time on educational activities, such as transferring their expertise in university courses and supervising BSc and MSc students.

3 Attracting, developing and retaining talent
CWI already has a tenure track system and a phased career path for talented young researchers. On top of this, we intend to develop concrete plans to attract, develop and promote scientific talent in cooperation with Dutch universities.

The semester programmes are the main levers of CWI to take its leadership role, team up with its communities to work together on scientific challenges with societal impact, create research consortia, develop grant proposals and tailored valorization approaches. CWI reallocates part of its basic funding towards support of its national role.


CWI

1 CWI Strategy Overview

In this Strategic Plan, CWI presents its research focus for the coming years and its plans to cooperate with the national mathematics and computer science communities.

Scientific foundations for the Digital Age

In just a few decades, digital technologies, powered by inventions like the computer, the internet and smart mobile devices, have transformed societies worldwide. At the start of 2022, over sixty percent of the world population had access to internet and over eighty percent owned a smartphone. According to the United Nations, digital technologies can make important contributions toward the achievement of the UN's Sustainable Development Goals. Digitalization creates new opportunities to deal with some of the most pressing issues of the 21st century including climate change, the energy transformation and sustainability. Digitalization is such an important global trend that both the EU and the Dutch government have formulated digitalization strategies for this decade.

Apart from creating many new opportunities that society can benefit from, digitalization can also threaten privacy, erode security, fuel inequality and deplete scarce resources. It is up to society to harness and manage digital technologies. And it is up to scientific institutions, such as CWI, to provide the solid scientific concepts and methods that enable society to do so and to create the required multidisciplinary, national and international collaborations.

CWI combines scientific excellence with service to its communities

The scientific foundations of digitalization are largely based on mathematics and computer science. These foundations keep advancing because of the interplay between scientific discoveries and technological inventions. Society is producing growing amounts of digital data, computing systems increasingly blend with physical systems, computing devices are getting smaller and cheaper, computing systems are becoming more interconnected and they can perform ever more complex tasks by using artificial intelligence. In addition, the communication between humans and digital technologies is becoming increasingly human-centred.

These technological changes, set in motion by mathematics and computer science, lead in turn to new scientific challenges.

At CWI, we are advancing the scientific foundations of our digital society through fundamental research at the interface of mathematics and computer science. Computer scientists and mathematicians work together in small teams, which act as kernels for collaboration with colleagues at universities, both from mathematics and computer science, and from other disciplines. We invest in long-term software development, aim for societal impact and encourage high-risk, high-gain research with sustained effort over a long period. We are a breeding ground for research talent, and we support the Dutch universities in their teaching tasks. Our strategic intent is to strengthen our role as connector and meeting place for scientific interaction that benefits the national research communities.

The first pillar of our strategy is the focus of our fundamental research on four areas:

First, our fundamental research on **Algorithms** deals with optimization and numerical simulation of complex systems. It includes tackling new classes of problems in the area of optimization, accounting for uncertainties in the use and design of algorithms, and integrating methods (notably machine learning) to extract information from data into algorithms for optimization and simulation.

Second, our research on **Data and Intelligent Systems** addresses the growing reliance on computing systems that can handle large amounts of data and perform intelligent tasks autonomously. We study the foundations of data science and machine learning, strategic agents in intelligent systems and the interaction between humans and computational systems.

The interaction between humans and computational systems also leads to concerns about data privacy and system safety and security. This calls for research on **Cryptography and Security**, our third focus area. That fundamental research will lead to efficient and robust protocols against adverse attacks, including those from quantum computers. It will also yield new concepts regarding secure collaboration between multiple parties in the absence of mutual trust.

Research on **Quantum Computing**, our fourth focus area, aims to identify applications that can exploit the special capabilities of quantum computers in comparison with classical computers. We combine research on algorithms and applications that can deal with the capabilities of quantum computers as they develop over time with complexity research that delineates their limitations. Quantum algorithms are now in a similar exciting opening phase to what algorithms were for conventional computers in the 1950s.

VALORIZATION

Since 2012 CWI has a valorization manager and a valorization team. The team supports the development of Public Private Partnerships with a wide range of companies and public institutions. Many of the partnerships range over a long time period, which enables measurable societal and business impact. We also team up with institutions, such as TNO to bring the knowledge from lower Technology Readiness Levels (fundamental research), to higher ones (engineering knowledge and software applications). For each of the focus areas we have established partnerships in the innovation chain to foster this process from fundamental knowledge to concrete products and services in the market place.

International role

With our research in these four focus areas, CWI continues to play a leading international role, as we have done since our foundation. Our challenging research themes and the achievements of our researchers have earned the institute an excellent international reputation. Virtually all CWI research groups have projects involving international colleagues and institutes. Over the years, researchers from the Netherlands and abroad have found it attractive to come and work at CWI: people from more than thirty different nationalities currently work here.

In the autumn of 2022, we will establish a strategic partnership with our French sister institute Inria aimed at collaborating on the four research focus areas and on applications in various domains, such as health, energy, and human-computer interaction. We will intensify our involvement in the European Research Consortium for Informatics and Mathematics (ERCIM), in various European research and policy programmes (like Horizon Europe) and through the receipt of European research grants (like ERC Grants and Marie Curie Research Grants).

STRATEGIC COLLABORATIONS

CWI collaborates with universities in the Netherlands, in Europe and across the world, with the NWO-I sister institutes, with the Humanities Cluster of the KNAW-institutes, with the French National Institute for Research in Digital Science and Technology (Inria), and with ERCIM and its sister institutes. CWI's strategic collaborations are crucial in identifying relevant research questions and evaluating new solutions.

CWI also collaborates with a range of partners such as the national institutes KNMI and RIVM, national applied science institutes like TNO, public organizations such as the Koninklijke Bibliotheek and the Rijksmuseum, with government ministries, and with numerous partners form industry, ranging from small and medium enterprises to big companies.

CWI aims to increase cooperation with and support for other sciences, for instance together with the Netherlands eScience Center, that provides world-class software engineers. Moreover, CWI's fundamental research potentially has a broad impact on other research disciplines, such as our safe statistics research. It will intensify its collaboration with societal sectors, for instance through virtual labs, such as the Cultural AI Lab (cultural heritage) and the ELSA Lab AI, Media, and Democracy (journalism).

The creation of spin-off companies demonstrably leads to direct economic value to society: the two spin-offs, Databricks Amsterdam and the Software Improvement Group, which originated from CWI, alone now employ more people in the Netherlands than CWI itself.

Furthermore, CWI continues to play an important role in developing international standards for digital products and services via our presence in international organizations like the Moving Picture Experts Group (MPEG) and the International Telecommunication Union (ITU), a specialized agency of the United Nations, responsible for all matters related to information and communication technologies.

Finally, most scientific staff play a steering role in international research development through editorships of journals and programme committee memberships of international conferences.

National role

The Netherlands is one of the most digitalized countries in Europe and even in the world. According to data from before the COVID-19 pandemic, it ranks 4th out of 27 EU Member States in the Digital Economy and Society Index (DESI), which benchmarks EU countries on relevant digital indicators such as connectivity, human capital and integration of technology. CWI, as the Dutch national research institute for mathematics and computer science, is committed to continually pushing back the scientific boundaries required for this digitalization.

In this context, the second pillar of our strategy is to strengthen CWI's national role to the benefit of the Dutch communities of mathematics and computer science. This implies close collaboration with Dutch and foreign universities, sister institutes from NWO and KNAW, and with other institutions, such as TNO, hospitals, infrastructure owners, and private companies.

QUSOFT

QuSoft is the Dutch research centre for quantum software. It was founded in 2015 as a collaboration between the University of Amsterdam and CWI. Its mission is to develop new protocols, algorithms and applications that can be run on small and medium-sized prototypes of a quantum computer. At QuSoft, researchers from mathematics, computer science, physics and chemistry collaborate on various topics such as quantum algorithms, quantum information science and quantum cryptography.

QuSoft is the founding kernel of the larger Amsterdam quantum technology initiatives that tie in with the National Agenda on Quantum Technology and the Quantum Delta NL National Growth Fund project. QuSoft is a partner and the coordinator of the Quantum Software Consortium (2017-2027) awarded funding from NWO's Gravitation programme. Furthermore, the Quantum Application Lab (QAL) was founded in early 2022 by CWI, University of Amsterdam, TU Delft, SURF, The Netherlands eScience Center and TNO. IBM is the first research partner of QAL. QAL and QuSoft are further complemented by Quantum.Amsterdam, which was established in late 2020. This is another collaboration within the Amsterdam quantum technology initiatives that focuses on outreach to society and industry to create awareness of the impact of quantum computers.

