CWI

Centrum Wiskunde & Informatica

Self-evaluation 2011 - 2016

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Self-evaluation **2011 - 2016**

Preface

CWI is the Dutch national research institute for mathematics and computer science, with a long-standing tradition in research that is both fundamental and societally relevant. At CWI, we pride ourselves in blazing new trails in mathematics and computer science, with excellence as our number one priority. This report provides an analysis and self-evaluation of our research in the period 2011-2016, giving an overview of the content and the impact of our work. We summarize our achievements and reflect on research developments, on the research landscape, and on their significance for our strategy for the coming years. We also bring to the fore our position in (inter)national mathematics and computer science. Below, we highlight a few aspects that are core to our institute:

Quality
Research quality is our highest priority. CWI is home to top researchers in both mathematics and computer science, many of whom hold prestigious positions, fellowships and distinguished memberships (such as ACM, SIAM and IACR). Two current CWI researchers are members of the Royal Netherlands Academy of Arts and Sciences (KNAW), which is regarded as a great honour in the Netherlands. In 2011-2016, one CWI researcher was awarded an ERC Consolidator Grant, and two obtained ERC Advanced Grants.

The institute is a breeding ground for talent for universities. Since its founding 71 years ago, it has 'produced' around 200 full-time full professors. At the end of 2016, 32 senior staff members held a part-time full professorship, at 11 Dutch universities. On average, 14 CWI-trained PhD students receive their degrees from universities each year.

Dynamic ability
To initiate and accelerate novel, promising lines of research is an explicit focus in our national role. We are able to take this role because CWI is a compact, flexible and agile organization that can afford to be selective. This is illustrated by the creation of two new research groups during the evaluation period. We launched a Computational Imaging group to give focus and impetus to this field with our extensive history in numerical analysis and large-scale computation. We also initiated a Machine Learning group, combining CWI's strengths in statistics and computer science with neuroscience. We invested in infrastructure, most notably the FleX-Ray CT Scanning Lab, which was opened by the State Secretary for Education, Culture and Science, Sander Dekker, in May 2017.

Synergy
One of our greatest strengths is that we are able to exploit the natural synergy between mathematics and computer science. This is illustrated by the interdisciplinary character of our research groups, as well as by the numerous inter-group collaborations. CWI is also in an excellent position to recognize when the synergy between mathematics and computer science can contribute to other disciplines, as we have demonstrated in e.g. logistics, energy and life sciences during the evaluation period.

National role
CWI provides a unique contribution to the national research landscape. CWI is an incubator for new research fields, many of which will be transferred to universities, spin-off companies or industry. Furthermore, CWI encompasses both fundamental and application-oriented research within one institute, which is rare in our field.

Our national role is illustrated by many collaborations with colleagues at universities and other scientific organizations. For instance, CWI is a co-applicant of the national consortium

NETWORKS. Recently, the QuSoft institute, initiated in 2015 by CWI, the University of Amsterdam and the VU University Amsterdam, has been instrumental in acquiring national Gravitation funding for long-term research into quantum software together with partners in Leiden and Delft.

We house several external parties in mathematics and computer science, including the national platform for mathematics (PWN), COMMIT (up to 2014) and the Royal Dutch Mathematical Society. We frequently host meetings of these and other external parties, thus welcoming a large portion of Dutch mathematics and computer science researchers and policymakers throughout the year.

Part of our mission is conveying new knowledge to society at large, and to industry in particular. CWI initiates public-private partnerships and spins off new high-tech companies to achieve this. CWI produced 24 start-up companies up to December 2016, three of which were launched during the evaluation period.

Ambition

During the initial years of the evaluation period 2011-2016, a shift took place in Dutch government research policy. Funding schemes for mission-driven research were initiated, while funding for curiosity-driven fundamental research substantially decreased. CWI initiated a new strategy for acquiring funding from industry. However, looking ahead to the future, we feel that national research policy should not overly favour short-term research at the expense of fundamental research. The importance of fundamental research is stressed in our strategy update.

We believe that in the upcoming years, CWI can continue to fulfil its mission with a healthy balance: committing ourselves to fundamental research, maintaining our ties with industry, and providing a mathematical and computer science foundation to research that contributes to solutions to major societal challenges.

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1 Introduction to CWI

1a Introduction

Mission

Centrum Wiskunde & Informatica (CWI) is the Dutch national research institute for mathematics and computer science[1]. It is one of the institutes of the Netherlands Organisation for Scientific Research (NWO). Our mission is to conduct pioneering research in mathematics and computer science, generating new knowledge in these fields and conveying it to society at large, and to industry in particular.

1 For the Dutch word 'Informatica' we use the English translations 'computer science' and 'informatics'.

Vision

Fundamental, curiosity-driven research is the base of our mission. At the same time, our research is strongly motivated by societal relevance, seeing that in today's digital world mathematics and computer science underpin every aspect of society. CWI conducts long-term research in these two vital fields, inspired by real-life issues such as energy, climate change, healthcare and security.

Knowledge transfer and valorization[2] play an increasingly important role in our work. We have an excellent national and international network and we collaborate with public and private partners. We nurture young research talent and foster spin-off companies. We also make our innovative software tools available to researchers, companies and the general public.

2 We define valorization as including knowledge utilization.

Objectives

Our objectives are to:

1 conduct advanced research of the highest level, tackling important questions of scientific and societal relevance, and initiating new lines of long-term research;
2 develop talent, both of junior researchers (objective is a PhD degree) and of senior researchers (objective is a full professorship);
3 be a centre and meeting point for contacts within academia, industry and government;
4 play a nationally leading role in science policy in the fields of mathematics and computer science.

CWI periodically re-evaluates its strategy to ensure that it stays true to its mission, while anticipating and adapting to scientific and societal developments. In section 1c we elaborate on our current strategy and the realization of our strategic targets in the 2011-2016 period.

1b Organization

CWI is home to 177 researchers (161.6 full-time equivalent (fte) in 2016). PhD candidates make up a little over 40% of the research staff in fte. The CWI staff also includes visiting researchers[3] (6.4 fte in 2016) and 40 support staff members (36.7 fte in 2016). For more information on the institute's composition between 2011 and 2016 please refer to appendix C.

3 Scientific staff or PhD students assigned to CWI and funded by external sources.

Research at CWI is organized into fifteen research groups, many of which consist of both mathematicians and computer scientists. Please refer to appendix G for a description of each research group.

- Algorithms and Complexity;
- Computational Imaging;
- Cryptology;
- Database Architectures;
- Distributed and Interactive Systems;
- Formal Methods;
- Information Access;
- Intelligent and Autonomous Systems;
- Life Sciences;
- Machine Learning;
- Multiscale Dynamics;
- Networks and Optimization;
- Scientific Computing;
- Software Analysis and Transformation;
- Stochastics.

The CWI Governing Board advises and monitors the general director. Jos Baeten, director since 2011, and CFO/COO Dick Broekhuis form the directorate, which is responsible for the day to day management of the institute and the implementation of (research) policies. The general director bears final responsibility. The directorate is supported by the Management Team. The three scientific staff members of the Management

Team each supervise the leaders of five research groups, monitoring their strategic results. A Scientific Advisory Committee advises in matters of strategy and long-term planning.

Up to 2016, theme coordinators monitored valorization activities within the institute. In 2016, a new body was established as part of our updated valorization strategy. The Valorization Team (VT) monitors valorization opportunities and is authorized to initiate new valorization activities. The VT consists of three scientific staff members: the Manager Research & Development and two Coordinators Partnerships & Transfer. They are supported by a Valorization Manager.

The CWI support departments are Communication, Financial Administration, Information and Documentation, IT and Facilities, Personnel and Organization and the Secretariat. Some of our support departments also have a strategic role. Communication is responsible for positioning CWI in the media and with stakeholders, and manages the W3C Benelux Office. Information and Documentation strongly advocates open access. It also discloses CWI research through our repository and manages an extensive library on mathematics and computer science. Personnel and Organization has a strategic role in developing policies around diversity and scientific integrity. The department supports our researchers in their career paths.

For an overview of the organization, please refer to the organizational chart in appendix A.

Funding

CWI has three types of funding: basic funding by NWO, external funding and bonus funding. About two-thirds of our budget consists of basic funding, which roughly covers the fixed costs of the institute (the salaries of permanent staff plus the fixed overhead). Growth of the institute with temporary staff is paid from external funding and/or bonus funding. The following developments can be noted in 2011-2016:

- **Basic funding**. CWI accommodated a decrease in basic funding of approximately 800 k€, as well as the lack of compensation for inflation until 2015. CWI was able to maintain its policy to balance basic funding and costs by critically reviewing the fixed costs of the institute, and reducing these to a minimum. Since 2015, compensation has been provided for inflation and collective salary advancements. Per 2016, 500 k€ additional basic funding was awarded by NWO for strengthening CWI's role in public-private partnerships. Overall the basic funding (not including inflation compensation) is about the same in 2016 as it was in 2011, but CWI's mission has been expanded to include public-private partnerships.
- **External funding**. CWI acquires external (project) funding via national and international programme competitions and contract research. Funding opportunities have been varying, but CWI has continuously been able to secure both national and European funding (see the total level of research grants and contract research in appendix D). We have successfully applied ourselves to increase collaboration with industry in public-private partnerships.
- **Bonus funding**. CWI received bonus funding from NWO for strategic purposes. In 2006 and 2012, CWI was awarded a bonus for the six-yearly evaluations with 'excellence' as a result (2.2 M€ and 1.7 M€ respectively). In 2009, a one-time impulse (2.7 M€) was made available. CWI invested these funds in new activities, such as starting a life sciences research group and initiating projects that enhanced internal collaboration and connected to external partners. In 2014, NWO granted CWI 1 M€ to invest in public-private partnerships in ICT research. CWI allocated these funds to projects that generated the same amount in co-funding by industrial partners.

1c Strategy

In 2012, we composed the 'Strategisch Plan 2013-2018': a strategic plan for CWI to maintain our excellent status, to better align ourselves with our changing environment and to tackle the issues brought up by the 2011 evaluation committee. We have made progress in realising our strategic goals, and we are facing new changes in our environment. By updating and reformulating our strategy (Update CWI Strategy 2017, appendix O), we aim to better equip ourselves for the coming years. The strategy update can be considered a preliminary version of the strategy that will go into effect in 2019 (Strategic Plan 2019-2024). We will later incorporate the recommendations that follow from the current evaluation in the new strategic plan, and the strategic plan will be agreed upon by our governing board before it comes into effect.

1c1 Strategy update

Our 2017 strategy update (appendix O) focuses on five strategic targets, in keeping with our mission and objectives:

1 explore new, promising research areas;
2 increase our research volume through extra funding;
3 safeguard the balance between fundamental and application-oriented research;
4 create an optimal research environment;
5 optimize research integrity, open access and open data.

1 Explore new, promising research areas

To further advance our role in the Dutch research landscape as birthplace and accelerator of new research areas in the Netherlands, we invest in novel, promising lines of research. We hire tenure track researchers in new areas whenever a position becomes available, and we aim to accelerate this process by creating new positions. In line with developments in (inter)national research policy, our core strengths and to redress the balance of fundamental and application-oriented research, we have selected the following cross-cutting themes, and will invest along these lines:

Computation. Computational science is often called the third scientific paradigm, next to theory and experimentation. With our extensive history in numerical analysis and large-scale computation, CWI can play a leading role in this field. We will invest in computational science for circular economy and sustainability, including the transition to renewable energy and smart cities. We also see opportunities in computational plasma and high voltage technology, computational life sciences and computational imaging. In 2016, we launched a new research group that focuses on the latter and we invested in hardware for this field, most notably the FleX-Ray CT Scanning Lab which was opened in May 2017.

Data. Big data is a crucial part of science and society. As one of the early pioneers in data science, CWI has a continued commitment to this theme. CWI invests in fundamental research into algorithms, systems and methodologies needed for data science. We research novel data systems architectures that help data scientists perform large-scale data analytics. In 2016, we launched a research group dedicated to Machine Learning. We strive to strengthen the connection between data and computation through big data simulation, and we see opportunities in social machines research and in applying a big data approach in life sciences.

Software. The quality of software is increasingly important to society, as software becomes a crucial aspect of our daily lives and is often the driving force behind innovations. CWI is the birthplace of fundamental software science. We currently work on verification, certification and research on software usage, design and transformation. We intend to further develop our research in software analytics, legacy problems, domain-specific programming languages and model-driven engineering.

Networks. CWI can provide a fundamental mathematical and computer science contribution to network research. Currently, CWI researchers play a leading role in NWO programmes concerning logistics networks and energy networks. We are also a member of a major NWO Gravitation research programme, NETWORKS, that will enter its second phase in 2018. We are going to develop our research in various types of networks, including logistics networks, enterprise networks, biological networks and software-defined networks. We will work on e.g. the analysis and optimization of large networks and network security.

Quantum. We are a long-term pioneer in the area of quantum computing, which currently puts us in the position to play a leading role in the quantum revolution. We aim at growth for QuSoft, the research centre for quantum software that CWI launched together with the University of Amsterdam and VU University Amsterdam, in 2015. We strive to develop QuSoft into an Advanced Research Centre and are working on external funding to achieve this, including an EC Quantum Flagship and public-private partnerships. In May 2017, a Gravitation grant (18.8 M€) was awarded to a CWI-led research programme, the Quantum Software Consortium.

Under the umbrella of these cross-cutting themes, we plan to invest in the following upcoming research topics:

- **Digital finance and blockchain technology**. Blockchain technology will be a disruptive technology. CWI has the potential to become a major international player in blockchain technology research. We have assembled a multidisciplinary group of experts on this topic, and we have initiated collaborations with several banks.
- **Control theory**. Control theory is of great importance to the high tech industry. In the Netherlands, current research in this field is mainly of an applied nature. This is especially the case for hybrid systems (cyber-physical systems). CWI could provide a substantial contribution with our fundamental research approaches, for instance in the study of hybrid systems by combining control theory research with our formal methods research.
- **Security and privacy**. The ongoing digitization of services makes security and privacy issues increasingly relevant. We are already investigating this topic through cryptography, and are exploring the possibilities for a broader research approach that includes various other cybersecurity techniques.

2 Increase our research volume through extra funding

Mathematics and computer science are essential tools to master and improve the increasingly complex digital world. The need to increase knowledge in these fields is widely acknowledged, on a European level by the Horizon 2020 Work Programme 2018-2020, and on a national level by the 2014 Deloitte report 'Mathematical Sciences and their value for the Dutch economy', as well as the Five Point Plan (Vijfpuntenplan) developed by the Dutch IT research platform (IPN) which urges extra investments to keep the leading position of the Netherlands in IT and digital science. To match the growing importance of our research areas, we aim to accelerate the growth of mathematics and computer science in the Netherlands. We will do this by continuously demonstrating the significance of these disciplines, creating extra research positions, and attracting and developing (inter)national talent.

In light of the upcoming portfolio analysis of Dutch research institutes, and the call by the Knowledge Coalition for an increase in governmental spending on research, we will demonstrate the increasing role of mathematics and computer science. We aim at an increase of basic funding, as well as personal grants and public-private partnerships. To increase our success rate in personal grant applications, we support our researchers in their application process. In 2016, we formed a Proposal Guidance Committee, which better coordinates these efforts and provides extensive (writing) support and coaching to our researchers throughout the grant application process.

In line with our intended growth we will continue to apply ourselves to attracting research talent, for instance by closely collaborating with universities, and through the efforts of CWI researchers offering education courses at universities and inter-university research schools.

3 Safeguard the balance between fundamental and application-oriented research

We will continuously safeguard the balance between application-oriented and fundamental research. Curiosity-driven and long-term research has an intrinsic value and is essential for bringing about ground-breaking innovations. Therefore, CWI will continue to have fundamental research at its base. We ensure that our researchers can commit to a long-term research strategy, without being forced to meet pre-determined application targets. However, we will also continue our efforts to increase valorization and visibility of our research results. To seize valorization opportunities at all levels of our institute, we provide valorization support to our research staff through the valorization team that we established as part of our current strategy. We will continue to explore opportunities to work with partners from society and industry, to provide software tools, to transfer knowledge and to found spin-off companies. To ensure transparency and public accountability, and to give the general public insight into our research, we will continue to invest in external communication.

4 Create an optimal research environment

The success of our institute primarily depends on our researchers. To be able to meet our strategic targets, we need the best researchers and we need to provide them with an optimal research environment. A pleasant working environment is also an essential requirement for attracting a diverse research staff (chapter 8).

We support both our junior and senior researchers to get the most out of their job. We coach our junior researchers as they enter the challenging and demanding world of scientific research. We maintain

a high quality support staff, and we continue to provide support for, e.g., writing research proposals, getting into contact with external collaboration partners and publicizing research results. The increased cooperation with NWO and the other NWO institutes provides an opportunity to further improve the support for our researchers.

5 Optimize research integrity, open access and open data

We play an active part in the national and international open access movement. In recent years, a broad movement, initiated by the Ministry of Education, Culture and Science, NWO and the Royal Netherlands Academy of Arts and Sciences, encourages open access of publicly-funded research results. As of December 2015, NWO requires that all publications resulting from NWO funding are open access. Within our own institute, CWI strives to optimize an open scientific culture, including research integrity, open access and open data (chapter 7).

1c2 Realisation of strategic targets in the evaluation period

Our course is based on strategy documents, currently our Strategic Plan 2013-2018. The five strategic targets in this plan were based on our vision, developments in science and society and on the recommendations of the 2011 evaluation committee. For each target, we formulated an action plan, which we periodically reflected upon to monitor our progress. In this section we give a brief description of the strategic targets we achieved in the evaluation period. More information can be found in appendix O.

1 Take advantage of available funding opportunities to anticipate the changes in research funding and the research landscape

The trends of increased competition for fundamental research funding and the growing importance of societal relevance of research results have continued. Funding for fundamental research is harder to obtain and is mostly concentrated in highly-competitive personal grants (NWO Innovational Research Incentives Scheme, ERC Grants), thematic research programmes and projects, and funding for large consortia, such as NWO Gravitation. There is also a funding shift towards public-private partnerships and societally-relevant research.

We have received less basic funding, and competition for fundamental research funds has increased. However, we succeeded in acquiring more earmarked funding from NWO and national personal grants. There has also been a marked increase in public-private partnerships over the past years (see appendix L), which has allowed us to keep our research volume intact. In 2016, we had not yet achieved our ambition concerning European personal grants (ERC Grants), but we feel that the quality of our researchers is competitive, and that by providing more professional assistance with proposal-writing, our success rate can increase substantially. We are proud to report that in March 2017, CWI's Ronald Cramer was awarded an ERC Advanced Grant from the 2016 round.

2 Determine and exploit new strategic, societal themes to guide our research

From 2013 to 2016, our focus was on the research themes Software, Information, Life Sciences, Logistics and Energy. The themes served as a guideline for strategic decisions, such as areas in which to appoint new tenure track researchers, and potential valorization opportunities. The themes also provided windows onto our research for external, non-academic parties, which allowed us to more easily reach out to potential industrial partners. In 2016, the cross-cutting themes were updated to: Software, Data, Networks, Computation and Quantum. These themes reflect the developments in CWI's focus and our environment. Most prominently the focus has broadened to not only address the national top sectors but also the Dutch National Research Agenda, published in 2016.