CWI benefits from being a compact research institute. Our focus on the research topics presented above, and our facilities for hosting conferences, workshops, and sabbaticals, enable collaboration with the Dutch and international communities of mathematics and computer science. This collaboration is necessary in order to compete in essential scientific and societal fields. The main means to strengthen our national role is the organization of semester programmes, which enable breakthroughs in current research topics, generate new ideas and topics and create the intensive collaboration needed to ultimately turn ideas into concrete contributions to science and society.

At CWI, we are aware of the enormous challenge the Dutch mathematics and computer science communities are facing for the coming decade in preparing new generations of students for the rapidly evolving digital society. As a consequence, for the coming five years, CWI will help the universities in their high educational workload by increasing our efforts in teaching courses on our focus areas, supervising BSc and MSc students and advising PhD candidates jointly with university staff. By doing so, we can help to attract and develop the research talent that both CWI and Dutch universities need to maintain their important role in research and education in the world.

If you want to stay updated on CWI's strategy in de coming years, please visit cwi.nl/strategy

Taming blackouts

Securing a reliable power grid is of tremendous societal importance due to the highly disruptive repercussions of blackouts. Yet, the study of cascading failures in power grids is a notoriously challenging problem due to their sheer size, physics and engineering specifications and due to human behaviour.

The advent of renewable energy sources, which will further increase in the next decade, makes this challenge even harder. In particular, there will be more uncertainties on the supply side of energy (due to fluctuations in solar and wind energy), as well as the demand side (for example, due to electric vehicles connecting to superchargers). A mathematical description of uncertain supply and demand takes the form of a high-dimensional random process.

On an abstract level, a blackout can be reformulated as an event that this random process leaves a ‘safe region’. This safe region is high-dimensional and can have a complicated shape: it may have sharp corners and may not be connected. Furthermore, approximating the probability of a blackout, for instance by using simulations on a digital twin, is just as difficult as this event is rare.

One of the major challenges is to develop fast rare event simulation techniques that are still efficient in high dimensions and can handle safe regions with ‘difficult’ shapes. The algorithms underlying these simulations not only provide estimates of blackout probabilities, but also identify key vulnerabilities in power grids, and can therefore lead to network designs that are more robust.

2 Focus areas of fundamental research

In building on the institute's strong research lines, in synergy with research at Dutch universities and responding to the needs of science and society, CWI focuses its resources on four areas of fundamental research.

In the coming years, CWI will focus on four research areas which combine mathematics and computer science and address major scientific challenges:

1 **Algorithms**
2 **Data and Intelligent Systems**
3 **Cryptography and Security**
4 **Quantum Computing**

These areas build on the strengths of CWI's fundamental research at the interface of mathematics and computer science, they require the long-term investment that CWI has a track record in, and they will have a substantial international impact on mathematics, computer science and their applications in other sciences and in society.

The required long-term investment implies a shift in CWI's allocation of funding: only research within the focus areas will be reinforced with attracting new scientific talent, and some research activities outside these areas will be refocused. With this, we continue our policy of enabling dynamics in our research portfolio.

Furthermore, the four focus areas are in line with national research ambitions, such as energy transition, healthcare, logistics, smart industry and big data from the Dutch Research Agenda. They also connect with the Dutch government's top sector approach and have the potential for a high societal impact.

The research in our focus areas covers many aspects of computer science, such as the study of algorithms and data structures, computer and network design, modelling data and information processes, and artificial intelligence. On the other hand, the focus areas require rigorous mathematics to enable formal proofs of important properties of algorithms, data structures, and networks.

At CWI mathematicians and computer scientists work jointly in small teams on the challenging research problems that naturally emerge when applying new information and communication technologies to business and institutional processes. Typical examples are the design and operational management of the 'smart grid', characterized by decentralized power production, and the development of personalized medical treatment, based on a combination of medical domain knowledge, empirical treatment data and machine learning.

Simulating climate

A major challenge for simulating the climate system is that the atmosphere and the oceans, both key components of the climate system, show all kind of fluctuations over a wide range of spatial scales, from individual clouds to planetary-scale flow patterns. Even on modern supercomputers, it is not computationally feasible to explicitly include all details in simulations of the climate system over years, decades or more. The computational burden is compounded by the need to explore different scenarios or to assess various uncertainties, which requires repeated simulations. Similar difficulties are encountered in other domains, for example in computational fluid dynamics to study aerodynamics, pipe flows or wind turbine design.

A new way to tackle this problem is emerging, one in which physics-based models are combined with machine learning to account for details that are not explicitly simulated but are too important to ignore. This 'hybrid' modelling approach is promising, but it entails major open questions that need to be addressed. Gaining confidence in computations with hybrid models requires, for example, an analysis of the stability and accuracy of the numerical algorithms on which these computations are based. The mathematical techniques for such analysis still need to be developed.

Furthermore, there are often physical constraints that must be respected, such as the conservation of energy. How to impose these constraints when building a hybrid model and when training the machine learning-based part of it, is another open problem. These and other questions are exciting topics for research in the emerging area of 'scientific machine learning' where scientific computing and machine learning are blended.

Our four focus areas are interlinked, which ensures that different CWI research lines reinforce each other. For example, a common theme in the focus areas Algorithms and Data and Intelligent Systems is the use and development of machine learning techniques. Both focus areas also develop fundamental solutions that can be applied in future energy systems. Another example is that the focus areas Cryptography and Security and Quantum Computing have a common interest in developing cryptography in a quantum world. There are many more examples of such cross-links between different CWI research lines.

In the remainder of this chapter, we will clarify the strategic choice for our four focus areas. For each focus area, the main text explains the key research challenges. The research cases in this strategic plan zoom in on examples, specific scientific challenges and applications in society.

Emergency logistics

In emergency logistics, an emergency fleet of vehicles (for example ambulances) needs to be routed such that good coverage of the network is provided and, in addition, short response times must be guaranteed in case of emergencies. The algorithms to tackle such problems need to be reliable under all circumstances, react instantaneously to emergency requests, guarantee short arrival times, and exploit real-time traffic data.

Such applications bear several new characteristics that trigger a series of research questions we need to address: How can we capture the new key characteristics arising in these problems through mathematical models? What are suitable means to assess the actual performance of the algorithms in practice? In particular, we need to come up with more fine-grained approaches that go beyond the traditional worst-case analysis. How can we accommodate the plethora of objectives and requirements that these algorithms need to fulfil? What are general techniques to achieve this? Can we make use of historical data or predicted input data to improve the performance of our algorithms?

Rob van der Mei at Universiteit van NL

2.1 Algorithms

From controlling the power grid to optimizing logistics and from making climate predictions to medical image processing, decision-making in modern society relies more than ever on information from computations based on algorithms. At the same time, hardware developments have resulted in very powerful computing systems that have opened up entirely new computational possibilities.

Due to the stronger reliance on computations and the increased computational power, algorithms nowadays must meet much higher expectations and fulfil a wide range of objectives. Our research in the focus area Algorithms focuses on mathematical and computational aspects of algorithms.

In many cases, decision-relevant information comes from algorithms that have some form of optimization at their core, such as information about how to make the most efficient use of resources. Although many algorithms for well-established, 'classical' optimization problems now exist, there still are major open research questions. These include questions about the performance of optimization algorithms, as well as broadening the scope of algorithms to tackle new paradigms and objectives in optimization, such as fairness or privacy.

Furthermore, there is an increasing need to account for uncertainty in the use and design of algorithms. Mathematical models employed, for example, in forecasting, design or optimization often have uncertain aspects, owing to the complexity and uncertainties of the underlying real-world phenomena. Accounting for these uncertainties in simulation and optimization algorithms is an important challenge.

We must rethink our algorithms to tackle new problem types, accommodate uncertainties and leverage data

A third challenge is how to incorporate data smoothly and efficiently in computations, for example in numerical simulation and optimization. There is currently an abundance of data from sources ranging from sensors and satellites to pre-existing computational results and information gathered online. Instead of treating the extraction of information from data and the use of this information in computations as separate steps, the aim is to seamlessly blend them.

These challenges and opportunities have led CWI to focus in the coming years on three research challenges within the focus area Algorithms:

- **Foundations of optimization algorithms**
- **Algorithms and uncertainty**
- **Data-informed algorithms**

Three-dimensional video

CWI has been exploring alternative options for remote communication for the last decade. We focus on three-dimensional video, also called volumetric video, and use our own VR lab to conduct the experimental part of our research. Volumetric video provides a natural environment for communication and collaboration, where the physical and virtual worlds merge appropriately. For example, by using volumetric video you can cut a birthday cake together with your friends even if you are all at a different location, visit a museum together or see a doctor who can examine you remotely.

The scientific challenges in volumetric video conferencing are diverse, and include novel compression and streaming algorithms, the study of human perception and interaction with volumetric data, the modelling of affective states and their visualization, and the development of novel Quality of Experience-metrics. They require a multidisciplinary approach, based on realistic testing grounds and data sets that combines data science with a strongly human-centric, empirical approach. This has the potential for a broad societal impact, from healthcare and remote consultation to education and from novel entertainment scenarios to more accessible cultural heritage exhibitions.

Virtual Museum

CWI has an excellent track record in fundamental research areas, such as optimization, applied probability and scientific computing, which are necessary to meet these challenges. Although algorithms play a role in the other three CWI focus areas as well, the focus area Algorithms studies challenges of algorithms in a generic sense, with an emphasis on optimization and numerical algorithms.

Foundations of optimization algorithms

The research challenge 'Foundations of optimization algorithms' is aimed at the design and analysis of algorithms to solve fundamental optimization problems. Such problems are at the core of many complex optimization challenges arising in application domains such as healthcare, emergency logistics, supply chain management, traffic control and energy systems.

Our goals are threefold:

- design new models that capture present-day computational challenges, for example in online, decentralized, or competitive environments
- develop improved algorithms for fundamental optimization problems
- discover mathematical techniques enabling a fine-grained analysis of the quality and behaviour of algorithms.

Identifying core mathematical structures that are limiting or enabling factors in optimization as well as using a broadly applicable level of abstraction is critical in pursuing these goals. One concrete example is to determine how power grids can meet electricity demand with power generated by various sources, at minimal cost and in real time (the so-called AC optimal power flow problem). To date, no scalable and efficient algorithm has been discovered that can solve this optimization problem.

Algorithms and uncertainty

Traditionally, algorithms have been designed with scant attention for uncertainties in the parameters or the structure of mathematical models, for example. However, the assumption that models and their parameters are known with full certainty is unrealistic in many cases. For example, uncertainties play a major role in modelling the earth's climate and in modelling electricity distribution. These systems can be inherently chaotic, not all details are known and randomness plays a role. What are the influences of uncertainties when simulating or optimizing these systems? How can we quantify the uncertainties and how far apart are various possible outcomes, for example when simulating with a digital twin? In the research challenge 'Algorithms and uncertainty' we investigate how uncertainty impacts the design and performance of algorithms. An example is the design of efficient computational algorithms to evaluate rare events such as blackouts or floods, which have a small probability, but a high impact.

Data-informed algorithms

The use of data in many areas of science and society has increased enormously over the last decade. This has a significant impact on the development of algorithms. There are major opportunities as well as challenges for developing methods that blend data and models, and for integrating modern machine learning techniques into algorithms for optimization, scientific computing and more. In the research

Intelligent trading agents for decentralized energy systems

An energy transition is needed to combat climate change. In this energy transition, energy systems are becoming more flexible and decentralized, with many consumers installing their own generation and storage. In this way, they become 'prosumers' - producers and consumers in one - and the reliance on a central grid is reduced. Smart energy communities, where prosumers can trade locally generated renewable energy with each other, are thus being developed.

Prosumers in such communities often aim to trade with each other to meet their needs in terms of comfort, price and carbon intensity. We design automated negotiation strategies for prosumers participating in local peer-to-peer energy markets, leveraging the latest advances in collective intelligence, algorithmic game theory and machine learning. Such agents are designed to deal with complex user preferences and implement automated offer and concession strategies to obtain the best possible deal for their owners.

Looking forward, future energy systems will require a radical redesign of the market and incentive structures, to enable micro-transactions and flexible use of intermittent renewable generation. Through our research, we make new, fundamental advances in algorithmic mechanism design, auction protocols and smart contracts to enable such peer-to-peer energy markets, and encourage self-interested prosumers to contribute to system flexibility.

challenge ‘Data-informed algorithms’, we investigate how we can design and analyze such data-informed algorithms, and how they can be implemented and used efficiently. Relevant application domains for CWI include climate science, computational fluid dynamics and plasma physics, as well as imaging for health care, cultural heritage and industry 4.0. For our research in computational imaging, we use a unique facility: the FleX-ray Lab, a custom-made, fully-automated X-ray CT scanner linked to large-scale computing hardware.

The FleX-ray Lab

DuckDB

Private data are currently often stored centrally in the cloud, which in practice means on the computers of companies like Google and Facebook. The data producers and rightful owners, often ordinary citizens, no longer have control over what happens to their cloud data. This has created all sorts of privacy nightmares in the past and there has been strong pressure from civil society to change that. CWI is investigating a new, decentralized data storage architecture where your data stays under your control, for example inside your phone. For this research, CWI has developed DuckDB, a new database system that can efficiently analyze data and is designed to run inside other programs.

DuckDB has been downloaded and used by millions of people who use it embedded in Python and R (popular data science software). It is also our platform for research into secure cloud query processing. For this, DuckDB is embedded inside special secure hardware, databases inside disk drives (computational storage) and analytics in the field, for example databases inside self-driving cars or smart traffic cameras (edge computing). DuckDB runs on very small computers and even inside your web browser or on your mobile phone (try: https://shell.duckdb.org). DuckDB perfectly fits CWI's mission for long-term innovative software development as a way to do research and achieve substantive societal impact. CWI is shareholder in the DuckDB Labs spin-off company, and has a board seat in the DuckDB Foundation that watches over the core open source software and collects donations for financing its maintenance.

2.2 Data and Intelligent Systems

The increasing digitalization and complexity of today's society have led to an unparalleled reliance on data and intelligent systems. Data will only grow in importance and so proper data management systems must be designed.

At the same time, processes in society and industry, communication between people, and the handling of information and data lead to an urgent need for intelligent systems, which learn from the past, are adaptive to the present, or lead to the proper emergent system behaviour between various actors.

Exploiting synergies between mathematics and computer science, we study the design of data management systems and intelligent systems, and the incorporation of these into other disciplines and applications. Within the focus area Data and Intelligent Systems our research will concentrate in the next years on three challenges:

- **Foundations of data science and machine learning**
- **Strategic agents in cyber and cyber-physical systems**
- **Human-focused intelligent systems**

CWI has an excellent track record in research areas that can contribute to these challenges. By building on and extending this expertise, we are well placed to address these challenges.

The robustness of the digital society depends on fundamental research into data science and intelligent systems

Foundations of data science and machine learning

CWI aims to achieve long-term impact by focusing on foundational research in the methods and techniques for data science and machine learning. Our data systems research has produced foundational techniques such as columnar storage and vectorized execution, adopted in analytical database engines worldwide, and now focuses on *embeddable analytics*: here the database system is placed inside another program and becomes part of it. This research takes shape around CWI's new open source DuckDB system. The aim is to provide data science functionality that can be inserted everywhere: from small local computers (edge computing) to large central servers (cloud computing).

Statistical methods are a fundamental tool in science and are applied in many scientific disciplines, from psychology to epidemiology. Unfortunately, these

Safe statistics

Since Stanford professor John Ioannidis published the paper 'Why Most Published Research Findings are False' in 2005, there has been growing awareness that a large number of published research papers, even in top journals, contain wrong conclusions. This is now called the 'replication crisis' in science.

The problem is that scientists use hypothesis testing to determine whether experimental results are significant and thus not just chance. Significance is traditionally computed using so-called p-values, but this can lead to errors. Specifically, if the experimental result is not significant, scientists may extend the experiment, for instance by adding more patients to a drug trial. This process may be repeated until the result is eventually significant. However, extending a p-values experiment is statistically wrong: it is like rolling the dice until you are lucky.

At CWI, we study the foundations of machine learning, which include the foundations of statistics, to address this replication crisis. We are developing 'safe statistics' that, unlike p-values, do allow the extension and combination of experiments without leading to wrong conclusions. This requires a complete redesign of statistical methods and techniques, as well as software.

methods are often applied incorrectly, leading to wrong conclusions and what is called the *replication crisis*: it has been found that the results of many scientific studies are difficult or impossible to reproduce. Our research on *safe statistics* aims to redesign statistical methods to address this crisis.

In the field of machine learning, we focus on the fundamental mathematical and computational characteristics of learning. We have a leading role in machine learning techniques that takes inspiration from the human brain and can create intelligent 'neuromorphic systems' that consume much less energy than present-day AI systems.