3 Intensify valorization to emphasize the societal relevance of our research

In 2011-2015, theme coordinators monitored valorization activities within their theme. As of 2016, our new Valorization Team (VT) monitors all valorization activities within the institute, keeps track of new funding and partnership opportunities and mobilizes CWI researchers to act upon these opportunities. The team has a budget allocated for valorization efforts, and advises the directorate on valorization matters. Awareness of societal relevance has grown within the institute and this has resulted in several new collaborations and applications. We were successful in launching new partnerships, and we established three spin-off companies in the 2011-2016 period (see chapter 3).

4 Strengthen our role as national institute and centre for mathematics and computer science

We have made progress in expanding our role as national institute and centre for mathematics and computer science activities in the Netherlands by strengthening our ties to the Dutch universities and industry and expanding our international network. We house various relevant external parties, such as COMMIT (2011-2016), a large programme that brought together scientific research, non-profit organizations and IT companies within the nine top sectors in the Netherlands, and the national platform for mathematics 'Platform Wiskunde Nederland'.

Internationally and nationally, CWI continues its role to accelerate developments in open access. CWI publications are listed in the publicly accessible CWI repository, and we stimulate our researchers to publish all their results open access. CWI is involved in creating an open access foundation for mathematics, MathOA, of which CWI director Jos Baeten is president. Baeten also played a leading role in initiating an open access policy within ERCIM, the European Research Consortium for Informatics and Mathematics.

5 Optimize our internal organization to be able to effectively implement strategic decisions

In line with the advice from the 2011 evaluation committee, as of January 2013 we focus on the group as the main organizational unit, thus being able to more dynamically explore new research fields. We have revitalized our strategic cycle to improve our strategic awareness. We turned our strategy into an action plan and monitored its progress in our annual Institute Plans. The management team holds an annual retreat to discuss the current status of strategic issues in depth. Important issues are discussed in regular meetings with our group leaders. We now feel confident that our organization can effectively implement strategic decisions, which gave us reason to no longer include this target in the Update CWI Strategy 2017.

1d Positioning and benchmark

CWI has a favourable location at Amsterdam Science Park, a booming ecosystem with the largest concentration in science research and education in the Netherlands and one of the largest in Europe. It is a hub for research, innovation and entrepreneurship because of its research institutes, the University of Amsterdam Faculty of Science, and some 130 companies. It houses the world's largest data transport hub AMS-IX (the digital port to Europe), the Netherlands eScience Center, SURFsara and the national supercomputing centre - all of which CWI has close ties with.

National positioning

CWI is one of the 24 national research institutes under the aegis of NWO and KNAW spanning the spectrum of research in the Netherlands. As national NWO institute, CWI fulfils a distinct role in the Dutch research landscape. CWI is home to a significant number of top researchers in both mathematics and computer science, which grants us the unique opportunity to exploit the natural synergy between the two. This is illustrated by the interdisciplinary character of some of our research groups, as well as the numerous intergroup collaborations. CWI is also in a unique position to recognize when the synergy between mathematics and computer science can contribute to other disciplines, such as life sciences.

CWI encompasses both fundamental and application-oriented research within one institute, which is rare in our field. The nature of the institute allows for flexibility, while the consistency of basic funding enables long-term lines of research. CWI distinguishes itself from a university department in terms of priorities and organization. CWI researchers contribute to higher education by offering specialized courses in various national education networks, but CWI's primary focus is on research. CWI is a compact, flexible and agile organization that can afford to be selective. New topics are brought into development, with room for high-risk, long-term research, without the pressure for short-term impact that characterizes applied research laboratories. This allows CWI to provide continuity, but also to be an incubator for new research fields, some of which will eventually be 'phased out' or 'transferred' to universities. Regarding technology transfer, CWI initiates public-private partnerships and has an incubator role with its creation of new high-tech companies that bring scientific results to society. CWI produced 24 start-up companies up to December 2016 (see appendix M).

The institute is a breeding ground for talent for universities. Since its founding, it has 'produced' around 200 full professors. At the end of 2016, 34 senior staff members held a professorship, at 11 Dutch universities. Of these, 32 held a part-time full-professorship and 2 held an associate professorship. On average, 14 CWI-trained PhD students receive their degrees from universities each year.

CWI is a member of national consortia such as the Gravitation programme NETWORKS, Data Science Platform Netherlands (DSPN) and Big Data Alliance (BDA). CWI researchers head major thematic NWO programmes on the subjects of logistics and energy. We are involved in large national programmes such as COMMIT/ and COMMIT2DATA, and in the Dutch National Research Agenda. CWI scientists serve on the boards of three of the four national mathematics clusters. CWI also took the initiative to unite the Dutch academic software engineering community by launching the VERSEN association. CWI is the administrative home of VERSEN, and houses its annual conference.

International positioning

The synergy achieved by accommodating mathematics and computer science under one roof, and the balance of fundamental and application-oriented research, leads to CWI's established position in the international research landscape. CWI's aim is to function at a scientific quality level comparable with the best institutes and universities in its fields worldwide, such as the Inria institute in France, the Max Planck Institutes in Germany, and the National Laboratories in the U.S., albeit at a smaller scale, in keeping with the size of the Netherlands (and its research budget).

CWI's international position is reflected in the number of CWI staff participating in distinguished international bodies and committees (see appendix G). CWI's prominent role is further demonstrated by its being a founding member of ERCIM, and a long-term participant in ERCOM. CWI supplies the current president of Informatics Europe, and is a core partner in EIT Digital, the European consortium of top research institutes and leading industry partners that aims to accelerate innovation in Europe. In 2016, Inria and CWI formed an Inria International Lab together. In 2013, CWI joined research network LIAMA, the Sino-European Laboratory in Computer Science, Automation and Applied Mathematics, as one of the founding members. CWI leads a European network of imaging specialists, EXTREMA, which works on the next generation of imaging techniques to advance science and industrial R&D. CWI provides the Dutch editor of the quarterly magazine ERCIM News (11,500 subscribers). Finally, CWI coordinates the Benelux office of the World Wide Web Consortium (W3C), the organization responsible for setting standards on the web.

Benchmark to other institutes

We performed a limited benchmark analysis with three institutes. These institutes were chosen as peers since their strategy, mission and organizational structure resemble that of CWI. The Max Planck Institutes have a different organizational structure, so they were not included. The three institutes that are part of the benchmark analysis, share CWI's strong focus on excellent science with a transfer role to society, embedded in a research landscape with both academia and industry:

- Inria, France, mathematics and computer science, 205 M€ turnover in basic and external project funding, 2,600 fte researchers;
- Simula, Norway, computer science, 16 M€, 145 fte;
- WIAS, Germany, mathematics, 13 M€, 123 fte.

In the table below the names of these institutes have been anonymized. The table shows the averaged h-index of all tenured and tenure-track researchers who were employed at CWI during (a part of) the 2011-2016 period. For researchers with a Google Scholar profile, the h-index was taken from Google Scholar; for those without, we used Harzing's publish-or-perish programme (reference date March 2017). The list of researchers from Simula and WIAS is based on the staff pages on their websites. Because we had no full list of Inria employees available, we only took those researchers with a LinkedIn profile that says 'currently works at Inria'. Since this is a source of potential bias, we redetermined the CWI average h-index in the same way and this returned the same outcome. Please note, the table gives a rough indication only. The data used for the benchmark analysis can be made available upon request.

	Institute A	Institute B	CWI	CWI mathematics	CWI computer science	Institute D
Average H	20	22	25	23	27	18
Spread H	7.1	9.1	9.2	9.0	8.6	9.0

Further benchmarking has been carried out by comparing the turnover, staff size and scientific output of the institutes. We collected data through open access archives, annual reports and the institutes' websites. Using these data, we calculated the following indicators:

- funding per scientific output (refereed publications and books, excluding PhD theses);
- PhD theses per fte scientific staff (senior staff, tenure trackers and postdocs);
- scientific output per fte scientific staff.

The indicators have been calculated for the year 2015, a year in which output for the other institutes was quite high compared to previous years, whereas CWI's output was average.

	Institute A	Institute B	CWI	Institute D
Funding / total scientific output	63 k€	67 k€	55 k€	70 k€
PhD theses / scientific staff	0.15	0.26	0.18	0.11
Total scientific output / scientific staff	3.2	3.9	4.2	2.1

Of course each parameter is dependent on local conditions, such as salary levels, length of PhD studies etc. Still, we can conclude that CWI is reasonably efficient (first row, cost of a publication), produces an average number of PhDs, and that CWI produces a sizable number of publications.

2 Research quality

2a Performance indicators

This self-assessment is done by considering a number of performance indicators. Below, we will describe and explain which research quality performance indicators correspond with the profile of our institute and thus can be best used to evaluate our performance.

The main research products of CWI are scientific publications: refereed journal articles, articles in conference proceedings, book chapters, books and PhD theses. Of increasing importance are (open source) software projects and products, and contributions to the development of web and multimedia standards (see chapter 3).

Metrics based on Web of Science (or other citation indexes) are meaningless in many branches of computer science, as top ranked publications often appear in conference proceedings rather than journals. Therefore, our assessment is based on Google Scholar, as this has a better coverage of publication venues and institutional repositories.

We chose not to use the impact factor of a journal as a performance indicator. The impact factor is not an adequate measure of the quality of a publication, since a high-impact journal can contain low-impact articles[4]. Also, in line with our open access policy, we discourage publication in journals with high subscription rates. In our view, the only way to properly assess the quality of our output is by peer evaluation. In appendices F and G, each research group lists its top publications. Some of these are in high impact journals, some are not. In the following section, we also chose to use citation count as a quality measure for publications. As a quality measure for researchers, we use h-index. To evaluate our up-and-coming researchers, we also use h-index since 2012 as a performance indicator.

4 Nature 535, 210–211 (14 July 2016) doi:10.1038/nature.2016.20224.

In the following section we highlight notable research products from the 2011-2016 period and their use and recognition by peers. For a full overview we refer to appendices B, E, F and G.

2b Evaluation of research quality

Research products for peers

In 2011-2016 we published 1,711 papers, 170 software products, 68 PhD theses, 64 web and multimedia standards, 17 books and 78 book chapters. For a full overview we refer to appendix E. This output rate is comparable to that in the previous evaluation period, with a slight shift towards more software output and fewer book chapters. We are satisfied with these results.

Among these publications were numerous high-impact discoveries. We would like to highlight a few publications, which we regard as some of our most important. Members of CWI's

- Computational Imaging group succeeded in 3D-imaging of nanoparticles (2011, Nature);
- Cryptography group analysed the Flame malware and provided detection software (2012), and proved the weakness of SHA-1 (2015);
- Networks and Optimization group announced the proof of Rota's Conjecture, settling a famous open problem in discrete mathematics (2014, Notices of the AMS);
- Life Sciences group had a major role in discovering sequence variation in the human genome (2014, Nature Genetics; 2016, Nature Communications);
- Multiscale Dynamics group modelled lightning inception by cosmic particles (2015, Physical Review Letters);
- Software Analysis and Transformation group analysed the relationship between CC and SLOC in Java and C (2015, Journal of Software);
- Algorithms and Complexity group used quantum techniques to resolve a long-standing open combinatorial optimization problem (2015, Journal of the ACM);
- Formal Methods group discovered and repaired a fundamental bug in the Java sorting library (2015).

An overview of more major publications can be found in appendices F and G.

Use of research products by peers

Our research products are widely used by peers, as demonstrated by the number of citations and the number of software downloads. To illustrate the impact of our scientific work, we list our top ten citation counts of books and peer reviewed articles published in 2011-2016, as measured by Google Scholar in February 2017. Reprints of books are excluded from this list.

1 S. van Aert, **K.J. Batenburg**, M.D. Rossell, R. Erni, G. van Tendeloo. Three-dimensional Atomic Imaging of Crystalline Nanoparticles, Nature 470 (7334), 374-377, 2011, [339][5];
2 **B. Sanderse**, S.P. Pijl, **B. Koren**. Review of Computational Fluid Dynamics for Wind Turbine Wake Aerodynamics, Wind energy 14 (7), 799-819, 2011, [232];
3 Genome of the Netherlands Consortium (with **A. Schönhuth**). Whole-genome Sequence Variation, Population Structure and Demographic History of the Dutch Population, Nature Genetics 46 (8), 818-825, 2014, [177];
4 M. Muller-Lennert, F. Dupuis, O. Szehr, **S. Fehr,** M. Tomamichel. On Quantum Rényi Entropies: a new Generalization and Some Properties, Journal of Mathematical Physics 54 (12), 122203, 2013, [168];
5 S. Fiorini, S. Massar, S. Pokutta, H.R. Tiwary, **R. de Wol**f. Linear vs. Semidefinite Extended Formulations: Exponential Separation and Strong Lower Bounds, Proceedings of 44th ACM Symposium on Theory of Computing, 95-106, 2012, [168];
6 C. Bizer, **P. Boncz**, M.L. Brodie, O. Erling. The Meaningful Use of Big Data: Four Perspectives - Four Challenges, ACM SIGMOD Record 40 (4), 56-60, 2011, [159];
7 **K.J. Batenburg**, J. Sijbers. DART: a Practical Reconstruction Algorithm for Discrete Tomography, IEEE Transactions on Image Processing 20 (9), 2542-2553, 2011, [151];
8 **S. Idreos**, **F. Groffen**, **N. Nes**, **S. Manegold**, **S. Mullender**, **M. Kersten**. MonetDB: Two Decades of Research in Column-Oriented Database Architectures, IEEE Data Engineering Bulletin 35 (1), 40-45, 2012, [128];
9 **W.J. Palenstijn**, **K.J. Batenburg**, J. Sijbers. Performance Improvements for Iterative Electron Tomography Reconstruction Using Graphics Processing Units (GPUs), Journal of structural biology 176 (2), 250-253, 2011, [128];
10 L.A. Grzelak, **C.W. Oosterlee**. On the Heston Model with Stochastic Interest Rates, SIAM Journal on Financial Mathematics 2 (1), 255-286, 2011, [110].

5 Number of citations.

We manage a number of major open source software products. MonetDB for column-store databases was downloaded 500,000 times in 2011-2016. Most notably, MonetDB is used for managing astronomics data in large-scale international projects such as LOFAR and SKA. Our meta-programming language Rascal had an estimated user base of 1,000 in 2011-2016. Rascal is used internationally in education and research, including various EU research projects. It is also being applied in forensics, finance, legal systems and gaming. Ambulant Player, a rich media player and authoring suite, was downloaded 60,000 times in 2011-2016. Other examples of software products frequently used in academia are the open-source ASTRA toolbox for tomography, which was created in collaboration with the University of Antwerp, and the counter-cryptanalysis for collision detection in MD5 and SHA-1. CWI software products also include Virtual Leaf, an open-source software framework for modelling plant development, Squint, an advanced method for prediction with expert advice, and numerical codes for multiscale plasma dynamics.

Additionally, we actively contribute to the development of web and multimedia standards such as a new point cloud compression contributed to MPEG, HTML, XForms and Xforms 2.0, RDFa 1.1 and OpenDocument 1.2, as well as standards for digital publishing.

Academic reputation

Our researchers receive many honours and grants for their work. Personal grants awarded in the 2011-2016 period include 12 NWO Veni grants, 2 NWO Vidi grants and 2 NWO Vici grants. We have seen an increase in the number of these national grants awarded to CWI in the last few years. CWI researchers were also awarded one ERC Consolidator Grant (Ronald de Wolf) and two ERC Advanced Grants (Lex Schrijver, and recently, in the 2016-2017 call, Ronald Cramer).

We acquired three tenure track positions through the Dutch Mathematics clusters ('wiskundeclusters'). CWI is a member of the Gravitation project NETWORKS, and coordinates the Gravitation funded Quantum Software Consortium (call 2016, awarded in 2017). We were also awarded three NWO Top Module 1 grants (Monique Laurent, Krzysztof Apt and Peter Grünwald). In 2011-2016, 29 European projects in FP7 and Horizon2020 were ongoing at CWI. The 2016 CWI project proposal GridFriends was the best-ranked proposal of the first ERA-NET call on smart energy. Finally, we are involved in one current EC Flagship project (The Human Brain Project), with another one planned (Quantum).

Our researchers hold various prestigious positions. 64% of our tenured researchers is a part-time professor at one of the Dutch universities. Lynda Hardman is the current president of Informatics Europe. Ronald Cramer and Lex Schrijver are members of the KNAW (Cramer was appointed in 2013). Jos Baeten and Ute Ebert are members of the Royal Holland Society of Sciences and Humanities (KHMW). In 2016 Martin Kersten was named as ACM Fellow and David A. Shamma was named ACM Distinguished Member; in 2014 Lynda Hardman was named an ACM Distinguished Scientist, and in 2013 Ronald Cramer became IACR Fellow. In 2011, Schrijver received an honorary doctorate at Eötvös Loránd University.

Many of our researchers are part of scientific committees and editors of scientific journals, including top publishers such as ACM, IEEE and SIAM (see appendix G).

In 2011-2016, major prizes received by CWI researchers included the EURO Gold Medal 2015 (Lex Schrijver), the ACM SIGMM Award for lifetime achievements in multimedia research (Dick Bulterman), the IEEE TCSE Software Engineering Distinguished Service Award for lifetime achievements in software engineering (Paul Klint), the Humboldt Research Award for researchers with a major impact in their discipline (Peter Boncz), the SIGMOD Edgar F. Codd Innovation Award and the ACM SIGMOD Systems Award (Martin Kersten), the ERCIM Cor Baayen Award for the most promising young researcher in computer science and applied mathematics in Europe (Stratos Idreos), the Van Dantzig Prize for the best Dutch researcher in statistics and operations research in the past five years (Bert Zwart), twice the Stieltjes Prize for the best mathematics thesis in the Netherlands (Benjamin Sanderse and Jop Briët), the 2016 Internet Defense Prize (Leo Ducas), the Google Security Privacy and Anti-abuse Applied Award and the Van Marum Prize 2013 for the best young researcher in natural science and technology in the Netherlands (Marc Stevens), the BioSB Young Investigator Award for the best PhD thesis in the field of bioinformatics and systems biology (Mohammed El-Kebir) and the five-yearly Andreas Bonn Medal for original work in natural sciences and medicine (Jop Briët).

In 2011, Jan Karel Lenstra and Jan Verwer were named Knight in the Order of the Netherlands Lion. Herman te Riele and Paul Klint were named Officer of the Order of Orange-Nassau, in 2011 and 2013 respectively.