Strategic agents in cyber and cyber-physical systems

In complex cyber or cyber-physical systems (like an online market or the smart grid), participants often have their own preferences and goals that are not aligned with those of the system as a whole or may even be opposite to each other. The participants are what we call 'strategic agents'. For example, individual consumers may collectively want more green energy produced by solar panels in their neighbourhood than would actually be available. This leads to a competition between consumer demands. A logical solution to this problem would be an intelligent system that allows for automatic allocation of the available green energy in an efficient, economic and fair way.

Energy is not the only domain of coordination between strategic agents: strategic agents can be used in distributed logistics with competitive transportation suppliers, in web-based procurement, in data sharing, or to stop the spread of disinformation in social networks. Another example is security in cyber and cyber-physical systems where surveillance and defence agents have opposite objectives compared to intruding and attacking agents.

Fundamental challenges in the field of strategic agents are to model and analyze such systems (for example, by game theory models or socioeconomic paradigms) and to design integrated methods and solutions that combine AI, data, algorithms and game theory. Important aspects are the design of proper strategies for agents to get the best results for their own objectives or designing systems and rewards to encourage agents in the right direction. Ethical, legal and societal aspects also play an important role in this. In addition, multidisciplinary research is performed with other groups and institutes, especially for challenges regarding cyber-physical systems, ethical, legal and societal aspects.

Human-focused intelligent systems

Intelligent systems help us to find optimal solutions for certain problems and play an increasingly pivotal role in our society. At CWI, we follow a human-focused approach for designing, developing, and evaluating intelligent systems and subsequent data analysis.

One topic that we study concerns systems for human interaction and communication. The main challenges are how to model and explain user perception, behaviour and interaction, and how to design systems that are data-driven and learn with complex data. Another important research topic is developing explainable artificial intelligence methods for a safe and responsible use of intelligent algorithms, which is in line with human values like equality and justice. This is needed to prevent phenomena like algorithmic bias, which occurs when algorithms unintentionally discriminate on the basis of gender or age, for example.

New cryptographic standards

One of the consequences of the expected arrival of a quantum computer is that current cryptographic standards (such as RSA) will no longer be secure. Society therefore needs new secure and efficient standards that are resistant to attacks by a quantum computer. The development and testing of new standards is a continuous process. When a new standard is being introduced, we should already be actively developing an even better standard for the future.

In 2017, the National Institute of Standards and Technology (NIST) launched a competition for new cryptographic standards in which CWI also took part. Roughly speaking, there are four mathematical platforms on which these new standards are based: lattice-based cryptography (based on ordered sets in a high-dimensional space – CWI works on this a lot), code-based cryptography (based on error-correcting codes), isogeny-based cryptography (based on elliptic curves), and multivariate cryptography (based on large systems of polynomials in many variables). One of the crucial scientific challenges for all these platforms is to determine how many bits give how much security.

During the course of 2022, NIST is expected to announce two winning standards. However, the rollout of these standards to government, business and society will, in general, take around ten years. At CWI, we develop the mathematical foundations of new cryptographic standards, but we also work on the engineering side and on the rollout of these standards. For example, together with TNO we are developing a migration manual for the Dutch government that enables the transition from current to new cryptographic standards.

We also address problems in ELSA settings (Ethical, Legal and Societal Aspects), for example via our new joint multidisciplinary lab ‘AI for Media and Democracy’, which focuses on how AI and digital technology are transforming media and democracy. One of its goals is to use AI to develop more human-centred and diverse systems.

In the field of software engineering, we develop new methods to build and analyze software, manage its complexity and understand it better. We approach software as data and tackle it with AI methods. This allows developers to maintain and extend software more efficiently and with better quality assurance. In a world that increasingly runs on software, this is vitally important.

Secure and private data analytics

It is increasingly common that competing parties can benefit from sharing certain data and jointly analyzing these without the data being completely revealed to a competitor. Such secure and private data analytics is already playing a role in the financial and medical sectors and the manufacturing industry. For example, it can enable banks to detect fraud more easily and hospitals to develop better treatments for rare diseases.

The central question is: how do we build a system that can analyze data, which is useful for all parties and at the same time makes sure that different parties only learn results from permitted analysis without one another's privacy being compromised? CWI has a decades-long tradition of developing fundamental tools that enable secure and private data analysis. We study three important tools at CWI: secure multi-party computation, zero-knowledge proofs and differential privacy. We focus on research questions like: What privacy guarantees do these techniques exactly provide? How do these technique scale with data reuse?

2.3 Cryptography and Security

The growing use of digital products and services poses enormous security and privacy challenges for society as a whole. In particular, the increasing interconnection of digital services, advancing surveillance technology and the combination with powerful AI techniques will constantly pose new security risks. Privacy and security issues will be crucial in almost all areas of computer science. Solving the underlying security problems requires an integrated approach that is strongly based on mathematics.

CWI's foundational research in cryptography has a long and strong tradition. Building on that tradition, CWI will focus in the coming years on four research challenges within Cryptography and Security:

- **Post-quantum cryptography**
- **Secure multi-party computation**
- **Security of large-scale computing infrastructures**
- **Secure intelligence augmentation**

The first two challenges have always been strongly based on mathematics. That is far less the case for the last two challenges, and CWI wants to contribute to these by applying rigorous cryptographic thinking to security engineering.

Security in the digital society relies on mathematical principles

Post-quantum cryptography

When adversaries start to use a quantum computer, which is still under development, many widely used encryption methods will be threatened. A new type of cryptography is urgently needed to protect digital services against attacks with a quantum computer. This is the so-called post-quantum cryptography. On the one hand, we focus on developing post-quantum cryptographical methods that can be used for public-key encryption and digital signatures, for example. On the other hand, we also cryptographically analyze these methods.

Secure multi-party computation

Secure multi-party computation enables secure collaboration between multiple parties in the absence of mutual trust, which is increasingly the case in application domains. An example is the use of massive patient data to improve patient care. In order to protect the privacy of patients, data analytics requires computation on

Secure smart lowlands

Protecting smart infrastructures in the Netherlands, like power grids and flood defence systems, requires secure software and secure hardware, such as computer processors and cyber-physical systems that combine hardware with software. One of the challenges is to protect control flow and data processing in such a way that sensitive pieces of code can be executed in secure enclaves that do not leak to other enclaves or to an untrusted operating system. Protecting cyber-physical systems leads to various challenges: legacy embedded devices may not easily allow security updates, malicious firmware updates may proceed unnoticed, secure communication protocols need to be in place and malicious sensors may compromise the dynamic physical process layer.

hospital input data without each hospital revealing its own data to another hospital. One of the main challenges in secure multi-party computation is how to do this efficiently with a growing data volume or with a growing number of parties. Secure multi-party computation is a subarea of cryptography in its own right, which has dedicated technical models and techniques that are now on the verge of large-scale industrial application.

Security of large-scale computing infrastructures

The Netherlands has many smart infrastructures, like cyber-physical systems that control traffic, smart homes, industrial control systems, water purification plants and flood defence systems. How can we be confident that they are correctly implemented and not maliciously tampered with? What methods can be used to protect the privacy of sensitive data? At CWI, we work on security mechanisms in order to make progress towards building the necessary secure large-scale computing infrastructures.

Secure intelligence augmentation

Present-day intelligent systems often operate in highly regulated environments, like automated guided vehicles in warehouses. They do not have the common sense knowledge to deal with the richness of the real world and serve more as a tool augmenting our own common sense. Secure intelligent augmentation needs to function in a potentially malicious world in which adversaries might manipulate training data, modify input data or otherwise break into the intelligent system.

Faster optimization

Solving optimization problems is one of the main applications of computers in industry and society: optimizing production processes, routing in logistics, reducing energy usage and scheduling classes are some examples. Faster optimization algorithms are among the main potential applications for future quantum computers. CWI has made significant progress in this area in the last few years. Examples include improved quantum algorithms for gradient descent (where we iteratively reduce a function by following its derivative, such as how neural networks are trained in machine learning), quantum algorithms for solving linear programmes (optimizing a linear function subject to linear constraints on its variables, which is used frequently for logistics problems), and quantum algorithms for optimization problems on networks.

2.4 Quantum computing

Quantum computing merges two of the greatest developments of 20th-century science and technology: quantum mechanics and computer science. Quantum computers are fundamentally different from our current classical computers. Using counterintuitive quantum effects like superposition, interference and entanglement, we can do certain computations much faster, or safer, or with less communication, by using qubits (the quantum-mechanical equivalent of the classical bit). In principle, one could redo all of computer science on quantum foundations. From the first suggestions in the 1980s, through the development of the first quantum algorithms in the 1990s, and the construction of the first quantum computers in the lab, this is now a very promising area, widely studied in academia and industry, with large investments from companies and governments.