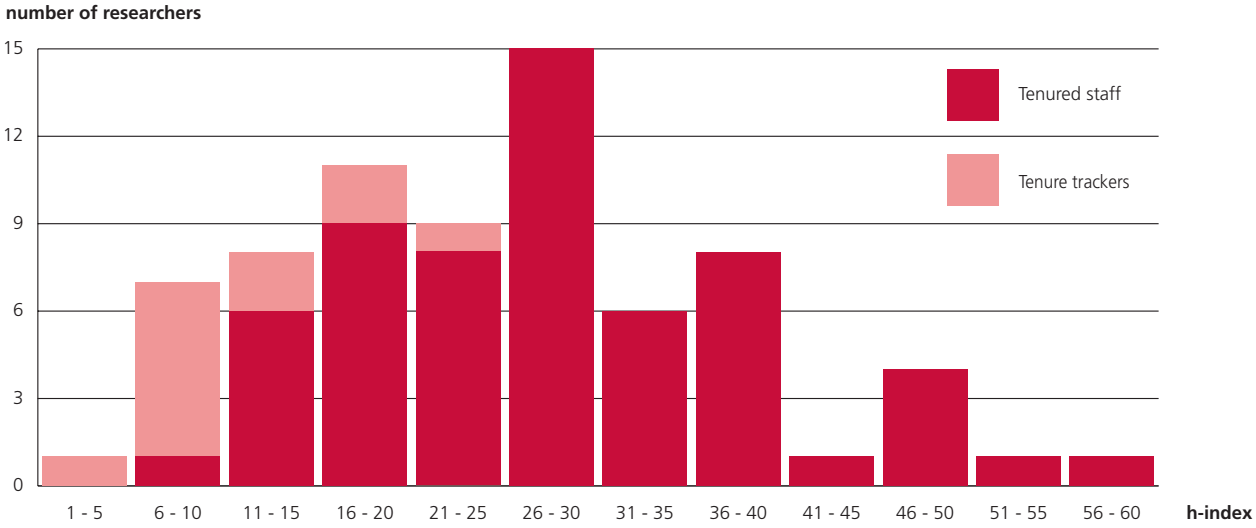
To illustrate the quality of our researchers, including CWI fellows, we list the top h-indices of our institute as evaluated by Google Scholar in December 2016:

1	Jan Karel Lenstra	57
2	Lex Schrijver	54
3	Krzysztof Apt	47
4	Martin Kersten	46
	Jan Willem Klop	46
	Paul Vitanyi	46
7	Jan Rutten	42
8	Ute Ebert	40
	Arjen de Vries	40
10	Harry Buhrman	39

To also focus on our up-and-coming researchers, we list h-indices since 2012 (not listing researchers not currently at CWI or retiring soon):

1	Peter Boncz	29
	Ute Ebert	29
3	Martin Kersten	27
4	Joost Batenburg	25
5	Jan Rutten	24
6	Stefan Manegold	23
	Ronald de Wolf	23
	Kees Oosterlee	23
	Harry Buhrman	23
10	Roeland Merks	21

For a full overview of the h-indices of CWI researchers, including CWI fellows, please refer to the chart below.



CWI has strategic relationships with various highly regarded parties. In 2016, we signed a strategic partnership to set up a joint International Lab with Inria, a partnership which Inria reserves for only the most excellent research institutes. In this context three associated teams have been created in early 2017, receiving funding from both Inria's associated research teams programme as well as from CWI. We managed one European COST network on tomography and mathematical imaging, and another on autonomous control methods and algorithms for the Internet of Services. We founded the QuSoft research centre for quantum software in 2015 together with the University of Amsterdam and VU University Amsterdam. Harry Buhrman, senior CWI researcher, is executive director of QuSoft.

3 Relevance to society

3a Performance indicators

Below, we will explain which performance indicators concerning societal relevance correspond with the profile of our institute and thus can be best used to evaluate our performance.

CWI's research is both fundamental in nature and relevant for society. Knowledge transfer has a high priority. In 2016, we updated our valorization policy to better align and integrate the valorization activities and to enhance internal knowledge exchange and support. The institute's valorization strategy has three pillars: industrial collaboration, developing innovative software tools and founding spin-off

companies. Another important performance indicator is our contribution to the development of several major web standards. We chose not to consider patents and licences as a performance indicator. By nature, fundamental mathematics and computer science are less suitable for patenting inventions. Rather, CWI encourages an open-source policy.

In the following section we highlight notable output from the 2011-2016 period. For a full overview we refer to appendices B, E, G and I to L.

3b Evaluation of societal relevance

In the table below, we list a number of valorization indicators as defined by NWO:

	2011	2012	2013	2014	2015	2016
Strategic cooperation in PPPs[6]	-	-	-	4	7	14
Strategic cooperation through contract work[7]	2	5	9	11	5	3
Software	8	9	11	13	11	12
Spin-offs	-	-	1	-	1	1
Co-publications with non-academic partners	30	36	44	69	46	46
Press releases	37	28	39	37	47	45

Note that as the number of PPPs grows, the number of contract work partnerships decreases. In 2014, NWO granted CWI 1 M€ to invest in public-private partnerships in IT research. This led to a distinct increase in the number of PPPs, and subsequently, to a decrease in the number of contract work partnerships. CWI aims to use PPPs to cement a relationship with industrial partners, and in the longer term, shape these relationships again into contract work.

6 Public-private partnerships are fundamental research collaborations that are partly funded by industrial partners and partly funded by CWI.

7 Here, 'contract work' is defined to include only projects fully funded by industrial partners. This work ranges from small-scale collaborations to large fundamental research projects. Please note that in appendix D, in terms of funding, we use a broader definition of 'contract work'.

Industrial partnerships

Knowledge transfer with industry partners is achieved in the context of EU, NWO (Take-Off Grant and thematic programmes), EIT Digital, the national top sectors and COMMIT/ projects. The institute also participates in an increasing number of national and international public-private partnerships in a variety of sectors and applications such as energy, logistics, smart industry, finance, security, data science and software services. Collaborations take place across the full range of companies ranging from high tech SME's to R&D departments of worldwide operating multinationals. For instance, at the China Holland Business Summit 2014 in Beijing, CWI and Chinese online news provider Xinhuanet signed a cooperation agreement to develop a user experience research programme which has successfully been implemented. For a full overview of our public-private partnerships, please refer to appendix L.

In the evaluation period, about a dozen CWI PhD students were funded by industrial partners. CWI organized three editions of CWI in Business ('CWI in Bedrijf'), our major networking event where our researchers meet with innovative companies. We also presented our work at industry conferences such as the IBC2014 conference (55,000 visitors) and ICTDelta (1,200 visitors).

Software

Sharing knowledge is also achieved by developing software, and making this software available to researchers, industry and society. In 2016, CWI conducted a self-assessment to determine the scientific and societal relevance of its software output in the evaluation period. For this, we adopted the criteria for software self-assessment as proposed by Inria. About 30% of the software developed at CWI is software that is used within the research team and by collaborating (industrial) researchers. The other 70% is external software. Around 6% of the institute's software is aimed to be used by a wide audience and is intended to become the reference software in its area. Dissemination of our software products takes place through the establishment of spin-offs, the development of open-source software tools and in collaborations with industrial partners.

The societal impact of CWI's software output is shown in its contributions to new industry standards in multimedia, internet security, database management systems and the development of programming languages. Furthermore, software research results have contributed to innovations in many domains such as life sciences, plasma technology and climate modelling. Below, we list some of the most notable software output in the evaluation period. For an overview of CWI software highlights, please refer to appendix N.

1 Database management systems

CWI is the breeding ground of the open-source and award-winning column store database technology MonetDB, that remains the premier open-source columnar analytical database engine (500,000 downloads in 2011-2016, 2,500,000 pageviews). MonetDBLite versions were introduced for Java and Python (NumPy) in 2016.

Actian Vector and Vector in Hadoop are commercial data warehousing systems originating from the 2008 CWI spin-off VectorWise. They were co-developed with CWI in 2011-2016. These systems, as well as MonetDB, have heavily influenced the industry, leading to a transformation of the analytical database marketplace with introductions of products like IBM DB2 BLU, Microsoft SQLserver columnar indexes with vector execution, Oracle in-memory columnar option and the whole of SAP HANA.

2 Research infrastructure

Created in 2011, SciLens is a large-scale experimental database platform that can analyse over 60 gigabyte raw data per second in the most efficient way possible. The mission of SciLens is to reveal knowledge stored in extensive scientific databases. Its Data Cyclotron architecture is especially suited for business analytics, data mining and web-log analysis.

3 Open source software tools

Rascal is an open-source meta-programming language developed at CWI and hosted at the UseTheSource open-source organization. It is used internationally in education and research, including various EU research projects. It is also being applied in forensics (Netherlands Forensics Institute), finance (banking and financial services corporation ING), legal systems (the Dutch General Intelligence and Security Service) and gaming (IC3Media).

The ASTRA Toolbox is an open-source toolbox for the development of high-performance algorithms for tomography and is developed in collaboration with University of Antwerp. This software is used extensively in the nanotechnology industry. The Toolbox is licensed by FEI Company for use in the software accompanying their electron microscopes. Through FEI's Inspect3D software, hundreds of users in industry and academia use the ASTRA Toolbox indirectly for 3D imaging in electron microscopy.

CLEVER-SV, developed at CWI, is used within large-scale clinical studies. It is in use in collaboration with the UMC Utrecht for a globally concerted study about amyotrophic lateral sclerosis (ALS), which aims at deciphering the molecular reasons for this disease and developing enhanced clinical treatment. The CLEVER-SV software has been downloaded more than 850 times since April 2015.

4 Standards

CWI has contributed to standardization bodies on web technologies (W3C), multimedia (MPEG), and Quality of Experience (ITU). Examples include RDFa as a canonical machine representation of schema.org (part of millions of webpages), a new roadmap for Digital Publishing by combining efforts from W3C and IDPF, XForms and XForms 2.0, and a new point cloud compression contributed to MPEG which provides standards that are used by billions of products (MP3, DVD, digital TV broadcasting).

5 Internet security

By making use of a new, award-winning counter-cryptanalysis method to protect against digital signature forgeries, CWI researchers developed new platform-independent security technology that can easily be incorporated in existing software for processing digital signatures. The library is currently used by Microsoft, Fox-IT, Amazon and other members of the CA/Browser Forum.

6 Future quantum software

CWI has a leading position in quantum software. Small and medium size quantum systems are gradually becoming available and it is important to understand how to exploit their power. The development of quantum software offers great economic opportunities for Europe, and for the Netherlands in particular.

With the exclusive focus on software of the recently launched QuSoft initiative, the Netherlands can become the central stage for the quantum software industry.

Spin-off companies

CWI has a long track record in establishing spin-off companies. To date CWI has founded 24 spin-off companies with a survival rate of 75% after the first 5 years, which is well above the national average of roughly 50%. This high survival rate can be explained by the maturity of the spin-off initiatives and their founders: our spin-offs are generally initiated by PhD graduates or senior staff members with high expertise in a proven technology.

In 2011 the 21st spin-off, MonetDB Solutions, was established to provide support to the expanding MonetDB user base. In 2015, CWI founded its spin-off Stokhos Emergency Mathematics, which provides software solutions for a faster relocation of emergency services. In 2016, with support of EIT Digital, CWI launched spin-off Seita, which focuses on new business applications and pricing mechanisms in the context of smart energy systems.

Outreach

Outreach to the general public is achieved through a wide range of activities. Major public outreach activities include the yearly Open Science Day and a contribution to Lowlands University, the scientific part of the popular Lowlands music festival, in 2012. Our researchers also participated in a number of popularising lectures for children in various museums, such as NEMO Science Museum, and contributed to the Night of Art and Knowledge, a science and culture festival. In 2012, during the worldwide celebration of the centenary of Alan Turing, CWI organized the exhibition Turing's Legacy. In 2016, CWI launched a temporary exhibition and published the book 'Geheugentrommels' (Memory Drums) to celebrate the 100th anniversary of the birth of Adriaan van Wijngaarden, one of the founding fathers of computer science in the Netherlands and former director of CWI. CWI also actively involves people in research projects involving user experience, e.g. in experiments with the National Theatre of China and during the Amsterdam Dance Event.

CWI pro-actively seeks opportunities to increase its exposure in national and international media. The table below gives CWI's exposure in national media. In 2015 and 2016, CWI researchers gave 'Universiteit van Nederland' lectures (online lectures by prominent professors aimed at the general public) which generated over 103,000 views. In 2014, CWI research on emergency logistics was featured in the national TV programme 'De Kennis van Nu' (Today's Knowledge). We also contributed to a documentary on the 25th anniversary of internet in the Netherlands. CWI work also featured in prominent international media such as the New York Times and WIRED. See appendix K for more examples of our outreach activities.

Publication type	#
National newspapers	65
National TV	15
National radio	33

Output for societal groups

In the evaluation period, CWI contributed to a number of policy reports and provided knowledge transfer to professional target groups. For instance, on a national level, CWI contributed to the 'Deltaplan Mathematics' (Deltaplan Wiskunde), to a strategic advice for the Dutch government concerning digital heritage infrastructure policies and to an advisory report on digital literacy in secondary education. On a European level, CWI researchers published the EIT Digital report 'Towards a European Smart Energy System, ICT innovation goals and considerations'. CWI's expert role in statistics led to crash-courses on statistics and probability for a specific group of professionals, public prosecutors and judges, organized by the Training and Study Centre for the Judiciary (see also appendix K).

Marks of recognition by societal groups

A number of prizes and awards illustrate the appreciation of CWI work by societal groups. In 2013 the programming language Python and the Software Improvement Group (SIG), which both originated at CWI, were awarded the National ICT Award. Python was awarded the prize for the most valuable product resulting from ICT research that is over ten years old. CWI research was also nominated for the Huibregtsen Prize in 2013 and 2014, a prize for the best scientific research in the Netherlands that is remarkably innovative and has a valuable social impact. In 2013, the nomination was for CWI's work on developing new universal computational algorithms that can be applied by a wide range of organizations such as banks, museums, medical institutions and engineering firms. In 2014 CWI was nominated for

developing quantitative mathematical models to improve performance in logistics processes such as mobile networks, transportation, complex large-scale ICT systems, emergency services and call centres. In 2016, W3C received the Technology & Engineering Emmy Award from the US national Academy of Television Arts & Sciences for its work on the Timed Text Markup Language standard that makes video content more accessible with text captioning and subtitles.

The contribution of CWI researchers is highly recognized by both public and industry organizations, and CWI staff are sought after for influential positions. One example: CWI Fellow Paul Klint is member of the supervisory board of BIT, the governmental bureau that oversees all ICT project plans over 5 M€.

4 Viability

Ever since its foundation, CWI has played a central role in mathematics and computer science research, both in the Netherlands and worldwide. As an independent national institute it is well placed to continue to do so because of its strategic choices in new research areas, wherever relevant joining forces with leading research groups and institutes around the globe. One example is the research for software for quantum computing, likely to contribute to a new digital revolution. Below, we will consider trends in the upcoming years which are relevant to CWI's viability.

Developments in the organization of the Dutch research landscape

NWO is currently changing its organizational structure. It aims to be more flexible, more effective, and more focused on collaboration. An NWO Institutes Organisation (NWO-I) has been initiated, which CWI will join as of January 1st, 2018. This transition is expected to lead to stronger cooperation within NWO, a better connection between the institutes and the scientific fields, and to an increased cooperation amongst the NWO institutes, and possibly with the KNAW institutes. CWI was able to retain its flexibility and decisiveness. We will remain in charge of fulfilling our mission, making strategic choices and decisions as we see fit.

In March 2017, NWO published a position paper entitled 'Knowledge essential for a sustainable and prosperous Netherlands' (Kennis essentieel voor een duurzaam welvarend Nederland). NWO stressed that national institutes have a crucial role in the Dutch research landscape. In 2018 there will be an analysis of the landscape of Dutch research institutes, where the portfolio of all NWO and KNAW institutes will be analysed and balanced.

Developments in funding

The European Commission's proposed Work Programme 2018-2020 (Horizon 2020) shows increased attention for digital technology. At CWI, we are convinced that a substantial increase in funding for research in mathematics and computer science is called for, since these fields are drivers of scientific advancement in all scientific disciplines.

Research in quantum computing will get an extra boost through an NWO Gravitation (Zwaartekracht) programme (awarded in 2017) and the EU Flagship Programme of €1 billion that is expected for 2018. This will open up possibilities for further investments in our quantum software research line in the QuSoft institute.

We expect the aforementioned NWO and KNAW institute portfolio analysis to lead to an increase and redistribution of research funds. We aim to justify the need for extra funding for mathematics and computer science, in line with the call for extra investments that was recently published by the Knowledge Coalition (Kenniscoalitie), which consists of Dutch knowledge organizations and societal and industrial parties. The coalition calls for an investment agenda of €1 billion for research and innovation (Spankracht and Daadkracht), which we hope will result in both increased basic funding as well as project funding opportunities. We observe momentum for an increase in investments in both fundamental and application-oriented research.

Digitization of society and economy will steadily continue so there will be a crucial role for mathematics and computer science in the Netherlands. A broad coalition of societal and industrial parties has urged the government to take leadership to transform the Netherlands into a successful digital society and economy. The Manifesto for a Sustainable Digital Society, signed by a large number

of parties from society, industry and large corporations, argues for extra investment in digital education and innovation. Also, the new COMMIT2DATA programme, the successor of COMMIT/, underlines the importance of computer science for the Netherlands.

CWI is involved in the Dutch National Research Agenda (Nationale Wetenschapsagenda) which increasingly determines both research agendas and funding in the Netherlands. We significantly contribute to several routes: Big Data (route 9), Logistics and Transport (16), Energy Transition (17) and Nano and Quantum (19). We also see opportunities for contributing in varying extents to the routes Personalised Medicine (1), the Origin of Life (4), Building Blocks of Matter (5), Between Conflict and Cooperation (7), Brain, Cognition and Behaviour (8), Smart Industry (10) and Smart Cities (11).

To NWO, CWI makes a plea for longer-term financial commitment in order to pursue high-risk fundamental research themes, in keeping with CWI's mission as an institute that initiates and gives impetus to new research fields.

5 SWOT Analysis

Assessing both CWI's internal strengths and weaknesses and the external opportunities and threats that we are dealing with, provides insights into the issues that are the most relevant for the successful implementation of CWI's strategy and the priorities we are setting for the coming years.

Strengths	Weaknesses
• the synergy between mathematics and computer science; • scientific excellence and high quality of research staff; • applicability of research results in a wide range of areas; • dynamic research organization with high-quality facilities and support; • close ties to all Dutch universities.	• internal communication and coordination between the different parts of the institute (i.e. directorate, research groups and support departments) can be improved; • due to our focused portfolio and limited size, we are not yet known by all potential societal partners and stakeholders; • we have not yet achieved an overall culture of diversity within the institute.
Opportunities	**Threats**
• increasing importance of mathematics and computer science due to the digitization of society and economy; • chance to show our value in portfolio analysis of Dutch research institutes; • strategic partnerships on a regional, national, European and global level.	• fundamental research is under pressure; • continuing increase in competition for limited research funds; • (inter)national 'war for talent'.

Opportunities vs strengths (enterprising)

- CWI as an institute is exceptional in that it is home to researchers in both mathematics and computer science. This allows us to exploit the synergy between the two fields, as well as to promote the increasing importance of both mathematics and computer science research in a digitizing society and economy.
- The scientific excellence and the quality of our research staff, combined with the increasing importance of mathematics and computer science, allows us to demonstrate our value in the portfolio analysis of Dutch research institutes and to argue for growth of the institute.
- The applicability of our research and the growing importance of our research fields provide excellent opportunities to set up new (public-private) partnerships.
- CWI provides an environment that stimulates growth of talented researchers to full professors. The appointment of CWI staff as full professor further strengthens our ties to the Dutch universities, which reinforces strategic partnerships on a national and international level.