Quantum computers expand the boundaries of efficient computation

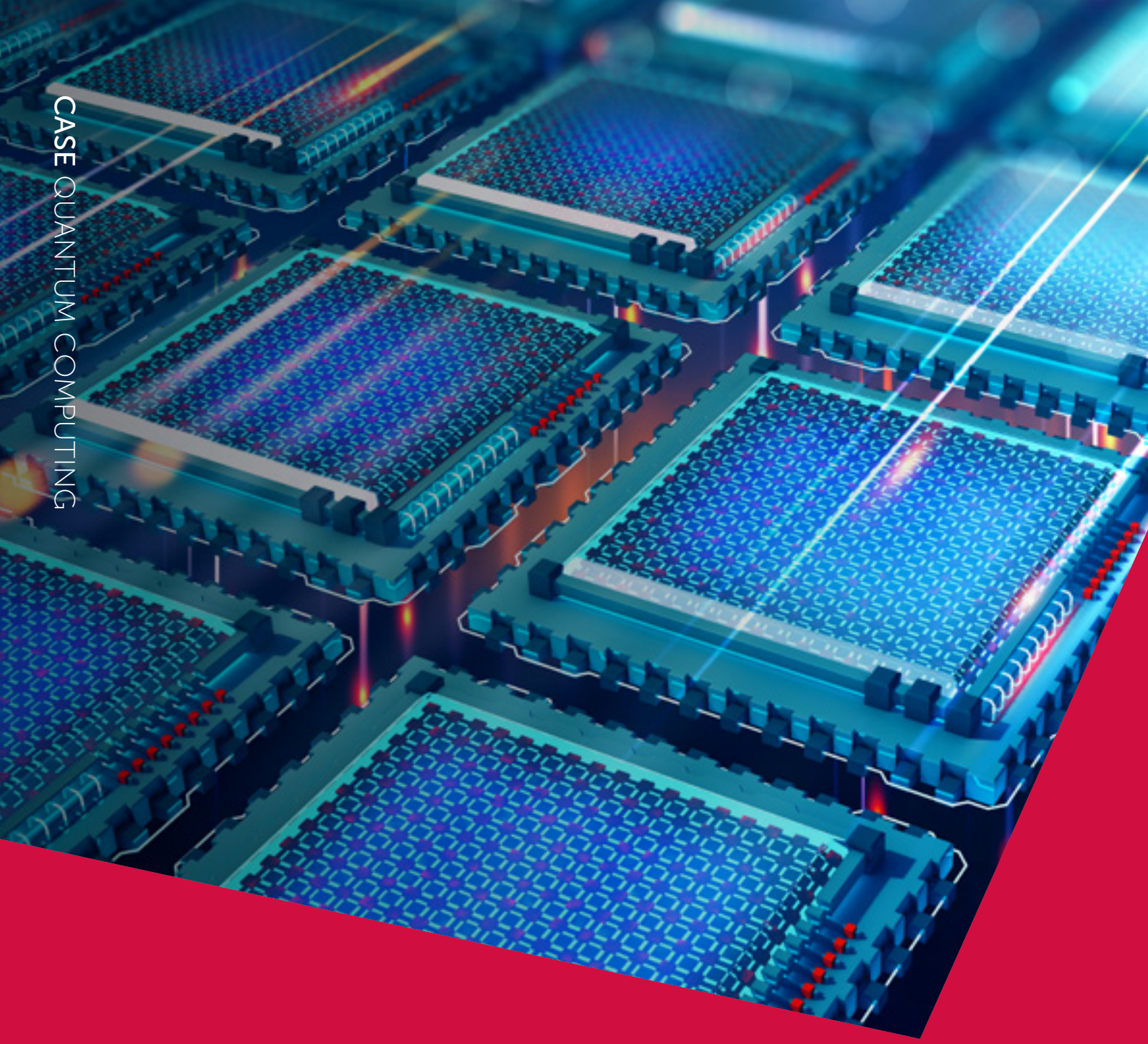
CWI started research in quantum computing in the mid-1990s. It was among the first worldwide to pioneer this field, contributing seminal results on efficient quantum algorithms, communication protocols, analysis of limitations of quantum computers, as well as links with other areas such as mathematics and physics. In 2015, CWI and the University of Amsterdam jointly established the world's first quantum software research centre: QuSoft. QuSoft brings together all the academic research in Amsterdam in the field of quantum computing and is physically located at CWI.

CWI's quantum computing research pursues four research challenges:

- **Quantum algorithms and complexity**
- **Quantum information science**
- **Quantum cryptography**
- **Quantum for society and business**

Quantum algorithms and complexity

Which computational tasks are amenable to quantum speed-up, and which are not? The very nature of quantum computing calls for fundamentally new algorithmic strategies. The research challenge 'Quantum algorithms and complexity' develops and investigates new quantum algorithms and also studies the limitations of quantum computers. Use cases for quantum algorithms can be found in optimization, machine learning, quantum chemistry, algorithms on networks and quantum attacks on classical cryptographic systems. Most of those use cases focus on the longer-term regime where fully-fledged error correction and fault-tolerant



Near-term quantum computers

The quantum computers being built around the world are still small and far from perfect. The best ones currently have roughly one hundred qubits and can do operations with an error rate of roughly one percent. With the unchecked accumulation of errors, such near-term quantum computers cannot perform long computations. In principle, there is a software solution for this problem. Quantum fault-tolerant methods can build near-perfect qubits from multiple less-perfect qubits, but this is not yet practical because of the required overhead in terms of the number of qubits and operations.

For the near future, we are looking for useful few-qubit applications that can already outperform classical computers without full quantum fault-tolerance and for ways to test, measure, verify and debug near-term quantum computers. Interesting quantum computations for chemistry problems would become possible if we have a few hundred good qubits and sufficiently precise operations, which might already happen in the next few years.

computation enable reliable quantum computers with many qubits. However, algorithms on fifty or more qubits quickly become impossible for classical computers to simulate, and so we also aim at use cases for small and medium-sized qubit platforms with ten to a few hundred qubits.

Quantum information science

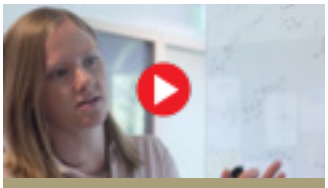
Quantum information science addresses the questions that arise when information is processed according to quantum-mechanical rules. Reasoning based on quantum notions such as superposition and entanglement leads to applications in computer science, mathematics, logic and physics that do not always need an actual physical device. Quantum information can be used in the study of non-locality, quantum thermodynamics, condensed matter systems and even the structure of space-time itself. This research challenge also addresses quantum network and communication protocols and distributed quantum computation.

Quantum cryptography

Cryptography is one of the core research subjects of the Cryptography and Security research focus areas. Within quantum computing, the research focus area quantum cryptography also engages in the constant tug-of-war between attempts to encrypt information and attempts to break those encryption schemes. Cryptography in a quantum world is a double-edged sword: quantum algorithms can break most public-key cryptographic systems currently in use, but there are also ways to repair cryptography. Quantum cryptography uses quantum effects to design fundamentally new cryptographic systems that run on quantum hardware.

Quantum for society and business

Within the challenge 'Quantum for society and business', we work with companies and societal organizations to explore, discover and develop novel algorithms, applications and use cases. CWI is one of the founding partners of the Quantum Application Lab (QAL). This recently formed public-private R&D partnership offers a unique team of scientists, researchers, engineers, application developers, software and hardware specialists the opportunity to explore and bring to market the benefits of quantum computing. Organizations that want to investigate how quantum computing can help their goals can connect to the knowledge and technical infrastructure offered by QAL. In addition, we cover the Ethical, Legal and Social Aspects (ELSA) of quantum information processing in ongoing cooperations with external partners.



Stacey Jeffery about working at CWI/QuSoft


Leading the Web to its Full Potential

3 National role

In the coming years, CWI will strengthen its role in the national mathematics and computer science communities by being a meeting place for research and cooperation, by contributing to university teaching, and by attracting, developing and retaining talent.

More than before, CWI will fulfil its national role through leadership and support. We will demonstrate leadership in terms of the four research focus areas outlined and illustrated in Chapter 2 of this Strategic Plan: Algorithms, Data and Intelligent Systems, Cryptography and Security, and Quantum Computing.

The support we provide to the national mathematics and computer science communities takes several different forms. We will strengthen our national role by organizing joint research activities, by contributing more than before to the teaching and supervision of university students, by becoming a place where the communities of mathematics and computer science come together around new and interesting topics, and by attracting, inspiring and supporting national and international research talents.

A round of consultations in 2021 with Dutch universities on CWI's national role and our mutual interests and responsibilities helped to shape our aims and ambitions for the coming years. We continue to involve representatives from the Dutch universities during the implementation of our strategy to ensure support for our new initiatives. Below is an overview of these new initiatives, some of which have already started.

3.1 Meeting place for research and collaboration

CWI will be a meeting place where the mathematics and computer science communities regularly come together to discuss new and promising research topics. In particular, young researchers, like those on tenure track, will benefit from regular visits to CWI to team up with senior researchers and expand their professional network. CWI also already hosts several community organizations, like the office of PWN (Dutch Platform for Mathematics) and some facilities of the Royal Dutch Mathematical Society (KWG).

Semester programmes

A scientific semester programme facilitates joint national research collaborations and brings together scientists on interesting, current topics that preferably fit within our focus areas. A group of researchers will be invited to work together on a regular basis over several months on a specific scientific subject. Such semester programmes will also include a series of satellite events that appeal to young

talents and will also be used to bring in international experts. Examples are a mini-symposium, masterclass, hackathon or data challenge. As stated earlier, the semester programmes are the main means to create dynamics in the research portfolio of CWI and its Dutch communities within the scope of the four research focus areas. These semester programmes should yield submissions, together with university researchers, of medium- and large-scale research projects funded by NWO and the European Commission. By 2027 we aim for participation in three NWO Gravitation programmes (or programmes of a similar scale).

Additionally, other regular scientific meetings like reading groups, seminars, collaboration sessions and open-problem sessions will be organized and hosted by CWI. The format will be very flexible to meet the preferences of the participants. Examples are one-day meetings on a weekly basis or two-day meetings on a bi-weekly basis.

International participants will also be encouraged to attend. However, by focusing more explicitly on talents at Dutch universities, CWI semester programmes are mainly aimed at supporting the Dutch scientific mathematics and computer science communities by bringing junior and senior researchers together to pave the way for the emergence of structural new research collaborations and identify promising directions for new research within the scope of our focus areas.

University staff can also take the initiative to organize a semester programme together with CWI on a subject that ties in with our research focus. A positive side effect is that this also contributes to the dynamics of CWI's research.

In 2022, two semester programmes are taking place: 'Data-driven Methods for Inverse Problems' and 'Polynomial Optimization and Applications'. We aim for two to three semester programmes per year.

Sabbatical programmes

CWI sabbaticals offer university staff from the Netherlands the opportunity to spend some time at CWI doing high-quality research and expanding their own research network. These sabbaticals will be specially tailored to attract talented young researchers such as tenure trackers and assistant professors.

In addition, we will invite prominent international researchers to spend time at CWI, for example during a semester programme. Such a research stay will be arranged with maximum flexibility for the visitor: while it is more likely for international visitors to arrange a sabbatical for a continuous period, it may be preferable for university researchers from the Netherlands to spend only a few days a week at CWI for a certain period. We aim for two to three sabbaticals of national or international renowned researchers per year, aligned with our semester programmes.

National seminars

Together with our university colleagues, CWI has already established a number of national seminars, for instance the Dutch Seminar on Data Systems Design, the Dutch Optimization Seminar, and the Dutch Seminar on Digital Energy. CWI staff develops the programme with university colleagues and CWI hosts the seminar. Ideas for new national seminars are welcome and will be discussed in regular meetings with universities.

CWI and its collaboration partners

See cwi.nl/collaborations for more information about our research partners.

3.2 Teaching and supervision

More than thirty CWI researchers currently hold part-time professorships (mostly 0.2 fte) at nine Dutch universities, where they contribute to the teaching and supervision of university students. CWI researchers also contribute to the national MasterMath and Landelijk Netwerk Mathematische Besliskunde teaching programmes.

As the teaching load in universities is heavy, especially in computer science, most universities welcome CWI researchers to alleviate their teaching load and to bring expert knowledge on specific topics. Besides giving lectures, our researchers can also act as supervisor or co-supervisor of BSc and MSc thesis projects.

For this reason, and as a result of CWI's consultations with the universities, we are offering an increase in its contributions to the education of young talents in the fields of mathematics and computer science. More particularly, CWI researchers will spend, on average, ten percent of their time on educational activities at universities. We will also regularly publish an overview of the institute's MSc projects open to university students, with CWI staff acting as a supervisor. Contributing significantly more to education supports our aim to build stronger relations with the Dutch universities.

CWI is now implementing a new education policy, introducing younger staff to university teaching and thesis supervision, and increasing the total number of senior researchers involved in university teaching. Universities agreed that structural educational activities by CWI should be financially compensated.

3.3 Fostering talent

Some universities are interested in the idea of having joint university-CWI appointments. CWI is open to exploring this further. The same holds for joint international recruitment activities. CWI will also discuss this with PWN and IPN (ICT-Research Platform Netherlands) in view of the international competition for talent faced by the mathematics and computer science communities. Further discussion is needed to see whether universities and CWI can jointly position a career in the Netherlands as a community asset. We will also consider how to organize the flow of talent from CWI to the universities in a more structured way.

3.4 Connecting with national community platforms

CWI is part of two major national community platforms, IPN and PWN. CWI also provides support to PWN activities and hosts its secretariat. To strengthen strategic ties with IPN, collaborations will be discussed in workshops with representatives of IPN membership and representatives from CWI.

Occasionally CWI management and staff provide input to policy discussions of two of the NWO advisory Roundtables, Mathematics and Computer Science, to ensure alignment in objectives and roles. In case IPN will initiate the development of a new 'sector outlook' with a resulting 'sector plan', CWI intends to participate.

PWN announced its intention to develop a sector outlook and a sector plan. PWN and CWI have started exploring the role CWI can take here.

3.5 Other connecting roles

CWI is home to and founding sponsor of VERSEN, the Dutch National Association for Software Engineering, and hosts its annual national SEN Symposium, bringing together researchers and practitioners in software engineering. CWI researchers are active in the executive board of VERSEN.

In our consultations with universities, various other connecting roles were suggested for CWI. Given our track record of valorization and public-private partnerships, we are well-positioned to take on a coordinating and facilitating role when groups from several universities work together in applications for grants with larger consortia. Wherever such a research programme aligns with our own research, CWI will consider taking up this role.

Finally, at a number of meetings with universities, a role of CWI as a publisher of Open Access journals was suggested. Since this aligns with CWI's initiatives in this domain, CWI has already started to explore the possibilities.

4 Organization

We adapt our organization in terms of personnel and finances to optimally support CWI's fundamental research and new national role.

4.1 Personnel

Attracting, developing and fostering talent

Research excellence starts with attracting, developing and fostering talent. In the fierce international competition for talent, we aim to recruit and foster talented people who want to investigate fundamental problems at the interface of mathematics and computer science.

Once we have succeeded in recruiting them, CWI's policy for PhD candidates and postdocs is to mentor them while at the same time giving them freedom and autonomy in their research. We have a tenure track system and a phased career path in which the development of all young researchers is central. One of our young talents recently described CWI's strategy of fostering junior researchers in her PhD thesis as follows: "CWI encourages uncompromising ideals".

Career

In general, the natural flow of a career at CWI is as follows: at CWI, scientists first focus on research for a period of ten to fifteen years, with a modest ten percent of working time spent on university teaching. After that, many move on to a university to become a full or associate professor. CWI considers this kind of mobility not as a loss, but rather as a success. Since the establishment of CWI in 1946, over 230 CWI researchers have become full-time professors at thirteen Dutch universities and numerous others have become professors abroad. Over the last decade, seventeen CWI researchers moved to universities.

Some researchers will extend their career within CWI after the initial phase. They might become a group leader in an existing group or start a new research group on an emerging topic. Still others continue their careers in industry or in the public sector.

CWI's links to Dutch universities
via part-time professorships

This map represents the situation in 2022

During their career at CWI, we support our researchers with facilities and training. Guidance for submitting research proposals for personal grants (such as an ERC grant and the NWO Talent programme) is one such aspect, and training, coaching and support in various skills, including academic leadership, are available. We also support researchers who want to start a spin-off company.

Research renewal

Because fundamental research has a dynamic character, CWI keeps a sharp eye on how to anticipate new and emerging research lines. We do this in various ways. One way is via the regular contacts CWI groups have with internationally leading researchers and institutes. For example, CWI is one of the participants in upcoming think tanks across Europe organized by the European Research Consortium for Informatics and Mathematics (ERCIM).

Another way of anticipating new and emerging lines of research is through grant applications, in which innovative ideas always play an important role. Both our external advisory bodies, the international Scientific Advisory Committee and the national Instituutsadviesraad, have a role in the research renewal as well.