Threats vs strengths (defensive)

- Researchers from all disciplines, from cancer research to astrophysics, compete for the same funds. Although our scientific quality makes us competitive, we often start from a less favourable vantage point in this competition because of the less demonstrable nature of our type of research and results.
- Thanks to the wide applicability of our research, a shortage of fundamental research funds can be partly accommodated by initiating more contract research and public-private partnerships.
- By consistently proving our scientific excellence and strategic position, we can argue for an increase of our basic funding from NWO.
- Fundamental research is under pressure. Firstly, because there is a shift in funding towards thematic programmes. Secondly, industrial partners expect short-term results, and do not readily invest in long-term work (but are interested in talent development). CWI's added value in the national research landscape is in maintaining the balance between fundamental and application-oriented research, in mathematics, computer science, and in the intersection between the two fields. We cover (new) research fields that will benefit the Netherlands as a whole.
- There is an (inter)national 'war for talent', and we experience increased competition with industry for personnel. Whereas industry can offer high starting salaries, in academia, young researchers are often confronted with an uncertain career path. However, due to our excellent reputation, CWI is a successful competitor in attracting talent in the academic world. We strive to be a very attractive employer, offer career planning support, and we provide a dedicated research environment for young researchers.

Opportunities vs weaknesses (reform)

- We see opportunities to increase our strategic partnerships. However, we are not yet widely known by all of our potential societal partners. We must continue our efforts in branding and external communication.
- By improving our internal coordination, e.g. by more effectively communicating management decisions to our researchers, we facilitate the CWI community to act more as a strategic and coherent research organization. This can also contribute to forging new alliances with potential strategic partners.
- We expect that the increased societal importance of mathematics and computer science will stimulate an increased participation of currently underrepresented communities. This should lead to an increase in the diversity of our talent pool, which, combined with our efforts to create a culture of diversity and inclusion within our institute, will lead to a better representation of women and minorities in our workforce.

Threats vs weaknesses (get by)

- An improved culture of diversity and inclusion within our institute will contribute to a stronger position in the 'war for talent'. Improvements will make for a more pleasant working environment, and an even higher research quality.
- Internal communication and coordination within CWI can be improved. Better internal coordination would allow us to better exploit all funding opportunities.
- The lobby for an increase of (long-term) funding will be more powerful if CWI aligns its efforts with other knowledge organizations and with industry. It is therefore important that we make ourselves better known to all potential partners and stakeholders.

6 PhD programme

CWI strives to create an optimal working environment for all research staff. Our PhD students are exempt from obligatory teaching duties and related administrative tasks. However, CWI is not a degree granting organization. Our PhD students obtain their PhD degree at the university where their CWI supervisor has a professorship. That means that each CWI PhD student has to be a member of the graduate school of the corresponding university. As a consequence, CWI has to comply with a variety of rules on the completion of PhDs, courses and evaluations. Regardless of differences in these procedures, there is one principle that CWI upholds for every PhD student: we strive for excellence. Quality is our first priority. Hence when needed, we allow our students to take longer than four years to complete their thesis. Almost 60% of our students graduate within 5 years, with almost 10% receiving a prestigious prize or graduating with honors (cum laude), as opposed to the national average of 5%.

Recruitment

On average, around 70 PhD students are employed at CWI. About 50% of our PhD students come from abroad. Recruitment of PhD students is done through advertising in international digital media, but most PhD students are found through senior staff networking. As most of our senior researchers teach or have a full professorship at a university, they can scout for talent among their master's students.

Individual programme for education and supervision

Every CWI PhD student has a daily supervisor. For some PhD students, their daily supervisor is their formal doctoral thesis promotor, for others, another supervisor is appointed. CWI offers all supervisors annual masterclasses on supervision.

In the first three months of their employment, each CWI PhD student, in cooperation with his or her supervisor, formulates a personal programme for education and supervision. The PhD student discusses the programme with the personnel advisor, who also functions as their counselor. The agreements in the programme are the basis for the annual evaluation interview between the PhD student, their daily supervisor and the group leader.

As of 2013, all PhD students are confronted with a go/no go decision within 18 months of their employment. In 2016, this was formally incorporated in the Terms of Employment. Each PhD student is initially employed on an 18 months temporary contract. The student gets an extension of their employment contract only in the case of a positive evaluation. CWI put this procedure in place because it encourages the PhD supervisor to intensify or change the supervision, if necessary, at the earliest possible moment. It also means that CWI and the student are obliged to make a judgement on the expectations regarding completion, which allows for more efficient decision making, and in case of continuation, increased commitment for timely completion.

Professional and personal development

CWI's own PhD education programme consists of courses for professional and personal development, such as presentation skills, academic writing skills, time management and communication skills, career development, English and Dutch language courses and Dutch culture awareness courses for our foreign students. In 2016, the programme was extended to include an obligatory course on scientific integrity.

To contribute to the social cohesion within our institute, a PhD student activity committee organizes monthly informal activities. These include board game nights, pub quizzes and other outings for all PhD students, trainees and postdocs.

Career

Career planning is a recurring topic in the annual evaluation interview. To help PhD students prepare for the labour market, CWI offers Imperial College London's course 'Boosting your career'. CWI also provides personal coaching, and helps organize trial periods or internships at organizations or companies of a student's choice. PhD students who consider initiating a start-up company can make use of the training offered by Science Park's Ace Venture Lab.

Of the PhD students appointed in the period 2008-2012, about 34% continued to pursue an academic career, 37% started working in industry, and 9% chose to continue their career in the public sector or not-for-profit. At the end of 2016, 13% of these students had not yet finished their degree, and 7% continued their career in a trajectory unknown to us. Of the 58 students who obtained a doctorate, 32 (including 10 students from abroad) remained in the Netherlands, and 26 students went abroad (including 10 Dutch students).

7 Research integrity

Research (or scientific) integrity is high on the agenda of the management team. Awareness of the importance of this issue has increased greatly within CWI over the course of the evaluation period.

Procedures and awareness

CWI researchers follow the Netherlands Code of Conduct for Scientific Practice as established by NWO, the Association of Universities in the Netherlands (VSNU), and KNAW. The NWO Scientific Integrity Desk ('Meldpunt Integriteit') is available when a person working in any of the NWO institutes is suspected of violating the code. CWI has a formal and strict procedure in place in case a possible breach of scientific integrity is suspected. During the evaluation period, this procedure was followed twice.

A number of activities has been organized for group leaders and the management team to raise awareness of possible scientific integrity issues. For instance, the MT and group leaders participated in a dilemma training activity called 'Professionalism and Integrity in Research'. To further increase awareness within the CWI community, the personnel department, with input from the director and the scientific staff, has developed an obligatory training programme for our PhD students: 'Awareness of Scientific Integrity'.

External partners

As CWI is strengthening its ties with external partners and industry, potential scientific integrity issues in public-private cooperation receive due attention from the CWI management team. The increasing number of public-private partnerships, valorization efforts and contract research by our scientific community need clear agreements on e.g. intellectual property and publication policy. CWI cooperates with industry and other external partners, but the scientific perspective is always leading: we work in an interesting problem area defined by a sponsor, but not to affirm the sponsor's desired outcomes. We keep a well-balanced separation between finances, publication of scientific results and ownership of such results.

Data management

In 2016, NWO, in collaboration with its institutes, established a data management policy framework. The framework concerns issues such as open science, open access and scientific integrity. CWI is developing and implementing its data management policy in line with this framework. NWO's recently implemented rule, 'open, unless', is the key principle of our policy. The CWI policy concerns not only data but also software. The guidelines around software developed at CWI may differ from those on data, but the principle is the same: 'open, unless'. Data and software that are the basis of a publication, as well as raw data, must be openly stored in a trustworthy external archive, while the depositions must be registered in the publicly accessible CWI repository.

Although the institute bears overall responsibility for data management, individual researchers are responsible for their own handling of data and software. Researchers can consult with CWI's data management expert.

Ethical aspects

CWI and the two Amsterdam universities together established an Ethical Committee for Information Sciences (ECIS). In 2016, the Royal Netherlands Academy of Arts and Sciences published an advisory report on the ethical and legal aspects of informatics research. The advisory committee was chaired by CWI Fellow Jan Willem Klop.

CWI also has a number of guidelines for all employees: a Whistleblower Procedure, a Code of Conduct Network Use, and Social Media guidelines. CWI also has a Regulation Ancillary Activities, which was established to avoid conflicts of interest, and the ancillary activities database will soon be publicly accessible.

8 Diversity

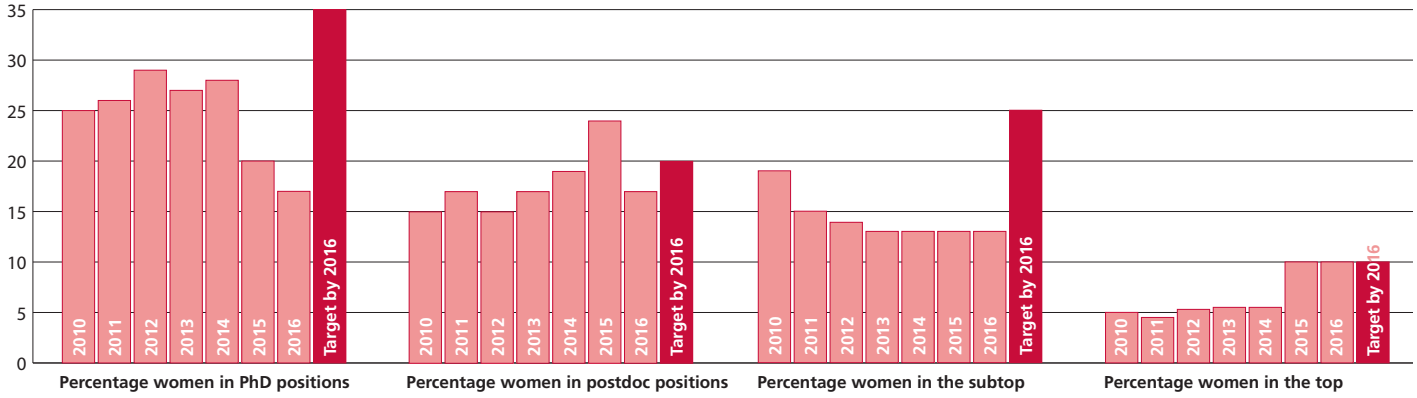
CWI management wants to develop and establish an overall culture of diversity and inclusion within the institute. In 2016, our focus has broadened from gender diversity, to create an inclusive policy that considers gender, age, ethnic and cultural background, sexual orientation and disabilities. Policy is still in development, with CWI adopting best practices from across the field of science. CWI also actively contributes to developing the diversity policy strategy in the larger NWO organization.

Results of gender diversity efforts

In the evaluation period, gender diversity has been strengthened in the governing board and management team (in both, 2 out of 5 members are female). Efforts have been in place to scout for female talent for CWI and to persuade more of these women to stay on at CWI. For instance, before any vacancy selection procedure, the chair of the selection committee (typically a group leader) is required to report on the efforts undertaken to achieve a sufficient gender balance amongst the candidates. CWI participates with other NWO research institutes in a scheme to offer tenure track positions to women (WISE), launched by the Dutch Minister of Education, Culture and Science, Jet Bussemaker at the 2016 Hannover Messe. Since then the first WISE tenure track position at CWI has been filled by a former Caltech researcher.

As co-signer of the Charter 'Talent to the Top' CWI's targets were 35% female PhDs, 20% female postdocs, 25% women in the subtop[8] (5 persons) and 10% women in the top of the institute (2 persons) by 2016. Our progress is illustrated in the following charts.

8 Staff in salary scales 13 and 14 (Dutch Collective Labour Agreement for Research Centres, 'CAO-onderzoeksinstellingen').



Our target for the top of the institute has been achieved. However, we regret that the number of female PhD students, postdocs and women in the subtop is not yet as desired. We do expect that by 2019, two female CWI tenure trackers will get tenure, which will bring them to the subtop salary scales. This brings the percentage of women in the subtop to 25%. We realize that there is still work to be done to attract more female PhD students and postdocs.

Raising awareness

For most CWI vacancies for PhD and postdoc positions, candidates are found through the networks of our senior scientists. We are proud that this leads to a research staff with over thirty different nationalities. However, we realize this means that raising awareness of the need for diversity amongst our scientific staff, as well as broadening the predominantly male scientific network, remains of crucial importance. In the yearly cycle of performance reviews with group leaders, the gender diversity of each group is a topic of evaluation. A gender diversity sounding board collected and evaluated ideas to increase the gender balance. We are currently exploring the options to institute a broader diversity sounding board with members of the LGBTI+ community, to broaden our diversity focus and to gather ideas on how to further build a culture of diversity and inclusion in our institute.

Outreach and communication

The internal and external visibility of senior and junior female researchers within CWI has increased over the past years, thanks to the joint efforts of the communication department and the personnel department. An online video showcasing female role models aims at lowering the barriers, specifically for women, to apply for internships and vacancies. Female scientists from CWI participate in a number of outreach activities aimed at girls. For instance, CWI researchers participate in DigiVita outreach videos and IT events for girls, organized by VHTO (the national expert organization on girls/women and science/technology). Role models of CWI also actively participate in the diversity debate. Amongst other things, this led to the publication of the Informatics Europe booklet 'More women in informatics research and education'. Finally, a CWI researcher is a Dutch coordinator of the European Women in Mathematics network.

Centrum Wiskunde & Informatica

Appendices

A Organizational chart

As per end of 2016.

B Table with output indicators relevant to CWI

		Quality Domains	
		Research quality	**Relevance to society**
Assessment Dimensions	**Demonstrable products**	**1. Research products for peers** - 888 refereed research articles; - 17 books; - 78 book chapters; - 68 PhD theses; - 813 conference papers; - 19 software tools; - 64 web and multimedia standards.	**4. Research products for societal target groups** - 81 professional publications; - 65 national newspaper features; - 15 national TV appearances; - 33 national radio appearances; - at least 5 features in prominent international media, e.g. the New York Times and WIRED; - 233 press releases; - at least 2 national and 1 european policy reports; - 45 software tools; - 2 exhibitions; - 1 popular history of science book; - 3 industry outreach events; - 6 Open Science Days; - 6 lectures at the 'Universiteit van Nederland' (over 103,000 views); - over 70 lectures for a broad audience; - more than 10 lectures for professional audiences.
	Demonstrable use of products	**2. Use of research products by peers** - 15 publications with a citation count over 100; - A few examples of our software products: • MonetDB: 500,000 downloads; • Rascal: estimated user base of 1,000; • Counter-Cryptanalysis: over 6,000 downloads.	**5. Use of research products by societal groups** - 271 co-publications with non-academic partners; - 25 strategic cooperations in PPPs; - 35 strategic cooperations through contract work; - 3 spin-off companies.
	Demonstrable marks of recognition	**3. Marks of recognition from peers** - over 80 science awards/scholarly prizes; - over 600 lectures; - 12 NWO Veni grants; - 2 NWO Vidi grants; - 2 NWO Vici grants; - 1 ERC Starting Grant; - 1 ERC Consolidator Grant; - 2 ERC Advanced Grants (one of which was from the 2016 call; awarded in 2017); - 24 European FP7 projects; - 5 European Horizon2020 projects; - 3 tenure track positions through the Dutch Mathematics clusters; - 3 NWO Top Module 1 Grants; - 1 WISE tenure track position; - 2 members KNAW; - 1 honorary doctorate; - over 100 editorships and memberships of scientific committees and boards.	**6. Marks of recognition by societal groups** - over 10 public and industry prizes; - 12 PhD students funded by industrial partners; - 4 M€ funding by industry for PPPs (started in 2014) and other contracts; - membership of 1 ethical committee (information sciences); - 2 members KHMW; - 3 royal decorations.

C Research staff

CWI (in fte)	Year 5 (2011)	Year 4 (2012)	Year 3 (2013)	Year 2 (2014)	Year 1 (2015)	Current (2016)
Scientific staff	48.0	47.5	47.3	48.1	49.3	48.9
Postdocs	30.6	23.3	24.7	19.7	22.2	32.3
Scientific programmers	7.6	8.6	9.8	10.9	12.4	12.6
PhD students	51.4	66.8	69.2	67.2	66.1	67.8
Total research staff	**137.6**	**146.2**	**151.0**	**145.9**	**150.0**	**161.6**
Support staff	43.4	41.6	38.2	37.2	36.7	36.7
Visiting fellows	5.5	6.0	6.7	6.4	6.2	6.4
Total staff	**186.5**	**193.8**	**195.9**	**189.5**	**192.9**	**204.7**

D Funding

CWI	Year 5 (2011)	Year 4 (2012)	Year 3 (2013)	Year 2 (2014)	Year 1 (2015)	Current (2016)
funding (k€)						
Direct funding[1]	10,814 *60%*	10,764 *59%*	10,474 *59%*	10,212 *60%*	10,250 *60%*	11,063 *60%*
Research grants[2]	3,510 *19%*	3,609 *20%*	3,616 *20%*	3,080 *18%*	3,981 *23%*	3,956 *21%*
Contract research[3]	3,217 *18%*	3,545 *19%*	3,294 *19%*	3,609 *21%*	2,752 *16%*	3,426 *18%*
Other	562 *3%*	476 *3%*	291 *2%*	108 *1%*	172 *1%*	117 *1%*
Total funding	**18,103**	**18,394**	**17,675**	**17,009**	**17,155**	**18,562**
expenditure (k€)						
Personnel costs	14,460 *83%*	14,508 *81%*	14,127 *85%*	13,463 *85%*	14,004 *86%*	15,307 *85%*
Other costs	2,945 *17%*	3,319 *19%*	2,480 *15%*	2,360 *15%*	2,215 *14%*	2,679 *15%*
Total expenditure	**17,405**	**17,827**	**16,535**	**15,823**	**16,219**	**17,986**

CWI	Year 5 (2011)	Year 4 (2012)	Year 3 (2013)	Year 2 (2014)	Year 1 (2015)	Current (2016)
funding (fte)						
Direct funding	57.3 *42%*	52.7 *36%*	57.3 *38%*	53.8 *37%*	51.8 *34%*	51.9 *32%*
Research grants	58.9 *43%*	67.5 *46%*	67.4 *45%*	60.4 *41%*	64.4 *43%*	73.9 *46%*
Contract research	21.4 *15%*	25.9 *18%*	26.1 *17%*	31.5 *22%*	33.8 *23%*	35.7 *22%*
Other	n/a	n/a	n/a	n/a	n/a	n/a
Total funding	**137.60**	**146.10**	**150.80**	**145.70**	**150.00**	**161.50**

1 Direct funding (basic funding / lump sum budget).

2 Research grants obtained in national scientific competition.

3 Research contracts for specific research projects obtained from external organizations, such as industry, government ministries and the European Commission. Please note that in section 3b, 'contract work' is defined in a less encompassing way (i.e. only project funded by industry, excluding PPPs).

E Research output

CWI	Year 5 (2011)	Year 4 (2012)	Year 3 (2013)	Year 2 (2014)	Year 1 (2015)	Current (2016)
Research quality						
Refereed articles	161	159	127	121	153	167
Non-refereed articles	3	3	1	0	3	0
Books	3	6	0	2	3	3
Book chapters	17	16	9	11	8	17
PhD theses	11	7	9	15	13	13
Conference papers	151	159	140	125	138	100
Relevance to society						
Professional publications	11	16	9	13	6	26
Publications aimed at the general public	0	2	2	1	0	0
Standards	4	4	5	12	22	17
Other	250	272	285	323	259	319
Total publications	**597**	**629**	**574**	**609**	**582**	**645**

F Top fifteen publications

Below, each research group lists their top publication of the 2011-2016 period and describes, in their own words, why they consider this publication to be one of their top achievements:

- **Algorithms and Complexity**

S. Fiorini, S. Massar, S. Pokutta, H.R. Tiwary, **R. de Wolf**. Exponential Lower Bounds for Polytopes in Combinatorial Optimization, Journal of the ACM 62 (2): 17, 1-23, 2015. The conference version received the Best Paper Award at STOC 2012.

"Proving that problems like the Travelling Salesman Problem (TSP) are not solvable by any efficient method is the biggest open problem in theoretical computer science (also known as the 'P vs. NP' problem). This paper for the first time proved that TSP cannot be efficiently solved by a large class of methods based on linear programming, answering a question of Yannakakis that had been open for more than two decades."

- **Computational Imaging**

S. Van Aert, **K.J. Batenburg**, M.D. Rossell, R. Erni, G. Van Tendeloo. Three-dimensional Atomic Imaging of Crystalline Nanoparticles, Nature 470 (7334), 374-377, 2011.

"This publication was the first to demonstrate the successful 3D reconstruction of a complex-shaped nanoparticle at atomic resolution. Obtaining the individual atom positions for all atoms in a crystal from electron microscopy measurements had been a long-standing goal for the electron microscopy community. This breakthrough was possible by a combination of advanced microscopy, statistical parameter estimation and a novel computational reconstruction algorithm."

- **Cryptology**

M. Stevens. New Collision Attacks on SHA-1 Based on Optimal Joint Local-collision Analysis, Advances in Cryptology - EUROCRYPT 2013, Lecture Notes in Computer Science 7881, 245-261, 2013.

"This publication was the first to introduce a rigorous optimal analysis of attacks on the widely used SHA-1 weak cryptographic hash function, making optimal practical attacks and their exact complexity analysis possible. It is the foundation for a series of papers advancing the state of attacks against SHA-1 that have been the driving force for the reluctant Industry-wide deprecation of SHA-1. Recently this culminated in the paper by Stevens et al. that presents the first successful practical break of SHA-1 at CRYPTO 2017 that won the Best Paper Award."

- **Database Architectures**

D. Abadi, **P. Boncz,** S. Harizopoulos, **S. Idreos**, S. Madden. The Design and Implementation of Modern Column-Oriented Database Systems, Foundations and Trends in Databases 5 (3), 197-280, 2013.

"CWI research around the MonetDB and Vectorwise projects has strongly influenced research and industry practice in data management systems architecture. In this overview paper, co-written with Harvard, Yale, MIT and HP Labs authors, CWI authors Boncz and Idreos give an in-detail description of column-oriented architecture and explain its impact on system performance and robustness. It addresses some of the main contributions of CWI in this area (cache-conscious join algorithms, vectorized execution, micro-adaptivity, database cracking)."

- **Distributed and Interactive Systems**

R. Mekuria, **M. Sanna**, E. Izquierdo, **D.C.A. Bulterman**, and **P. Cesar**, Enabling 3D Tele-Immersion with Live Reconstructed Mesh Geometry, IEEE Transactions on Multimedia, 16 (7), 1809-1820, 2014.

"Highly realistic reconstructed 3D representations are becoming part of our daily online interactions. This paper presented novel components for fast compression and reliable transmission of reconstructed 3D data in the internet. Tests on a large dataset showed an encoding speed-up of 10 times, when compared to the state of the art. These components were successfully integrated into a larger tele-immersion environment that could capture, compress, transmit and render triangle mesh geometries in real-time. The article has influenced multimedia standards, being the origin of the MPEG's ad-hoc group on 3D Graphics Compression. It won the Best Paper Award on 3D Technology on Multimedia at the ACM Multimedia Systems conference in 2013."

- **Formal Methods**

  S. de Gouw, J. Rot, F.S. de Boer, R. Bubel, R. Hähnle. OpenJDK's Java.utils.Collection.sort() Is Broken: The Good, the Bad and the Worst Case, Computer Aided Verification - 27th International Conference, Proceedings Part I, 273-289, 2015.

  "In this paper we formally analyse a crucial error in TimSort: the default sorting algorithm used in major programming languages (e.g. Java and Python) and platforms such as Android. The number of computers, cloud services and mobile phones that use TimSort is well into the billions. We showed that this error causes programs to crash when used on certain inputs. We also report in this paper on a correctness proof of an improved version which is therefore guaranteed to be free of bugs. The proposed correction has been adopted by Python and Android; Java followed another approach on the basis of a worst case analysis of this bug, also described in this paper."

- **Information Access**

  J. He, M. Bron, **A. de Vries**, L. Azzopardi, M. de Rijke. Untangling Result List Refinement and Ranking Quality: a Framework for Evaluation and Prediction, Proceedings of the 38th International ACM Conference on Research and Development in Information Retrieval SIGIR, 293-302, 2015.

  "We demonstrate the importance of questioning commonly accepted evaluation methods that do not take users' tasks and behaviour into account. We provide the information retrieval community with a new evaluation framework that can be applied to a wide variety of interactive tasks, and the industry with a practical method to predict and measure the user's effort to perform a given task."

- **Intelligent and Autonomous Systems**

  J. Han, **E.J. Pauwels, P.M. de Zeeuw**, P.H.N. de With. Employing a RGB-D Sensor for Real-Time Tracking of Humans across Multiple Re-Entries in a Smart Environment, IEEE Transactions on Consumer Electronics 58 (2), 255-263, 2012.

  "This paper deals with user identification in smart environments: physical spaces equipped with sensors that enable it to become responsive to the presence and needs of its occupants. A key issue is to determine the location and identity of these occupants. In this paper, we fused data from different color and depth (RGB-D) cameras to simultaneously achieve three goals: object labeling, human re-entry identification, and human tracking. The efficiency of the algorithms allowed for real-time processing using off-the-shelf hardware, while the accuracy rate achieved by the tracker outperformed other existing algorithms at the time."

- **Life Sciences**

  The Genome of the Netherlands Consortium (**T. Marschall** and **A. Schönhuth** are consortium members). Whole-genome Sequence Variation, Population Structure and Demographic History of the Dutch Population, Nature Genetics 46, 818-825, 2014.

  "There are plenty of genetic variants in human genomes that have been stubbornly resisting discovery. Highly likely, many of those are associated with disease risks. We have made it possible to close the discovery blind spot in the frame of the Genome of the Netherlands project. We designed a unique, ultra-fast, highly engineered algorithm by which to discover these 'dark matter variants'. Our methodology has since inspired the development of other, similar algorithms, but is yet unprecedented in its predictive power."

- **Machine Learning**

  T. van Erven, **P.D. Grünwald,** S. de Rooij. Catching Up Faster by Switching Sooner: A Predictive Approach to Adaptive Estimation with an Application to the AIC-BIC Dilemma, Journal of the Royal Statistical Society - Series B: Statistical Methodology, 74 (3), 361-397 (discussion 397-417), 2012. Presented as a 'Read Paper" at the RSS Ordinary Meeting, 19 October 2011.

  "How to choose between several models for the same data? Two classical methods for addressing this fundamental problem of statistics are AIC and BIC. Both of these have different strengths and weaknesses, and according to a well-known result by Yang, there can be no method that combines their strengths in general. By using new techniques from a different area (information theory), we design new, computationally efficient methods that, Yang's result notwithstanding, provably outperform both AIC and BIC, and we show that in some special contexts, their strengths can be combined after all."

- **Multiscale Dynamics**

  S. Nijdam, **J. Teunissen**, E. Takahashi, **U. Ebert**. The Role of Free Electrons in the Guiding of Positive Streamers, Plasma Sources Science and Technology 25 (4), 044001, 2016.

  "The paper contains a careful experimental investigation of puzzling discharge behaviour and the first simulations of these phenomena with the new simulation framework afivo; experiments and simulations show that our models now can make quantitative predictions. The 3D time dependent simulations with adaptive mesh refinement are challenging through the global electrostatic coupling expressed by an elliptic equation. The afivo framework that defines a new state of the art is further described in the preprint submitted to Computer Physics Communications."

- **Networks and Optimization**

  J. Geelen, **B. Gerards**, G. Whittle. Solving Rota's Conjecture, Notices of the AMS, 61 (7), 736-743, 2014.

  "The most striking outcome of the 2011 Matroid Minor Structure Theorem is that networks are provably ubiquitous among geometric models over finite fields. This also constitutes the backbone of the Matroid Minor Theory that we developed over the last two decades because of its own intrinsic value and as an instrument in the 2013 proof of Rota's Conjecture. Our Matroid Minors Project takes the same structural perspective as the Robertson-Seymour Graph Minor Project but we do not use any graph minor result as such; we had to rebuild the entire theory from scratch, including its intersection with Graph Minors Project. (cf. Bert Gerards' comment on a blog by Gill Kalai)."

- **Scientific Computing**

  M.J. Ruijter, C.W. Oosterlee. Two-dimensional Fourier Cosine Series Expansion Method for Pricing Financial Options, SIAM Journal on Scientific Computing, 34 (5), B642–B671, 2012.

  "In this paper, the successful COS method from Fang and Oosterlee (2008) is generalized to higher dimensions (multiple assets underlying the option). The multidimensional method converges fast and is numerically highly efficient. It performed very strongly in an option pricing benchmarking study (BENCHOP, 2015) and has been implemented for use by various banks. It is a strong example of innovative research in numerical mathematics that has direct application relevance."

- **Software Analysis and Transformation**

  D. Landman, A. Serebrenik, E. Bouwers, **J.J. Vinju**. Empirical Analysis of the Relationship between CC and SLOC in a Large Corpus of Java Methods and C Functions, Journal of Software: Evolution and Process, 28 (7), 589-618, 2015.

  "With this paper we refuted the 'common knowledge' and much cited belief that two often used metrics for source code complexity 'measure the same thing'. Motivated by a thorough reading of the available literature, this extensive study examines a very large corpus of Java methods and C functions and investigates plausible reasons for all reported contradictory results of the past decades. The surprising refutation has direct consequences for the software engineering field; namely for software quality assessment, bug prediction and automatic fault repair."

- **Stochastics**

  D. Kiss. Frozen Percolation in Two Dimensions, Probability Theory and Related Fields, 163 (3), 713-768, 2015.

  "This paper concerns a fundamental aggregation model which until then had been only successfully analysed in more simplified or mean-field settings. It is trailblazing in its detailed, mathematically rigorous description of the behaviour in two dimensions and shows that the crucial events take place in a tiny time slot, called the near-critical window."

G Research groups

Central to CWI research are mathematics and computer science, and the synergy obtained by their interaction. Our research activities are performed by fifteen research groups of varying sizes. The research groups and group leaders are listed below:

- Algorithms and Complexity (A&C) - Harry Buhrman;
- Computational Imaging (CI) - Joost Batenburg;
- Cryptology (CR) - Ronald Cramer;
- Database Architectures (DA) - Stefan Manegold;
- Distributed and Interactive Systems (DIS) - Pablo Cesar;
- Formal Methods (FM) - Frank de Boer;
- Information Access (IA) - Jacco van Ossenbruggen;
- Intelligent and Autonomous Systems (IAS) - Eric Pauwels;
- Life Sciences (LS) - Gunnar Klau;
- Machine Learning (ML) - Peter Grünwald;
- Multiscale Dynamics (MD) - Ute Ebert;
- Networks and Optimization (N&O) - Guido Schäfer;
- Scientific Computing (SC) - Daan Crommelin;
- Software Analysis and Transformation (SWAT) -Jurgen Vinju;
- Stochastics (ST) - Bert Zwart.

Below, each group provides a page with a short description of their work, and a selection of their top achievements in the 2011-2016 period. Please note that some research groups have recently been established (in the 2011-2016 period). However, since some group members were already working at CWI in other research groups, the new groups may still list highlights from before their formal starting date. Also, some researchers moved from one group to another in the assessment period. Occasionally, this can cause achievements to be listed by more than one research group.

Algorithms and Complexity (A&C) Group

The A&C group designs software for the computing technology of the future, with an emphasis on quantum computing. Quantum software requires fundamentally different techniques and approaches, based on superposition, interference and entanglement. Ultimately, our research will result in better, faster and more reliable computer systems for society.

Overall highlights

- In 2015, Buhrman, together with Schoutens (UvA), launched QuSoft: the first research centre for Quantum Software in the Netherlands.
- The NETWORKS project, of which Buhrman was co-applicant, was awarded a Gravitation grant (22.7 M€) in 2013.
- Buhrman coordinates the Gravitation funded Quantum Software Consortium (18.8 M€, call 2016, awarded in 2017).

Publications highlights

- S. Fiorini, S. Massar, S. Pokutta, H.R. Tiwary, **R. de Wolf**. Exponential Lower Bounds for Polytopes in Combinatorial Optimization, Journal of the ACM 62 (2): 17, 1-23, 2015;
- **J. Briët**, **H. Buhrman**, D. Gijswijt. Violating the Shannon Capacity of Metric Graphs with Entanglement, PNAS, 110 (48), 19227-19232, 2013;
- H. Buhrman, R. Cleve, M. Koucký, **B. Loff**, **F. Speelman**. Computing with a Full Memory: Catalytic Space, Proceedings of the 46th ACM Symposium on Theory of Computing, 857-866, 2014;
- **P.T.S. van der Gulik**, W. Hoff. Anticodon Modifications in the tRNA Set of LUCA and the Fundamental Regularity in the Standard Genetic Code, PLoS ONE, 11 (7), e0158342, 2016.

Invited lectures and talks highlights

- Buhrman was a keynote speaker at the KPN Alert Online conference (2016) and addressed European policy makers at the conference Quantum Europe (and served on its PC).
- De Wolf gave invited talks at the IEEE Conference on Computational Complexity (Palo Alto, 2013) and the ALGO conference (Aarhus, 2016). He gave his inaugural lecture at the UvA in 2012 and was the kick-off speaker for the popular online seminar series TCS+ (2013).

Peer recognition and service highlights

- Buhrman: member of the advisory boards of the Canadian Institute for Advanced Research (2008-) and University of Waterloo's Institute for Quantum Computing (2006-).
- Buhrman was invited on the occasion of the state visit by the king of the Netherlands to Canada at the Institute for Quantum Computing (2015).
- De Wolf: editor of the journals Theory of Computing (2008-), Quantum Information and Computation (2011-) and SIAM Journal of Computing (2016-). He was on the PC of STOC (2013, 2016), Complexity (2014) and QIP (2012, 2014), and was PC chair of QIP (2015).
- Buhrman: editor of the journals Theory of Computing Systems, Journal of Computational Complexity, and ACM Transactions on Computation Theory, and member of the steering board for the Open Journal of Quantum Science (2016-). He was on the PC of FOCS (2012), QCRYPT (2013), PODC (2014), QIP (2016), ICALP (2011, 2012, 2016).

Public lectures, media appearances and outreach highlights

- Buhrman gave five lectures on quantum computing for online Universiteit van Nederland (2015), resulting in almost 100,000 views.
- Briët gave lectures at the annual Holiday School for secondary school mathematics teachers of the national platform for mathematics 'Platform Wiskunde Nederland' (PWN) and at the Math Festival 'Leve de wiskunde' (Long live maths) (Amsterdam and Eindhoven, 2016).

Grants highlights

- De Wolf was awarded an ERC Consolidator Grant (2013) and with Laurent and Bansal, an NWO TOP grant (2013).
- Briët was awarded an NWO Rubicon grant (2012) and an NWO Veni grant (2014).
- Jeffery was granted a WISE tenure track position.

Prizes highlights

- De Wolf won the STOC Best Paper Award with Fiorini, Massar, Pokutta and Tiwary (2012).
- Briët was awarded the Stieltjesprijs (2011) and Andreas Bonn medal (2013).
- Dulek was awarded the Ngi-NGN master thesis Information prize for Informatics and Computer Science 2016.
- Gilyén won second prize in the Microsoft Quantum Challenge 2016.

Computational Imaging (CI) Group

Computational Imaging concerns a broad range of imaging techniques where mathematics and computation play an integral role in the image formation process. The group performs fundamental and application-oriented research on new approaches for combining modern imaging equipment with advanced computational techniques to create and visualize 3D images. CI develops algorithms, numerical solution techniques and software for large-scale inverse problems in imaging. Our approach is interdisciplinary, combining mathematics (numerical linear algebra, discrete optimization, Fourier analysis), computer science (large scale parallel computing, visualization) and physics (image formation modelling).

Overall highlights

- We developed the foundation of a new approach for bridging analytical and algebraic reconstruction methods for tomography, which is a crucial building block for real time tomography algorithms.
- We created new discrete tomography algorithms that address the key obstacles for wide practical adoption of the technique: automation and robustness.

Publications highlights

- S. van Aert, **K.J. Batenburg**, M.D. Rossell, R. Erni, G. van Tendeloo. Three-dimensional Atomic Imaging of Crystalline Nanoparticles, Nature 470 (7334), 374-377, 2011;
- **D.M. Pelt**, **K.J. Batenburg**. Fast Tomographic Reconstruction from Limited Data using Artificial Neural Networks, IEEE Transactions on Image Processing 22 (12), 5238-5251, 2013;
- W. van Aarle, **W.J. Palenstijn**, J. De Beenhouwer, T. Altantzis, S. Bals, **K.J. Batenburg**, J. Sijbers. The ASTRA Toolbox: A Platform for Advanced Algorithm Development in Electron Tomography, Ultramicroscopy 157, 35-47, 2015;
- **X. Zhuge**, **W.J. Palenstijn**, **K.J. Batenburg**. TVR-DART: a more Robust Algorithm for Discrete Tomography from Limited Projection Data with Automated Gray Value Estimation, IEEE Transaction on Image Processing 25 (1), 455-468, 2016.

Invited lectures and talks highlights

- Van Liere: Virtual Revolution Symposium, Eindhoven 2015;
- Batenburg: Real-Time 3D Tomography, Symposium of the Swiss Society for Optics and Microscopy, Les-Diablerets, Switzerland, 2016.

Peer recognition and service highlights

- Van Liere was member of the programme committee of various international conferences, e.g. Eurographics Virtual Environments (2012-2014).
- Batenburg is a.o. associate editor of the Journal of Mathematical Imaging and Vision (2016-) and IEEE Transaction on Computational Imaging (2016-). He is general chair of the network EU COST Action EXTREMA (2013-) and was member of the working group for the Roadmap ICT of the Dutch top sectors (2015).

Software highlights

- ASTRA Toolbox, an open-source toolbox for the development of high-performance algorithms for tomography; developed in collaboration between CWI and University of Antwerp, used by at least 50 different groups and institutes.

Use of research results highlights

- CI collaborates with FEI Company in the context of the STW project AMTIC (advanced semiconductor quality control);
- CI has a successful public-private partnership project with ExxonMobil Chemical (2014-2016) on advanced tools for electron tomography.

Public lectures, media appearances and outreach highlights

- Batenburg gave a public lecture about looking through walls with wifi at national research festival Bessensap 2015.

Grants highlights

- Batenburg was awarded an NWO Vici grant in 2015.
- Zhuge was awarded an NWO Veni grant in 2014.

Cryptography (CR) Group

Digital security is an increasingly pressing concern for industry, government and society at large. The CR group investigates how cryptologic methods can contribute to solving security issues, for example through encryption, digital signatures and secure computation. The group investigates the reliability of current cryptologic methods and how they can be improved, but also seeks for and studies potential future alternatives. Quantum safety, meaning security in a possible future age of quantum computing, is a particular focus of the group.