Traditionally, an important part of the research renewal at CWI is the launch of new research groups and the transformation of existing ones. Over the last years, CWI has started or transformed research groups on computer security, human-centred data analytics, life sciences and health, computational imaging and machine learning.

At the level of our institute, our main mechanisms of monitoring progress within each research line are the annual research group reviews and individual performance interviews. With the four research focus areas as our main guiding principles, we regularly decide to further concentrate or prioritize the topics we work on. We also consider new and emerging research topics lines when hiring new researchers. Thus, the process of renewal and transformation of our research portfolio continues.

Scientific integrity

At CWI, everyone involved in scientific research is responsible for safeguarding scientific integrity. As NWO-I states on its website, we believe it is vitally important that scientific research is carried out with integrity, that is in a reliable, honest, careful, transparent and responsible manner.

Therefore we wholeheartedly subscribe to the Netherlands Code of Conduct for Research Integrity. This code describes the principles of scientific integrity in all stages of research, what is expected of a researcher and what are considered breaches of scientific integrity. The code distinguishes between violations of scientific integrity, questionable behaviour and minor shortcomings.

CWI intends to support its researchers by promoting an open and inclusive environment and a culture in which everyone can work together, discuss problems and dilemmas and admit to errors (blame-free reporting). CWI provides training and supervision with this in mind and guidelines for research management, such as data management.

Teaching as part of activities of CWI researchers

The approximately thirty senior CWI researchers who are part-time professors already contribute ten percent of their time to university teaching. New is that also PhD candidates, tenure trackers, other senior staff and – if they choose to do so – postdocs, will teach at a university or supervise MSc projects for ten percent of their working time. PhD candidates will, in most cases, be teaching assistants. Contributing to university education will become a regular part of CWI's work over time, although we will not make it mandatory. For most of our younger employees, it is likely to be in line with the career paths they have mapped out for themselves. If applicable, they will be given the opportunity to obtain a BKO, the didactic competence certificate for teachers in university education. The time spent on educational activities will be considered when decisions are made regarding promotion and tenure track. In terms of content, educational activities should be aligned with the research activities of the CWI researcher.

Recognition and rewards

When recruiting new talent and assessing performance, CWI considers all aspects of a researcher's work in accordance with the national policy Recognition and Rewards ('Erkennen en Waarderen'). This is not only about research but also about education, contributing to CWI's national role, impact, leadership and management.

CWI research often leads to extensive collaborations with public institutions and private companies, both as part of research consortia and through public-private partnerships (PPPs). Over time we have learned how to align such service to society with important contributions to science. We continue to pursue and reward these types of activities that serve both science and society.

CWI invests in long-term software development, as this contributes to our mission. Thus, open source software is seen as an important result of scientific research. At the same time it is CWI's special contribution to Open Science as well. The impact of CWI open source software such as Rascal, MonetDB and DuckDB is easily measured by the thousands of downloads per week. An inspirational example is the programming language Python, whose development started at CWI, which has become the most widely used programming language in the world.

Diversity and inclusion

At CWI, we believe that diversity promotes creativity, which stimulates breakthroughs in scientific research. Thus, we use every hiring opportunity to increase the diversity at our institute. We have concrete workflows and procedures to ensure diversity and inclusion are effectively addressed during the selection of scientific and support staff. Across all institutes of NWO-I the agreed target for 2025 is 25% women. In the CWI Diversity Plan 2021- 2025 we have set our targets for 2025 for PhD candidates on 30% women and for tenure trackers on 35%.

Targetgroup % women	Measurement 2021	Target 2025
Top scale 15-18	15%	25%
Subtop scale 13-14	9%	25%
Tenure Track scale 11-12	25%	35%
Postdoc scale 10-11	21%	30%
PhD	20%	30%

At CWI, personnel should not be hindered by their gender identity or expression, cultural or socioeconomic background, ethnicity, sexual orientation, age or disability. The rollout of the broad CWI diversity action plan, started in 2021, will contribute to the recognition of all talent. Our human resources department is one of the driving forces within NWO-I's LGBTI community.

Part of the diversity plan is the launching in 2022 of the new Constance van Eeden PhD fellowship to recruit more female PhD candidates. This fellowship is named after Constance van Eeden (1927-2021), who worked at CWI from 1954 to 1960 and was one of the first female PhD candidates in statistics in the Netherlands. The fellowship offers a PhD position to a talented young female student in mathematics, computer science or a related discipline, such as chemistry, biology and physics. Its aim is to bring CWI to the attention of a broader range of talented female PhD candidates who are not immediately on our radar and recruit them.

Support staff

Putting a greater emphasis on CWI's national role, as outlined in Chapter 3, not only presents our researchers with a new task. It also means more work for CWI's support staff. We will therefore invest in more staff. Furthermore, we are currently engaging all staff in creating a framework for multidisciplinary support so that our researchers can concentrate on the scientific content of our new initiatives. We note, however, that the tight labour market in the coming period is an extra challenge in the search for new personnel.

Constance van Eeden Fellowship

4.2 Finances

In the previous Strategic Plan, CWI set out an ambitious growth scenario that depended on an increase in core funding. Unfortunately, government policy in recent years has not allowed a growth in funding for fundamental research in the Netherlands. Our basic funding budget from NWO only could be increased to compensate for inflation. The budget for 2022 is 21 million euros, of which 12 million euros in basic funding. However, in 2021 the NWO board decided to reallocate the basic funding of all its nine institutes. As a result, CWI will face a reduction of €800,000 in annual core funding by 2024.

We expect that such a cut can be absorbed within our institute, given the recent and expected outflow of staff, our healthy financial reserves and the potential to generate income from externally funded projects. However, the budget cut will certainly mean reduced possibilities to invest in the new research focus areas and appoint new tenure trackers. In the coming years, CWI will need to choose wisely to strengthen the research focus areas where and when needed. The increased activity in the context of our national role, such as organizing new initiatives like semester programmes and sabbaticals, also requires investment in facilities and support staff.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5 Science for society

Our strategies on valorization, Open Science and communication play an important role in increasing the impact of CWI research on society.

5.1 Valorization

Since CWI's foundation in 1946, actively transferring knowledge to society and industry has been part of our mission. Our concept of valorization consists of three aspects:

1. Partnerships: research with partners from industry, government and civil society over a longer period of time
2. Developing software (or prototype software) and internationally recognized standards
3. Creating research-based spin-off companies

A strong feature of CWI's research environment is that our researchers develop long-term partnerships, sometimes acquiring the specific domain knowledge to eventually develop prototypes of software tools and standards for a particular scientific discipline or industry. CWI considers such software to be scientific output comparable to scientific articles and also invests specifically in scientific software developers.

The Valorization Team of CWI supports our researchers. Our spin-off incubator CWI Inc. was created to facilitate the process of creating a spin-off company. CWI has a proven track record: it has founded 28 spin-off companies and most of these still exist. That is an exceptionally high success rate. Recent examples are DuckDB Labs (services and development for the DuckDB data management system) and Photosynthetic (hardware solutions for the micro-fabrication industry).

CWI's valorization strategy for the coming years will focus on increasing CWI's visibility for its contribution to societal issues, identifying opportunities or potential partnerships and monitoring the harmonization of IP policy in cooperation agreements.

5.2 Knowledge security and intellectual property

CWI's research results include scientific articles, data, software and standards. The fundamental character of our research allows for sharing these results publicly. Moreover, our international cooperation offers our institute and the Netherlands many opportunities. At the same time, we also cannot neglect the importance of Dutch knowledge institutions being and remaining alert to possible risks related to foreign interference, misuse of knowledge or ethical issues associated with the application of research results. Therefore, the Ministry of Education, Culture and Science has issued a guideline to help us with this.

In this context, we carefully assess our so-called crown jewels on an annual basis: intellectual property that represents potentially high economic value, or in general, high societal value, and that should be protected against misuse. We take appropriate measures regarding procedures and systems to ensure that these crown jewels are delivered to society in the right form, at the right time and to the right stakeholders while strongly adhering to the basis of our valorization policies, namely maximizing value.

5.3 Open Science

Given the principle that publicly funded research should be available to the public, CWI attaches great importance to Open Science. In recent years national and international Open Science policies have come into effect that require publications and data to be shared and made available for reuse at the earliest possible stage. In line with NWO policy, we will continue to ensure these research outputs are made publicly available through CWI's Institutional Repository and other trustworthy repositories.

Publishing in immediate Open Access at a reasonable cost is becoming increasingly important. We have new ambitions in this direction for the coming years, such as a publishing platform for CWI to host community-driven scientific journals. We will continue to support other community initiatives in this area as well, such as MathOA.