Overall highlights

- Development of the theory of arithmetic codices;
- Asymptotic cryptanalysis of certain lattice-based cryptosystems;
- Invention of novel, useful Rényi-type measures of quantum information;
- Various attacks on SHA-1, resulting in the first collision for full SHA-1;
- Reverse-engineering of the cryptanalytic attack used in the Flame super-malware;
- Invention of counter cryptanalysis for the detection of attacks against hash functions.

Publications highlights

- **R. Cramer**, I. Damgård, J. Nielsen. Secure Multiparty Computation and Secret Sharing, textbook, Cambridge University Press, 2015;
- **I. Cascudo**, **R. Cramer**, C. Xing. Torsion Limits and Riemann-Roch Systems for Function Fields and Applications, IEEE Transactions on Information Theory, 60 (7), 3871-3888, 2014;
- **R. Cramer**, **L. Ducas**, C. Peikert, O. Regev. Recovering Short Generators of Principal Ideals in Cyclotomic Rings, Advances in Cryptology – EUROCRYPT 2016, Lecture Notes in Computer Science 9666, 559-585, 2016;
- E. Alkim, **L. Ducas**, T. Pöppelmann, P. Schwabe, Post-Quantum Key Exchange - A New Hope, Proceedings of the 25th USENIX Security Symposium, 327-343, 2016;
- M. Müller-Lennert, F. Dupuis, O. Szehr, **S. Fehr**, M. Tomamichel. On Quantum Rényi Entropies: A New Generalization and Some Properties, Journal of Mathematical Physics 54 (12), 122203, 2013;
- **M. Stevens**. Counter-cryptanalysis, Proceedings of Annual International Cryptology Conference 2013 - CRYPTO 33, Lecture Notes in Computer Science 8042, 129–146, 2013;
- **M. Stevens**, P. Karpman, T. Peyrin. Freestart Collision for full SHA-1, Advances in Cryptology – EUROCRYPT 2016, Lecture Notes in Computer Science 9665, 459-483, 2016.

Invited lectures and talks highlights

- Cramer was invited speaker at the 30th Annual IACR EUROCRYPT conference (2011).
- Ducas was invited speaker at Mathematics of Lattices and Cybersecurity, ICERM, Brown University (2015) and at the Conference on Mathematics of Cryptography, UC Irvine (2015).
- Fehr was invited speaker at the 6th ICITS conference in Montreal (2012) and at the 14th Annual QIP conference (2011).
- Stevens was invited speaker at the SHARCS workshop in Washington (2012); the 80th Anniversary of Breaking the Enigma-Code in Warsaw (2012).

Peer recognition and service highlights

- Cramer: Fellow of the International Association for Cryptologic Research (2013);
- Cramer: Member of the Royal Netherlands Academy of Arts and Sciences (KNAW) (2013);
- Cramer served on the Fellows of IACR selection committee (2012-2016) and on the IACR TCC Test-of-Time Award jury (2014-2016);
- Cramer: on the Editorial Boards of Journal of Cryptology, IEEE Transactions on Information Theory, Journal of Algebra and Its Applications, Designs/Codes/Cryptology and Journal of Mathematical Cryptology;
- Cramer: initiator and scientific co-organizer of workshop and school series Mathematics of Information-Theoretic Cryptography (IPAM, UCLA Los Angeles), 2011;
- Ducas obtained the Facebook and USENIX Internet Defense Prize in 2016;
- Fehr: on the Editorial Board of Journal of Cryptology;
- Fehr: Programme Chair for ICITS 2012 and for PKC 2017, both in Amsterdam;
- Stevens obtained the IACR CRYPTO Best Young Researcher Paper Award in 2013, the Martinus van Marum Prize for his PhD thesis in 2013 and the Google Junior Faculty Applied Research Award in Security, Privacy & Anti-abuse in 2016;
- Stevens: on the Editorial Board of IACR Transactions on Symmetric Cryptology.

Public lectures, media appearances and outreach highlights

- Cramer gave a Cleveringa lecture at the residence of the Ambassador of the Netherlands in Singapore (2014).
- Stevens gave a lecture at the NLUUG spring conference in Utrecht (2016).

Grants highlights

- ERC Advanced Grant for Cramer (call 2016, awarded in 2017);
- ERC Starting Grant for Pietrzak (2011);
- NWO Veni grant for Ducas (2016) and for Stevens (2014);
- NXP Semiconductors grant for Cramer and Ducas (2016).

Database Architectures (DA) Group

The Database Architectures group performs system-oriented research in the broad area of data management systems and infrastructure for supporting big data, data science, large-scale data analytics, data-driven scientific discovery, and data driven industry and economy. It is known in academia and industry for its pioneering column store technology, fast compression methods, vectorized query execution, online query-driven indexing (cracking), adaptive caching, hardware-optimized data structures and algorithms, and integration of statistical languages and analysis in database systems. The group develops, distributes and maintains the MonetDB open-source data management system, and has spawned multiple spin-off companies, including Data Distilleries, VectorWise and MonetDB Solutions (2013). The group also operates a self-built cluster, SciLens, that is bandwidth-optimized and thus better suited as a data-science infrastructure.

Publications highlights

- D. Abadi, **P. Boncz**, S. Harizopoulos, S. Idreos, S. Madden. The Design and Implementation of Modern Column-Oriented Database Systems, Foundations and Trends in Databases 5 (3), 197-280, 2013;
- **H. Mühleisen**, **M. Kersten**, **S. Manegold**. Capturing the Laws of (Data) Nature, 7th Biennial Conference on Innovative Data Systems Research, 2015;
- G. Graefe, F. Halim, **S. Idreos**, H. Kuno, **S. Manegold**, B. Seeger. Transactional Support for Adaptive Indexing, VLDB Journal 23 (2), 303-328, 2014 (one of the best papers of VLDB 2012).

Invited lectures and talks highlights

- Boncz: The story of Vectorwise, Keynote, Base de Données Avancées 2011;
- Boncz: Benchmarking Graph Data Management Systems, keynote, International Conference on Extending Database Technology, in 2014;
- Kersten: DataFungi: from Rotting Data to Purified Information, Keynote, IEEE International Conference on Data Engineering, in 2016.

Peer recognition and service highlights

- Kersten was made ACM Fellow; Boncz was made Hans Fischer Fellow at TU Munich.
- Kersten served as programme chair for IEEE eScience 2016.
- Boncz serves on the Board of Trustees of the VLDB Endowment since 2014, as editor-in-chief for PVLDB volume 10, and as associate editor for The VLDB Journal, IEEE Data Engineering Bulletin and PVLDB volume 9.
- Manegold served as associate editor of PVLDB three times (volumes 6, 8 and 10) and was guest editor of ERCIM News 89 (Big Data special issue) in 2012.
- Manegold, Boncz, Kersten won the bid for organizing SIGMOD/PODS 2019 in Amsterdam.
- Boncz, Mühleisen, Manegold take a central role in the education programme of Amsterdam Data Science, teaching two master's courses (Large Scale Data Engineering, Big Data) and two postgraduate courses on Big Data Infrastructures and Technology at VU University Amsterdam and University of Amsterdam/ABS.
- Alumni: M. Zukowski (co-founder of Snowflake), S. Idreos (assistant professor at Harvard University), H. Pirk (postdoc at MIT), T. Sellam (postdoc at Columbia University New York).

Software highlights

- MonetDB, MonetDB-R connector, integrated R and Python in MonetDB, MonetDB-lite for R.

Public lectures, media appearances and outreach highlights

- Mühleisen is co-initiator of the WikiStats and Common Crawl projects.

Grants highlights

- Kersten participated in the EU FP7 Human Brain Project;
- We received ~2.5 M€ from the COMMIT/ programme and ~1 M€ direct industry funding;
- Idreos (2012) and Mühleisen (2015) were awarded NWO Veni grants;
- NWO Middelgroot: SciLens (Kersten, 2010-2015), SciLens2 (Kersten, 2016-2018);
- Kersten & Scheers NWO Big Bang Big Data (2014).

Prizes highlights

- Kersten won the 2014 ACM SIGMOD Edgar F. Codd Innovations Award and the 2016 ACM SIGMOD Systems Award (for MonetDB).
- Boncz won the 2013 Humboldt Research Award.
- Idreos won the 2011 ACM SIGMOD Jim Gray Doctoral Dissertation Award and the 2011 ERCIM Cor Baayen Award.
- Kersten, Idreos, Manegold and Liarou were awarded Best Paper at VLDB Challenges & Vision Track 2011.

Distributed and Interactive Systems (DIS) Group

Future multimedia systems will be intelligent and empathic, capable of understanding the user and the environment. Extending techniques from distributed networking and contextual modelling, DIS adapts and extends traditional research on multimedia systems from this new perspective. Our research not only addresses how fast bits are delivered, but also how well they are utilized. We combine data science with a strong human-centric, empirical approach. This results in a full-stack methodology that enables us to bridge socio-technical gaps in society and science, by instrumenting the appropriate infrastructures and communication protocols using realistic testing grounds. DIS enjoys a number of fruitful partnerships with companies and organizations in the areas of creative industries and smart cities.

Overall highlights

- Six paper awards in top venues such as ACM MMsys and PhyCS;
- Over 100 conference papers and around 50 journal papers;
- Four PhD theses on multimedia systems, HCI, and multimedia authoring;
- Societal impact by active participation in standardization activities in MPEG, ITU, W3C.

Publications highlights

- **J. Jansen**, **P. Cesar**, **D.C.A. Bulterman** et al. Enabling Composition-Based Video-Conferencing for the Home, IEEE Transactions on Multimedia 13 (5), 869-881, 2011;
- **R. Mekuria**, **K. Blom**, **P. Cesar**. Design, Implementation and Evaluation of a Point Cloud Codec for Tele-Immersive Video, IEEE Transactions on Circuits and Systems for Video Technology 27 (4), 828- 842, 2016.

Invited lectures and talks highlights

- Cesar: keynote at WebMedia (2011), International Workshop on Immersive Media Experiences (2015), Intelligent Valley Conference (2016), and Sense of Contact (2016);
- Bulterman: keynote at NEM Summit (2013), ACM Multimedia (2013), IEEE ISM (2014), ACM TVX (2014), IEEE BigMultimedia Data (2015), IEEE ISM (2016);
- Bulterman: distinguished lecture at National Academic of Science (Washington), 2014.

Peer recognition and service highlights

- Editorial board: ACM TOMM (Cesar, Bulterman), ACM/ Springer Multimedia Systems (Bulterman), Springer MTAP (Cesar);
- PC co-chair of ACM Multimedia (2015, Bulterman) and ACM TVX (2014, Cesar);
- Bulterman as ACM SIGWEB chair and W3C SYMM chair;
- Steering committee: Cesar ACM TVX (since 2013), Herman IW3C2 (since 1997).
- Shamma was named ACM Distinguished member in 2016.

Software highlights

- A rich media player and authoring suite (Ambulant, 60,000 downloads in 2011-2016), a reference implementation for 3D point cloud coding (3DPCC), and a tool for measuring end-to-end video latency (VideoLat).

Use of research results highlights

- Over 170,000 downloads of our open source software, with XForms used in government departments and websites like the Royal Netherlands Meteorological Institute (KNMI);
- RDFa as a canonical machine representation of schema.org (part of millions of webpages);
- Two PPPs with Xinhuanet (2014) and ByBorre (2016).

Public lectures, media appearances and outreach highlights

- Cesar: distinguished lecture at CBS (Statistics Netherlands), 2016;
- Pemberton talked at the Ministry of the Interior and Kingdom Relations and at the UK Cabinet Office;
- DIS has extensively appeared in media outlets such as Wired, New Scientist, RedBull.tv.

Grants highlights

- Over 2.5 M€ in funding from competitive calls (FP7, H2020) and PPPs.

Prizes highlights

- The programming language Python was awarded a National ICT Award (2013).
- Bulterman was awarded the ACM SIGMM Award 2013 for Outstanding Technical Contributions to Multimedia Computing, Communications and Applications.
- Bulterman and Blom were members of the W3C Timed Text Working Group that received a 2016 Technology & Engineering Emmy Award from the U.S.

Formal Methods (FM) Group

Formal Methods aims at the development and application of mathematically founded methods for the design and analysis of software. The research of the FM group focusses on component-based models and software architectures, programme semantics and logics, and co-algebraic models of computation. Our work yields new technologies that support and improve the practice of software engineering and service-oriented computing.

Overall highlights

- Development of the Abstract Behavioral Specification (ABS) language and its application to modelling and analysis of Cloud applications;
- coalgebraic generalisation of enhancements of the coinduction/bisimulation proof method, leading the way to new applications, e.g., in automata theory;
- Code generation for the execution of the coordination language REO on multicore architectures.

Publications highlights

- **S. de Gouw**, **J. Rot**, **F.S. de Boer**, R. Bubel, R. Hähnle. OpenJDK's Java.utils.Collection.sort() Is Broken: The Good, the Bad and the Worst Case, Computer Aided Verification - 27th International Conference, Proceedings Part I, 273-289, 2015;
- D. Sangiorgi, **J. Rutten**. Advanced Topics in Bisimulation and Coinduction, Cambridge Tracts in Theoretical Computer Science 52, 2011 (196 citations);
- **S.S.T.Q. Jongmans**, T.W.J. Kappé, **F. Arbab**. Composing Constraint Automata, State-by-State, Revised Selected Papers of the 12th International Conference on Formal Aspects of Component Software 9539, 217-236, 2015 (Best Paper Award).

Peer recognition and service highlights

- Rutten is editor of Logical Methods in Computer Science, Scientific Annals of Computer Science, and Advances in Group Theory and Applications; Arbab is editor of Computing Journal of Springer and Scientia Iranica; De Boer is editor of ACM Transactions on Computational Logic, Scientific Computing, and Formal Methods of Frontiers.
- De Boer co-chaired the international conferences Formal Methods (2015) and Theoretical Computer Science (2012).
- De Boer has been a driving force behind the Software Engineering Symposium in the Netherlands (SEN), which was initiated in 2014.
- Baeten is chair of the steering committee of the CONCUR conferences.

Software highlights

- Development of a software tool for runtime verification of Java programs;
- IDE for the coordination language REO.

Use of research results highlights

- Our proposed correction of the fundamental error we discovered in the implementation of the sorting algorithm TimSort in mainstream libraries has been adopted by Python and Android.
- Java followed another approach on the basis of our worst case analysis of this error. The corresponding blog post (on http://www.envisage-project.eu) has been viewed more than 4,477,000 times.

Grants highlights

- EU projects: in 2013 and 2014 De Boer as PI acquired two EU FP7 projects (one of which as coordinator).
- NWO projects: as PI Rutten was awarded two NWO projects on co-algebra in 2013 and 2014.
- In 2014 De Boer as PI acquired a PPP with the e-commerce company SDL-Fredhopper; in 2014 Arbab was awarded an internal CWI/NWO project; in 2015 Arbab was awarded as PI a project funded by the Office of Naval Research, USA, through SRI International, California.

Prizes highlights

- Rutten got the 2015 Elsevier Theoretical Computer Science (TCS) Award for the paper 'Universal coalgebra' as the most cited paper published in 2000. It is in the top 10 most cited of all (11000+) papers ever published in TCS;
- Cum laude for the FM PhD students Rot (2015) and Jongmans (2016);
- Rot received the IPA Dissertation Award (2015);
- Best Paper Award for 'Composing Constraint Automata, State-by-State', co-authored by Arbab, venue: Proc. Formal Aspects of Component Software (FACS), in 2015.

Information Access (IA) Group

The Information Access group develops methods and techniques to better support users in accessing information that is heterogeneous, subjective and potentially inconsistent. The IA group focuses on the information context, using knowledge graphs to model differences in time and other relevant perspectives. The group works together with social scientists and humanities researchers to evaluate how technology can be used to best interpret complex data, by modelling and comparing different assumptions underlying the interpretation. IA advocates the notion of transparency in all critical use of technology to improve trust assessments.

Overall highlights

We established new research lines around:

- the theme of algorithmic transparency and trust in scientific workflows, with publications on retrievability bias (JCDL'2016) and end-user understanding of classification errors in machine learning (ACM Multimedia Systems Journal, 2015);
- modelling time and context in knowledge graphs, with a first publication on combining distributional semantics and structured data and a demo prize at ICT Open 2016.

Publications highlights

- **J. He**, M. Bron, **A. De Vries**, L. Azzopardi, M. De Rijke. Untangling Result List Refinement and Ranking Quality: a Framework for Evaluation and Prediction, Proceedings of the 38th International ACM Conference on Research and Development in Information Retrieval SIGIR, 293-302, 2015;
- **J. He**, **V. Hollink**, **A. De Vries**. Combining Implicit and Explicit Topic Representations for Result Diversification, Proceedings of the 35th international ACM Conference on Research and Development in Information Retrieval SIGIR, 851-860, 2012.

Peer recognition and service highlights

- Hardman is the current president of Informatics Europe, chair of the advisory board of SOCIAM (theory and practice of social machines), and member of the editorial board of the Journal of Web Semantics.
- Hardman was named Distinguished Scientist by the Association for Computing Machinery (ACM) in 2014.
- Hardman was a member of the advisory board of Lorentz Center 2011-2014.
- Van Ossenbruggen was chair of several national and international conferences.

Software highlights

- With our VUA colleagues, we co-developed the ClioPatria RDF application platform, used by academic and commercial third parties, and now evolving into an online platform for transparent data science.
- Our 'white box' alignment platform Amalgame was brought to the market by the group's spin-off company Spinque.

Use of research results highlights

- Van Ossenbruggen co-authored with Frank van Harmelen 'Connected content, connected organisations', strategic advice for Dutch governmental digital heritage infrastructure policies.
- We implemented the research described in our IJHCS'09 paper in 2014 in the collection management tool used by the Rijksmuseum and the majority of other Dutch museums.

Public lectures, media appearances and outreach highlights

- Hardman gave keynote lectures at JENUI 2014 and womEncourage (ACM) 2016.
- Hardman co-edited the Informatics Europe booklet 'More Women in Informatics Research and Education', 2013.

Grants highlights

- J. He was awarded an NWO Veni grant in 2014.
- Several national (including 2 COMMIT projects) and European (Fish4Knowledge, VRE4EIC) projects.

Prizes highlights

- Hollink won the LODLAM Open Data Prize at the SUMMIT 2015 for Linked Open Data for Libraries, Archives and Museums.

Intelligent and Autonomous Systems (IAS) Group

IAS investigates various types of complex systems in which interacting nodes (agents) continuously exchange digital or physical resources, including information, energy, materials and products. The agents in these systems often only have access to partial and noisy information and need to operate in a constantly changing environment. The IAS group studies generic and fundamental mechanisms that enable the development of various degrees of (self-)organization, intelligence and autonomy in such systems. These include adaptive optimization and decision making under uncertainty, allocation mechanisms in agent systems, extracting actionable information from noisy data, and strategy development for cooperation and competition. The theoretical insights are applied to concrete problems of societal relevance, including smart energy systems, agent-based markets, and data-driven logistics.

Publications highlights

- **J. Han**, **E.J. Pauwels**, **P.M. de Zeeuw**, P.H.N. de With. Employing a RGB-D Sensor for Real-Time Tracking of Humans across Multiple Re-Entries in a Smart Environment, IEEE Transactions on Consumer Electronics 58 (2), 255-263, 2012;
- **S. Dulman**, **E.J. Pauwels**. Self-Stabilized Fast Gossiping Algorithms, ACM Transactions on Autonomous and Adaptive Systems 10 (4), 1-20, 2016;
- **N.H. Luong**, M.O.W. Grond, **H. La Poutré**, **P.A.N. Bosman**. Scalable and Practical Multi-Objective Distribution Network Expansion Planning, Proceedings of the IEEE Power & Energy Society General Meeting, 2081-2086, 2015;
- **G. Methenitis**, **M. Kaisers**, **H. La Poutré**. Incentivizing Intelligent Customer Behavior in Smart-Grids: A Risk-Sharing Tariff & Optimal Strategies, Proceedings of the 25th International Joint Conference on Artificial Intelligence, 380-386, 2016;
- T.V. Kanters, F.A. Oliehoek, **M. Kaisers**, S. R. vd Bosch, J. Grispen, J. Hermans. Energy- and Cost-Efficient Pumping Station Control, Proceedings of the 30th AAAI Conference On Artificial Intelligence, 3842-3848, 2016.

Invited lectures and talks highlights

- La Poutré: invited speaker Union Française de l'Electricité. 'De la smart city à l'Europe connectée', Paris 2016;
- Pauwels: invited lecture at LifeWatch (ESFRI) closing symposium (2011).

Peer recognition and service highlights

- La Poutré was member of senior programme committees of AAMAS (Autonomous Agents and Multiagent Systems); editorial board of ACM TOIT (Transactions on Internet Technology).
- La Poutré was member of Scientific Directorate of Dagstuhl (Leibniz Center for Informatics).
- La Poutré is scientific head of Energy division of Commit2Data and NWO call ESI-bida, member VICI 2011 selection committee, NWO Exact Sciences.
- La Poutré was co-chair IEEE Symposium on Computational Intelligence for Financial Engineering & Economics, 2011, 2013.
- Pauwels was guest editor, special issue: Few-shot learning for multimedia content understanding. Multimedia Tools and Applications, Springer, 2016.

Use of research results highlights

- Pauwels was coordinator PPP Smart Industry project CWI-Engie on optimal scheduling.
- La Poutré led several programme definitions and supervisions for NWO in the area of future energy systems, (URSES, ESI-pose, ESI-bida, Commit2Data/Energy).
- Launch of spin-off SEITA to commercialize IAS research into energy flexibility (2016).

Public lectures, media appearances and outreach highlights

- IAS members appeared in newspapers (e.g. Trouw), books and BNR News Radio.

Grants highlights

- NWO-ISCOM Project Scalable Interoperability in Information Systems for Agile Supply Chains (2015-2019);
- IAS acquired smart energy related projects in EIT Digital (formerly EIT ICT Labs), for a total amount exceeding 1 M€, as well as project grants from NWO, Era-Net, TKI, and STW.

Prizes highlights

- Luong, La Poutré, Bosman, Best Paper Award at ACM GECCO 2015;
- Peter Bosman, together with Brys, Drugan, De Cock and Nowé: Best Paper Award at ACM GECCO 2013;
- Hoogland won 2nd prize with the agent cwiBroker at the Power Trading Agent Competition (PowerTAC) at AAMAS 2013 and AAMAS 2014.

Life Sciences (LS) Group

The group is an interdisciplinary team of computer scientists, mathematicians and mathematical and computational biologists who develop new algorithms, models, theories, and decision support systems in collaboration with experimental biologists and medical experts. The focus is on:

- data science methodology (including data mining, data integration and uncertain data analysis);
- latent variable modelling, and sequence and graph-based analysis;
- modelling and simulation for cell motility, embryonic development and cell processes;
- model-based evolutionary algorithms for single- and multi-objective optimization and machine learning, deformable medical image registration, and radiotherapy treatment plan optimization;
- optimization and enumeration algorithms for cell processes and symbiosis, phylogenetic networks.

Overall highlights

- We developed novel methods for 'big uncertain data' analysis, that combine ultra-fast enumeration techniques with latent variable modelling: significant contributions to genomics and genetics oriented personalized medicine research and to computer science in general.
- Driven by the fact that many real-world clinical challenges are multi-objective optimization problems, we design, and successfully apply, cutting-edge evolutionary algorithms (EAs).
- We significantly increased our impact on the health and bio field, e.g. through the Genome of the Netherlands (GoNL) Consortium (a.o. Nature Genetics paper, 2014).

Publications highlights

- J. Hehir-Kwa et al. (**Schönhuth** co-corresponding author, as a leader of this research team). A high-quality Human Reference Panel Reveals the Complexity and Distribution of Genomic Structural Variants, Nature Communications 7, 12989, 2016;
- **R.F.M. van Oers** et al. Mechanical Cell-Matrix Feedback Explains Pairwise and Collective Endothelial Cell Behavior In Vitro, PLoS Computational Biology 10 (8), e1003774, 2014;
- **P.A.N. Bosman**. On Gradients and Hybrid Evolutionary Algorithms for Real-Valued Multi-Objective Optimization, IEEE Transactions on Evolutionary Computation 16 (1), 51-69, 2012.

Peer recognition and service highlights

- Schönhuth was PC and publicity chair for leading conferences 2016/7 (RECOMB/-Seq).
- Merks is president of the European Society for Mathematical and Theoretical Biology.
- Bosman is appointed in 2016 general chair of leading conference on EAs (GECCO).

Software highlights

- Snakemake: workflow management system. 110,000 downloads since 2012; used in the GoNL project and by various international high impact studies published in, e.g. Nature Genetics, Cell, Cancer Cell, and Nature Methods;
- CLEVER-SV: clique-enumerating variant finder; significant contributions to GoNL;
- VirtualLeaf: plant tissue simulation package; applied in research published in e.g. Science.

Use of research results highlights

- Marked increase in collaborations with hospitals and industry on real-world applications. This enabled (shared) project funding from new sources such as cancer funds (> 2 M€);
- A partnership in an Inria European Project-Team (ERABLE) provides critical mass and networking in algorithmic biology. Two European projects have resulted.

Public lectures, media appearances and outreach highlights

- Merks gave a lecture for children at the Natural History Museum Rotterdam 'How does a zebra gets its stripes?'

Grants highlights

- Merks (2010) & Schönhuth (2013) were awarded Vidi grants; Köster (2016) a Veni grant;
- Bosman: 3 fte partially financed by industry; 2 fte by grants from domain-specific funds;
- Blom: EU-FP7 BioPreDyn (2011-2015).

Prizes highlights

- El-Kebir: BioSB Young Investigator Award 2015;
- Klau: Certificate of Excellence, 11th DIMACS challenge: Steiner Tree Problems;
- Bosman: 2 times Best Paper Award, ACM GECCO 2013 and 2015;
- Marschall, Schönhuth: Faculty of 1000 paper award, 2013 (for GoNL methods paper).

Machine Learning (ML) Group

Machine learning concerns the design and analysis of computer programs that learn from data. These algorithms integrate insights from various fields, including statistics, information theory, (convex) optimization and neuroscience. The CWI ML group specifically targets probabilistic modelling, in the common situation in which models are wrong, yet useful; sequential prediction, with algorithms that provably perform well both in worst-case and in average-case scenarios; and spiking neural networks, an energy-efficient alternative to 'deep learning' algorithms that draws from how the brain processes information.

Overall highlights

- We showed that the popular Bayesian techniques can dramatically overfit for wrong-yet-useful models, and we designed the novel safe Bayesian method (available as an R package) to deal with the issue.
- We developed a new type of online sequential prediction methods that exhibit worst-case (minimax) optimal behaviour yet simultaneously perform much better on so-called easy data sequences.

Publications highlights

- **T. Van Erven**, **P. Grünwald**, **S. de Rooij**. Catching Up Faster by Switching Sooner, Journal of the Royal Statistical Society Series B 74 (3), 361-397 (with discussion 397-417), 2012 (presented as Read Paper at the RSS Ordinary Meeting, 19 October 2011);
- **J. Rombouts**, **S. Bohté**, P. Roelfsema. How Attention Can Create Synaptic Tags for the Learning of Working Memories in Sequential Tasks, Plos Computational Biology 11 (3), 2015.

Invited lectures and talks highlights

- Bohté gave an invited talk at the EAPCogSci conference (Turin, 2015).
- Koolen gave an oral presentation (best 2% out of 2500 submissions) at NIPS 2016.
- Koolen and Grünwald gave invited mini-courses in Japan, UK, Hungary and France and invited talks at four NIPS workshops.

Peer recognition and service highlights

- Grünwald was general chair of UAI (Uncertainty in AI) 2011, and co-programme chair of COLT (Conference on Learning Theory) 2015, both prestigious ML conferences.
- All group members co-organized NIPS and several other workshops, including two Lorentz workshops.
- Grünwald was driving force behind the establishment of the annual W.R. van Zwet Award (best Dutch PhD thesis in statistics/operations research) and also became first chairman of the jury (2012-2015).
- Grünwald and Bohté were external PhD examiners for several theses in UK and France.
- In 2015 and 2016 Grünwald was member of the NWO Top-2 Evaluation Committee.
- Since 2014 Bohté is Associate editor of IEEE Trans. on Neural Networks and Learning Systems and is editor of a special issue of Frontiers of Computational Neuroscience (2016).

Public lectures, media appearances and outreach highlights

- In 2011-2014 Grünwald gave lectures on the use of statistics in court for Dutch judges.
- In 2015 Grünwald gave the plenary lecture at the annual Dutch Math Days (Nederlandse Wiskunde Dagen).
- ML members appeared on Dutch public television ('De Rekenkamer') and were interviewed by national newspapers (Trouw, De Volkskrant, Telegraaf), radio and various magazines.
- Bohté gave public talks at AwesomeIT 2015 and the Who's in Town AUC seminar series.

Grants highlights

- Koolen was awarded a Veni grant (2014) and Grünwald was awarded a Vici grant (2011).
- In 2016, a TOP-Module 1 grant was awarded to Grünwald.
- Bohté co-proposed an NWO IDEAS programme which was expanded into the 2013 NWO programme Natural Artificial Intelligence (NAI). From this programme Bohté obtained a PI and a co-PI grant (2014).
- Bohté obtained an UvA ABC co-PI grant.

Multiscale Dynamics (MD) Group

To model dynamical phenomena which develop on multiple scales in length, time and energy, we combine scientific computing with techniques of model reduction and machine learning. We develop new multiscale computational codes and analytical approximations, and we apply them mainly to phenomena in collision-dominated or collision-less plasma dynamics. We study natural phenomena such as lightning propagation, terrestrial gamma-ray flashes and space weather, and we contribute to developing new technologies based on the same mechanisms such as switchgear for high voltage electricity nets, air purification and disinfection with corona reactors, and space weather predictions for the protection of satellites and electricity nets.

Overall highlights

- Rademacher, an expert in (nonlinear) dynamical systems, joined on tenure track in 09/2006, and left for a full professorship at Bremen University in 03/2013.
- Camporeale joined on tenure track in 01/2014. He now very successfully sets up research on scientific computing and machine learning for space weather predictions.
- Ebert, Camporeale, Hundsdorfer et al. published over 80 papers in international journals from 2011 to 2016. In March 2017, these papers were cited more than 1000 times.

Publications highlights

- Much cited articles and open source software on general computational methods:
  - Comparing superparticle methods, Journal of Computational Physics, 2014, by Teunissen and Ebert;
  - Plasma-chemical pathway analysis (www.pumpkin-tool.org), Computer Physics Communications, 2014;
  - AMR framework afivo by Teunissen and Ebert.
- Much cited articles for computations of pulsed gas discharges:
  - articles (one, two) in Journal of Computational Physics and one article in Plasma Sources Science and Technology, 2012, by Luque, Li et al. on 3D PDE models and on hybrid particle-PDE models;
  - articles (one, two) by Teunissen et al. in Plasma Sources Science and Technology, 2016, with unprecedented 3D dynamic discharge simulations, with particle and with PDE models.
- Much quoted papers relating discharge modelling to results of dedicated experiments were written with Nijdam et al. and with Kochkin and Van Deursen of Eindhoven University of Technology.
- Lightning inception and its intra-cloud conditions were studied with colleagues at KVI Groningen within the LOFAR collaboration. The first results were published in Physical Review Letters (one, two), 2015, that received broad international media attention.
- Much cited articles on space weather in Journal of Geophysical Research (2013), Astrophysical Journal (2011, 2014).
- New plasma models in Plasma Physics and Controlled Fusion (2014) and Physics of Plasmas (2015).

Peer recognition and service highlights

- Ebert, Hundsdorfer and Camporeale gave 5 plenary and 23 invited talks at international conferences and workshops during 2011-2016.
- Ebert was member of the international scientific committee of 5 international conferences or workshops, Camporeale was session convener at 3 international conferences.
- Ebert is editor of Contributions to Plasma Physics (2011-2012), Journal of Physics D: Applied Physics (since 2013), Plasma Sources Science and Technology (since 2016), Hundsdorfer is editor of Applied Numerical Mathematics.
- Ebert is co-author of the international Plasma Road Map 2017.
- Ebert is member of the Royal Holland Society of Sciences and Humanities (KHMW).
- http://www.spaceweather.wiki/ - an interactive web-based platform for space weather predictions based on neural networks architectures by Camporeale et al.

Grant highlights

- 6 STW projects (2008-2012, 3 in 2010-2015, 2011-2016, 2016-2021) with partners at TU/e and with industrial users committees; Ebert leads 3 of these projects. Each project had at least one PhD student at CWI. A postdoc was employed in a PPS after one project;
- 2 FOM projects (2012-2017), in open competition and in Computational Sciences for Energy Research;
- 3 European networks (2 EU-COST, ESF) where Ebert was in the management team;
- Innovative Training Network SAINT (2016-2020) in Marie Skłodowska-Curie Actions Programme with 15 PhD students in Europe, of whom 2 at CWI. Ebert coordinates the work package on Modelling and Scientific Computing within the network;
- CWI-Inria-project and associated team on Machine Learning for Space Weather;
- Camporeale received an NWO Vidi grant (call 2016, awarded in 2017).

Prizes highlights

- Teunissen obtained his PhD cum laude in November 2015, and he won the Student Award of Excellence of the 68th Gaseous Electronics Conference in October 2015 in Hawaii.

Networks and Optimization (N&O) Group

N&O focusses on the development of algorithms to solve fundamental optimization problems, both in centralized and decentralized settings. Key to our research is the understanding and exploitation of combinatorial structures such as graphs, networks, lattices and matroids. By developing and combining methods from algebra, geometry, combinatorics, game theory, discrete mathematics and optimization, we provide efficient algorithmic techniques to tackle hard optimization problems, for example in planning, routing and scheduling.

Overall highlights

- We announced the solution to a conjecture posed by Rota in 1970 about matroids.
- We developed the fastest known algorithms for the shortest and closest vector problems.
- We designed efficient SDP-based approximations for polynomial optimization, also in the general non-commutative setting with applications to quantum information.
- Seven completed PhD theses.

Publications highlights

- D. Aggarwal, **D. Dadush**, O. Regev, N. Stephens-Davidowitz. Solving the Shortest Vector Problem in 2n Time via Discrete Gaussian Sampling, Proceedings of the 47th annual ACM symposium on Theory of computing, 733-742, 2015;
- **K.R. Apt**, **B. de Keijzer**, **M. Rahn**, **G. Schäfer**, S. Simon. Coordination Games on Graphs, International Journal of Game Theory, 1-27, 2016;
- E. de Klerk, **M. Laurent**, Z. Sun. Convergence Analysis for Lasserre's Measure-Based Hierarchy of Upper Bounds for Polynomial Optimization, Mathematical Programming 162 (1), 363-392, 2016 (online);
- J. Geelen, **B. Gerards**, G. Whittle. Solving Rota's Conjecture, Notices of the AMS, 61 (7), 736-743, 2014;
- D.C. Gijswijt, H.D. Mittelmann, **A. Schrijver**. Semidefinite Code Bounds Based on Quadruple Distances, IEEE Transactions on Information Theory 58 (5), 2697-2705, 2012.

Invited lectures and talks highlights

- International Congress of Mathematicians (sectional lecture, Laurent, 2014);
- Hausdorff Center Conference 'Panorama of Mathematics' (plenary, Schrijver, 2015);
- Mini-courses and research schools in Ireland, Poland, France, UK, Greece and Brazil.

Peer recognition and service highlights

- Editorships: Mathematical Programming A, Mathematics of OR and SIAM Journal on Discrete Mathematics (Laurent); Combinatorica (Schrijver, EiC); OR Letters (Lenstra, EiC); Journal of Logic and Computation (Apt);
- PC memberships: EC, WINE, SAGT, APPROX, ESA, AAAI, AAMAS (Schäfer); IPCO (Dadush);
- Member scientific committee MFO Oberwolfach (Schrijver until 2013; Laurent from 2015);
- Member of the Optimization and Control panel for ICM 2018 (Laurent, 2016);
- Conference organizations: Combinatorial Optimization (Oberwolfach, 2011, Laurent), Game Theory Cluster ISMP (Berlin, 2012, Schäfer), Web and Internet Economics (Amsterdam, 2015, Schäfer);
- Juries: Gödel Prize (Apt), Farkas Prize (Laurent), Ostrowski Prize (Schrijver), van Wijngaarden Award (Lenstra).

Use of research results highlights

- Developed an algorithm to optimize coach schedules which is integrated in TourExpert, the new standard software for coach companies (public-private collaboration with Rovecom);
- Developed an algorithm used daily for hedge accounting (consultancy for BNG Bank).

Public lectures, media appearances and outreach highlights

- Public lecture during the Lowlands festival (Schrijver, 2012); appearance in television programme 'Nieuwsuur' (Lenstra, 2015); radio interview in NTR (Schrijver, 2014);
- Lectures for children, teachers, professionals.

Grants highlights

- EU: ERC Advanced Grant (Schrijver, 2014), EU Marie Curie ITN (Laurent, 2012);
- NWO: two TOP Module-1 grants (Apt, 2013; Laurent, as PI, 2013, joint with De Wolf and Bansal), two Veni grants (Kang, 2012; Dadush, 2015), Free Competition grant (Schäfer, 2013);
- NWO Gravitation Consortium NETWORKS (Schrijver co-applicant, 2013).

Prizes highlights

- Prizes: EURO Gold Medal for Schrijver (2015), A.W. Tucker Prize for Dadush (2015), SIAG/Optimization Prize for Vallentin (2011);
- Awards: Honorary Doctorate from ELTE Budapest for Schrijver (2011), Knight in the Order of the Netherlands Lion for Lenstra (2011);
- Fellowships: KNAW Royal Netherlands Academy for Arts and Sciences, AMS Fellow, SIAM Fellow (Schrijver); Academia Europaea (Apt, Schrijver).

Scientific Computing (SC) Group

The Scientific Computing group develops efficient computational methods for systems with inherent uncertainties. Such uncertainties arise from e.g. uncertain model parameters, chaotic dynamics or intrinsic randomness, and can have major impact on model outputs and predictions. Current research in the SC group includes numerical algorithms for stochastic differential equations, uncertainty quantification, data assimilation, Monte Carlo methods, stochastic multiscale modelling, risk assessment and rare event simulation. The main application areas for the group are energy systems, finance and climate science.