Open Science has so far focused on publications, data, and software, but may well develop to include other forms of scientific information or information processes. Other recent policies also involve Open Science, such as Recognition and Rewards, and Scientific Integrity and Ethics. On these topics, CWI will continue to be alert to the translation of principles to policy and implementation, and to integrate requirements with community-developed norms and initiatives.

CWI houses the NWO-I Coordinator Data Stewardship, who leads the Digital Competence Center of NWO-I. The DCC is the centre of expertise for FAIR data and software management, and Open Science for NWO-I. It aims to bundle, expand and deploy existing activities for the nine institutes and the national network of DCCs, and represents the institutes at the national and international level. In the coming years, CWI will contribute to the NWO-I DCC with our expertise and active participation, starting with collaboration in Software Carpentries courses.

5.4 Communication

CWI wants to communicate and engage with the world outside the institute by telling and writing meaningful and understandable stories about what we do and how this affects society.

CWI scientists regularly share their expertise on current topics in newspapers and magazines, on radio and TV, for online news media, in podcasts and in public lectures. Some recent examples include telling stories about how an algorithm can help citizens better negotiate the price of a house, how AI is used for a more precise radiotherapy of prostate cancer and how the CoronaMelder app developed at the start of the corona pandemic can meet the important preconditions on privacy and security.

CWI research can be made even more visible by building a bridge between our specific research and important current societal issues, like the energy transition, climate change, digitalization, automation and cyber security. We encourage our scientific staff to engage in public debate about these issues. The starting point is the question: How can CWI researchers, with their expertise in mathematics and computer science, contribute to the demands of society? This will increase our visibility and make us more newsworthy.

With the introduction of a new website and a continuing professional online presence with relevant content through social media channels, CWI supports its mission to connect with its environment as a national institute and stimulate collaboration. We want to increase our outreach and promote collaboration with our stakeholders through current and socially relevant content (ranging from long reads to social media posts).

We will strengthen the connection with the national mathematics and computer science communities by actively drawing attention to CWI events like the semester programmes, CWI lectures and seminars in order to position CWI as a meeting place for its communities. We connect and collaborate with business by organizing tailor-made workshops and events like 'CWI in Business'. The communication department will also promote CWI's contribution to education for master's students more strongly, for example by publishing an overview of our open MSc projects.

Finally, CWI's communication department also supports the human resources department in labour market communication, like attracting and recruiting new staff.

6 Outlook

If we look ahead and express our ambitions, it is also wise to look back on what has been accomplished so far. Genuine scientific creativity requires a thorough knowledge of what predecessors have done. CWI continues to build on its legacy of scientific and societally relevant research at the interface of mathematics and computer science, inspired by new technological developments and urgent societal challenges in the age of digitalization.

Society is discovering how to best leverage the abundance of data generated by imaging devices, communication devices, business information systems and social media and more. Such leveraging requires, among other things, new imaging techniques, new optimization methods, new types of data analysis and new cryptographic protocols to ensure data security and privacy.

At CWI, we explore the fundamentals of machine learning and use it to complement new mathematical methods for modeling and analyzing the climate systems, clinical treatments, mobility systems and supply chains, to name but a few. We are also contributing to the next generation of virtual presence, creating new forms of interaction between individuals and groups, improving the quality of decision making and reducing the need for travel, with its impact on greenhouse gas emissions.

Climate change and the consequent need for an energy transition are important global challenges. By combining mathematical techniques, from for instance rare events theory and agent systems, with computer science techniques, we can contribute to their solutions.

The coronavirus pandemic has once again shown that we need a deeper understanding of uncertainty and its impact on society. By combining machine learning with probabilistic formulations and mathematical analysis, while at the same time exploiting increasing computational speed, we can understand the implications of uncertainty for strategic, tactical and operational decisions that impact the daily lives of everyone on this planet.

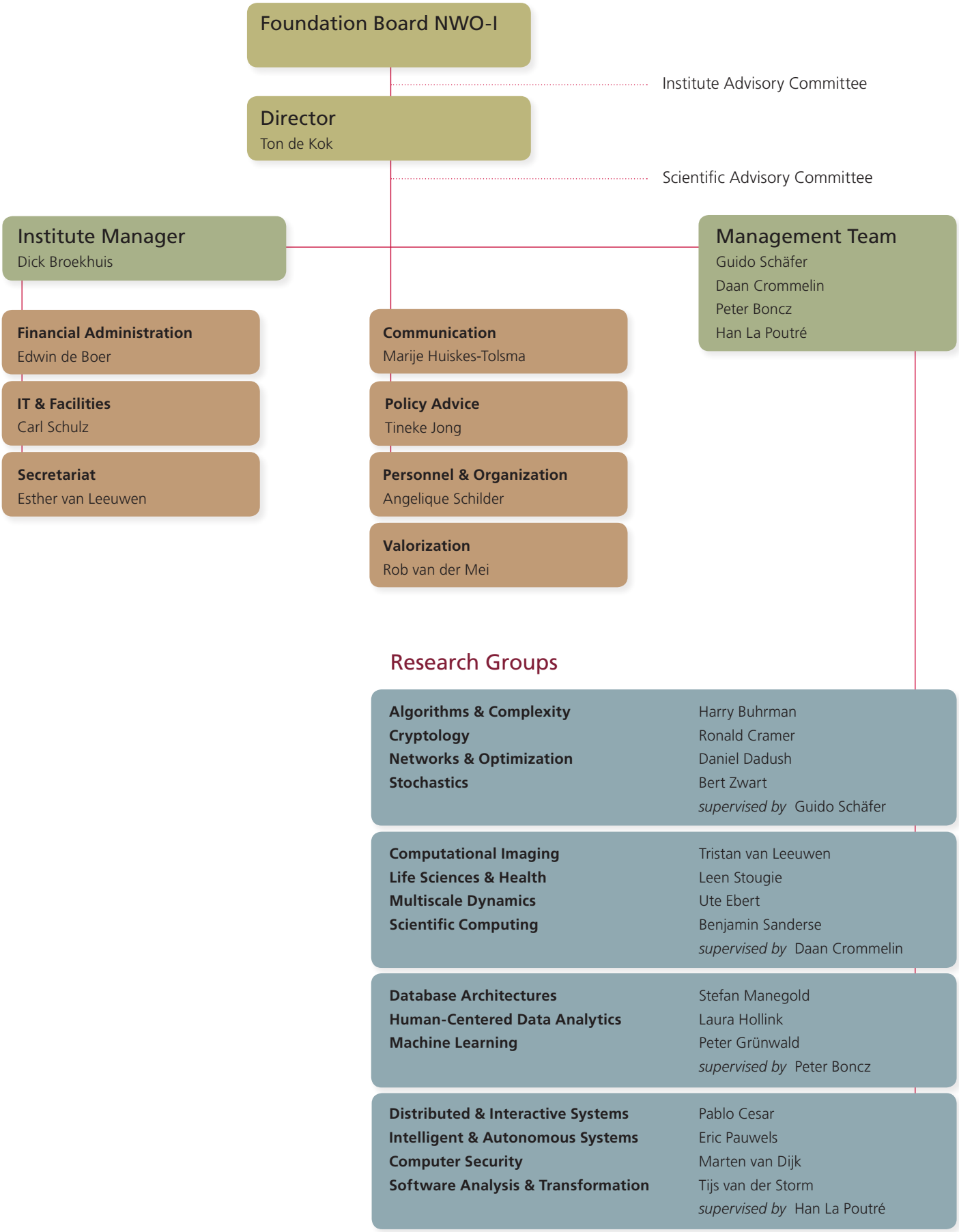
The quantum computer is about to deliver on its promise. At CWI, we contribute to this by developing the algorithms that exploit the quantum computer's unique power to solve optimization problems that yield new medicines and enable complex systems to be optimized.

More than before, CWI will fulfil its national role for the mathematics and computer science communities through leadership and support. We will collaborate with our colleagues at Dutch universities, host them for sabbaticals and workshops, define new research topics and write research proposals for funding by NWO, the European Commission, public institutions and private companies. We look forward to exciting times.

Appendixes

Appendix A

Organogram 2022



Appendix B

Research Groups

If you want to know more about the work and expertise CWI's research groups, please visit their group web page.

Algorithms and Complexity

Database Architectures

Computational Imaging

Distributed and Interactive Systems

Computer Security

Human-Centered Data Analytics

Cryptology

Intelligent and Autonomous Systems

Life Sciences and Health

Scientific Computing

Machine Learning

Software Analysis and Transformation

Multiscale Dynamics

Stochastics

Networks and Optimization

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