Publications highlights

- **B. Sanderse**, S.P. Pijl, **B. Koren**. Review of Computational Fluid Dynamics for Wind Turbine Wake Aerodynamics, Wind energy 14 (7), 799-819, 2011;
- L.A. Grzelak, **C.W. Oosterlee**. On the Heston Model with Stochastic Interest Rates, SIAM Journal on Financial Mathematics 2 (1), 255-286, 2011;
- **J. Dorrestijn**, **D.T. Crommelin**, A.P. Siebesma, H.J.J. Jonker. Stochastic Parameterization of Shallow Cumulus Convection Estimated from High-Resolution Model Data, Theoretical and Computational Fluid Dynamics 27 (1), 133-148, 2013.

Invited lectures and talks highlights

- Invited plenary lectures at the 2015 AMMCS-CAIMS Congress (Waterloo, Oosterlee), the 27th IFIP TC7 Conference 2015 (Sophia Antipolis, Oosterlee), SciCADE 2011 (Toronto, Frank), IMA workshop 2013 (Minneapolis, Crommelin);
- Inaugural lectures of Frank and Crommelin at the University of Amsterdam (2011, 2016).

Peer recognition and service highlights

- Editorships: SIAM Journal on Scientific Computing (Frank), SIAM Multiscale Modeling and Simulation (Crommelin), Journal of Computational Physics (Koren). Oosterlee is editor-in-chief of Journal of Computational Finance;
- Frank was appointed professor at Utrecht University (2013). Crommelin was appointed as professor by special appointment at the University of Amsterdam (2014);
- Oosterlee organized workshops at the Lorentz Center (2011 and 2015) and the Weizmann Institute (2013). Crommelin was member of the organizing committee of RESIM 2016;
- Oosterlee is chair of the national committee 'Scientific Computing' (WSC).

Use of research results highlights

- Algorithms developed by Witteveen (uncertainty quantification) and by Wadman (rare event simulation) are used by energy consulting firm DNV-GL.
- Numerical methods for computational finance developed by Oosterlee and co-workers are used by banks and insurers (including Rabo, ING, Nationale Nederlanden).
- CFD methods for wind farms developed by Sanderse and Koren are used by ECN.

Public lectures, media appearances and outreach highlights

- TV and radio appearances of Haverkort (De Wereld Leert Door, 2013), Koren (De Wereld Draait Door, 2014), Oosterlee (Hoe?Zo! radio, 2013);
- Dorrestijn's work on cloud prediction featured in national newspaper NRC (2013);
- Crommelin was guest editor for a theme issue of the Nieuw Archief voor Wiskunde and co-organized a public outreach day, both on Mathematics of Planet Earth (2013).

Grants highlights

- Crommelin was awarded a Vidi grant in 2012;
- Oosterlee was awarded an EU Horizon2020 EID project and is project coordinator;
- Four grants in the FOM-Shell programme Computational Sciences for Energy Research;
- Three STW grants for projects with industry partners; one direct grant from Rabo bank;
- Crommelin and Frank proposed the NWO Ideas programme which resulted in the 2014 NWO programme Mathematics of Planet Earth. The SC group obtained two grants in this programme.

Prizes highlights

- Stieltjes Prize for best PhD thesis in mathematics in the Netherlands for Sanderse (2013);
- Best Student Paper Award for Wadman at WinterSim 2013 Conference (Washington D.C.);
- Oosterlee was nominated for the Huibregtsen prize (2013);
- Ruijter obtained her PhD cum laude (2015).

Software Analysis and Transformation (SWAT) Group

The Software Analysis and Transformation group performs software engineering research in three layers. The application layer comprises R&D questions, focusing on improved engineering techniques for complex software. We design domain-specific languages, analyse and transform software systems, and answer empirical research questions using repository mining. Example application domains are banking and digital forensics. To achieve this we invest in a reusable middle layer, based on language-parametric metaprogramming formalisms, namely Rascal and Ensō. To enable these frameworks, the third and deepest layer investigates algorithms and data structures for the analysis and synthesis of the syntax and semantics of computer languages. Examples are object algebras, data-dependent context-free general parsing, optimized immutable hash-trie-based collection libraries and co-routine-based pattern matching.

Overall highlights

- SWAT contributed a number of high-profile software products and prototypes with substantial uptake in academia, education and industry: Rascal, Ensō, Derric & Capsule.
- In 2016, Inria evaluated the ATEAMS/SWAT project team as 'excellent' within their theme 'Architectures and Compilation'.

Publications highlights

- **D. Landman**, A. Serebrenik, E. Bouwers, **J.J. Vinju**. Empirical Analysis of the Relationship between CC and SLOC in a Large Corpus of Java Methods and C Functions, Journal of Software: Evolution and Process, 28 (7), 589–618, 2015 (surprising result);
- **M.J. Steindorfer**, **J.J. Vinju**. Optimizing Hash-Array Mapped Tries for Fast and Lean Immutable JVM Collections, Proceedings of the 2015 ACM SIGPLAN International Conference on Object-Oriented Programming, Systems, Languages, and Applications, 783-800, 2015 (replicated in Scala and Clojure);
- S. Erdweg, **T. Van der Storm**, M. Völter et al. Evaluating and Comparing Language Workbenches: Existing Results and Benchmarks for the Future, Computer Languages, Systems and Structures 44, Part A, 24-47, 2015 (most cited).

Peer recognition and service highlights

- In 2014 Vinju was appointed Professor at the Eindhoven University of Technology.
- In 2016 Van der Storm was appointed professor at the University of Groningen.
- Van der Storm is vice-chair of the IFIP working group on language design (IFIP 2.16).
- Vinju is chair of the steering committee of the ACM SLE Conference.
- Vinju is member of the IFIP WG 2.4 on Software Implementation Technology.

Software highlights

- Rascal: Metaprogramming Language: http://www.rascal-mpl.org;
- Ensō: Self-describing DSL Workbench: http://enso-lang.org/;
- Capsule: Immutable Collections: http://usethesource.io/projects/capsule/;
- Rebel: Lightweight Specification of Financial Products: https://github.com/cwi-swat/rebel.

Use of research results highlights

- PPP with ING Bank: Rebel and Rascal applied for core financial products;
- Application of Rascal and Derric at Netherlands Forensic Institute (NFI);
- Rascal used for lab exercises of master courses at OU, TUE, UvA/VU, ECU;
- Uptake of immutable collection results in libraries of Clojure[script] and Scala.

Public lectures, media appearances and outreach highlights

- In 2012-2013 Klint appeared in several national radio shows, such as Hoe?Zo! Radio and Goedemorgen Nederland, and lectured a series for children in science centre NEMO.
- In 2015 Klint appeared in national news show RTL Nieuws.
- In 2014 Vinju appeared in national radio show De Kennis van Nu.

Grants highlights

- NWO TOP – DSLs a Big Future for Small Programmes (900 k€);
- EU FP7 OSSMeter – Automated Measurement & Analysis of Open Source Software (540 k€);
- NWO Big Software – MERITS: Model Extraction for Reengineering Traditional Software.

Prizes highlights

- In 2015 Klint, IEEE TCSE Software Engineering Distinguished Service Award;
- In 2016 Steindorfer and Vinju, Distinguished paper award at ACM ICPE;
- In 2016 Vinju, Distinguished paper award at ACM SLE.

Stochastics (ST) Group

Many natural and man-made systems and processes are driven by random phenomena, e.g. in communication, energy, information, logistics, and physics. In order to model, describe, and improve random systems, the Stochastics group develops and studies probabilistic, operational and statistical models. The group's analysis of these models relies on techniques from fundamental probability theory, queueing theory, stochastic scheduling, spatial stochastics and stochastic geometry, and also contributes to the further developments of these techniques.

Overall highlights

- ST launched spin-off Stokhos Emergency Mathematics focusing on ambulance planning.
- A dynamic pricing method developed by ST has been commercialized (DynaPrice).
- We organized prestigious conferences: Performance ('11) and Stochastic Networks ('14).
- New research lines in dynamic pricing, emergency logistics, energy and road traffic.
- Van den Berg, Kiss and Nolin (ETH) have set new standards in frozen percolation, significantly refining a classical scaling relation of Kesten. Van den Berg and Jonasson (Gothenburg) extended the BK inequality, settling a conjecture of Grimmett (1994).
- Lambert, Simatos and Zwart developed a new method to develop process limit theorems.
- Van Lieshout developed new tools to analyse spatiotemporal point processes.

Publications highlights

- **T.C. Van Barneveld**, **S. Bhulai**, **R. Van der Mei**. The Effect of Ambulance Relocations on the Performance of Ambulance Service Providers, European Journal of Operational Research 252 (1), 257-269, 2016;
- **J. van den Berg**, A. Gandolfi. BK-Type Inequalities and Generalized Random-Cluster Representations, Probability Theory and Related Fields 157 (1), 157-181, 2013;
- A. den Boer, **B. Zwart**. Simultaneously Learning and Optimizing Using Controlled Variance Pricing, Management Science 60 (3), 770-783, 2014;
- **P.M. van de Ven**, A.J.E.M. Janssen, J. van Leeuwaarden. Balancing Exposed and Hidden Nodes in Linear Wireless Networks, IEEE/ACM Transactions on Networking 22 (5), 1429-1443, 2014;
- L. Florack, R. Duits, G. Jongbloed, **M.C. van Lieshout**, L. Davies (Eds.). Mathematical Methods for Signal and Image Analysis and Representation, 2012;
- I.M. Verloop, U. Ayesta, **R. Nunez-Queija**. Heavy-Traffic Analysis of a Multiple-Phase Network with Discriminatory Processor Sharing, Operations Research 59 (3), 648-660, 2011.

Peer recognition and service highlights

- In 2015 Zwart was appointed professor at Eindhoven University of Technology.
- In 2015 Van Lieshout was appointed professor at the University of Twente.
- Main editorships: Zwart (area editor at Operations Research), Van den Berg (associate editor at Annals of Probability). ST researchers hold 12 additional associate editorships.
- Zwart is chairman of the Dutch stochastics cluster STAR since July 2015, was chairman of the INFORMS Lanchester prize committee 2016 (best publication in OR/MS), TPC chair of Performance 2015, and chairman of the Stochastic Networks steering committee.
- Van den Berg was visiting fellow of the Isaac Newton Institute, Cambridge (Programme Random Geometry), April-July 2015. Zwart was visiting fellow of the Simons Institute, Berkeley (Programme on algorithms and uncertainty), November-December 2016.

Public lectures, media appearances and outreach highlights

- In 2014-2015 Van der Mei gave a number of national media performances on the topics of dynamic pricing and ambulance planning. In 2016, Van der Mei gave a lecture at the 'Universiteit van Nederland', a virtual university that presents academic topics to a wide audience (over 4,000 views).

Grants highlights

- We have obtained about a dozen competitive NWO grants including a Vici grant in 2015, we coordinate a European COST network, secured 9 PPP projects, and are active in consulting.

Prizes highlights

- In 2015 Zwart was awarded the Van Dantzig Prize - the highest Dutch award in statistics and operations research. Den Boer was awarded the Gijs de Leve Prize (best PhD thesis in operations research 2012-2014). Van der Mei was runner-up for the Huibregtsen-prize (national prize for research with most societal impact). In 2016, Zwart and Den Boer were awarded the INFORMS Revenue Management & Pricing Section Best Paper Award. Rhee won the INFORMS Simulation society Best Paper Award. The PhD theses of Den Boer (runner-up EURO dissertation award, Van Zwet award), Dorsman (runner-up Stieltjes prize), Frolkova (runner-up Takacs prize) and the MSc thesis of Kerkkamp (Hemelrijk award) received additional recognition.

H PhD candidates

T = 2016

Enrolment				Success rates, graduated ...					
Starting year	Enrolment (male / female)		Total (M+F)	<= Y4	<=Y5	<=Y6	<=Y7	Not yet finished	Dis-continued
T-8	9	5	14	7 *50.0%*	2 14.3%	0 0.0%	1 7.1%	3 *21.5%*	1 *7.1%*
T-7	14	5	19	11 *57.9%*	3 15.8%	1 5.2%	0 0.0%	3 *15.8%*	1 *5.3%*
T-6	15	2	17	8 *47.0%*	3 17.6%	2 11.8%		2 *11.8%*	2 *11.8%*
T-5	16	5	21	7 *33.3%*	6 28.6%			6 *28.6%*	2 *9.5%*
T-4	14	8	22	7 *31.8%*				10 *45.5%*	5 *22.7%*
Total	**68**	**25**	**93**	**40** ***43.0%***	**14** **15.1%**	**3** **3.2%**	**1** **1.1%**	**24** ***25.8%***	**11** ***11.8%***
				58 ***62.4%***					

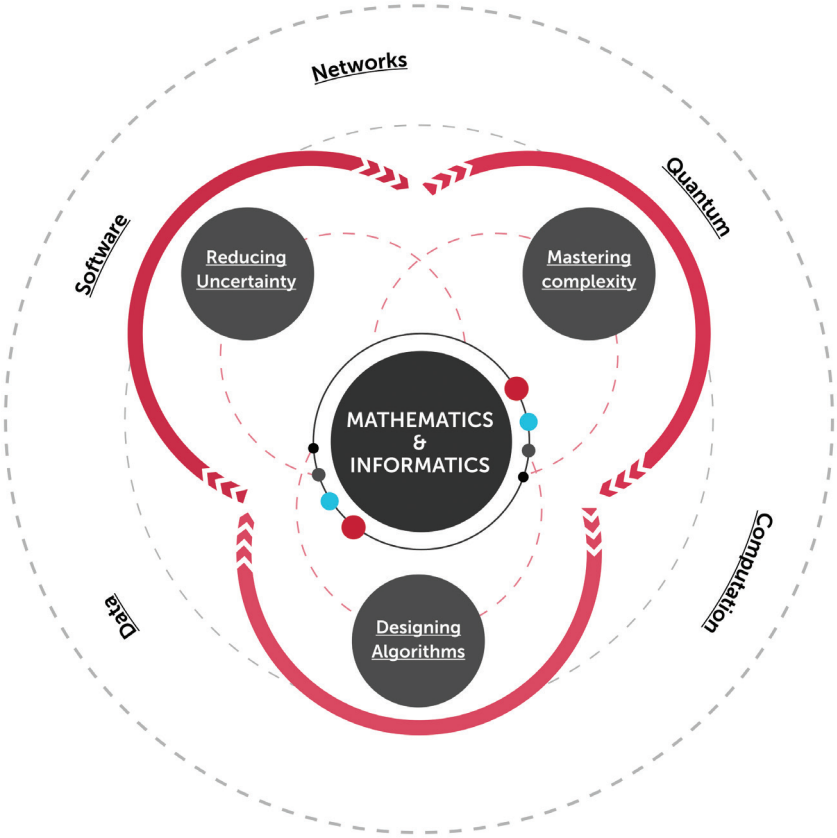
The finishing date used in this evaluation is the date of the student's PhD defences, which is often several months after the actual completion of the thesis.

Please note, of the ten PhD students who started in 2012 (T-4) who have not yet finished their doctorate degree, six will almost certainly finish their degree in 2017.

I Multilevel valorization strategy

Valorization has become an important activity within CWI. An increasing number of public organizations and industrial partners collaborate with CWI in national and international research projects, e.g. in public-private partnerships. Anticipating on a new strategy, we implemented a multi-level valorization strategy in 2016. Through valorization activities, we can create more funding opportunities, which is in line with our strategic targets (Update CWI Strategy 2017).

The aim of our valorization strategy is to secure knowledge transfer to industry and society. Key to our strategy is increasing the transparency and visibility of CWI research to potential partners. We target a broad scope of potential industrial partners, from R&D centres to high-tech SME's. Because of their varying levels of involvement in academic research, we categorize and describe our research on three different levels: our core activities, the societal-relevant themes of our research and our application domains. We thus offer industrial partners insight in our expertise, and in the ways our knowledge can contribute to their future innovations.



Core activities

The following core activities form the fundamental base of all scientific investigations at CWI:

Designing Algorithms
Daily life is increasingly influenced by algorithms, for instance through large software systems. It is therefore essential to design algorithms that are correct, transparent, efficient, and secure, and to incorporate them in high-quality systems.

Understanding the possibilities and limitations of algorithms leads to fundamental research questions about computability and hence touches upon the ultimate limits of scientific knowledge. Under what conditions do hard optimization and prediction problems become efficiently solvable? Are there problems that will remain forever outside our computational reach (most famously, the /P versus NP/ problem)? Can we ingeniously turn this question around and use the computational complexity of

algorithms to create encryption systems that are provably secure? And how can we design algorithms that take full advantage of the astonishing properties of quantum computers to perform multiple calculations simultaneously, resulting in dramatic speed-ups? While such questions are abstract, curiosity-driven and motivated by scientific excitement rather than day-to-day pressures, their potential long-term impact is huge.

Our scientific investigations also address problems related to the pressing demands for guaranteed quality in complex software systems. We therefore investigate formal tools and methods to define, measure, validate and optimize specific quality aspects. Examples include the design of special-purpose languages that simplify the expression of domain-specific actions while guaranteeing certain properties, database architectures that can efficiently manage intricate queries using large datasets, and mathematical proofs that formally show the correctness of software.

Mastering Complexity

Complexity is a subtle concept that comes in a wide variety of flavours. It is associated with systems composed of large numbers of components interacting through numerous positive and negative feedback loops, thus giving rise to global behaviour that is notoriously hard to predict. This type of complexity pervades every level of our world, from multicellular organisms to urban infrastructures, and from socio-economic networks to climate change. It is an intriguing fact that these systems often show striking parallels in the ways in which they behave or evolve, despite their differences in scale and organizational detail. Examples of this include the emergence of new and hierarchically ordered levels of internal organization, the occurrence of global transitions triggered near tipping points, and even the vulnerability to catastrophic collapse due to cascading failures propagating throughout the system. However, complexity also appears in a different guise at an even more fundamental level, where it is closely related to pattern extraction, compression and randomness. As such, it is instrumental in opening up new methodologies for information extraction from data sequences, suggesting novel principles for machine learning, and providing insights into the limits of computability. At CWI, we are interested in all these aspects of complexity. Related questions that we face include: how can we build computational models that describe all relevant interactions across a wide range of spatio-temporal scales? How do we efficiently handle the massive amounts of computation and data that are required for reliable simulations? And how can we design local interactions in complex systems so that they result in global behaviour that is controllable, efficient and robust?

Investigating complexity at an abstract, rather than a specific, level means that our findings are applicable across a wide range of applications and can therefore be used by a host of other disciplines.

Reducing Uncertainty

Uncertainty is an unavoidable fact of life. Most processes, whether in science or society, are highly complex and hence hard to predict. At CWI, research is focused on investigating the nature of uncertainty inherent in complex processes of all kinds, covering a wide range of fundamental questions. Can we chart the various sources of uncertainty in a complicated process and how do they propagate towards the end result? More specifically, how do noisy input data, and approximations or even misspecifications of models, impact on the uncertainty of the outcome? What noise characteristics capture pre-defined properties, and how can we accurately compute them, either through analytical means or via simulation? What amount of variation is intrinsic to a process and therefore unavoidable, and closely related to this, when is a result unusual and indicative of aberrant causes? Or – cunningly turning the tables – can we exploit our understanding of the nature of uncertainty to create applications in which it is maximized, for example in order to devise secure cryptographic encodings.

As uncertainty can never be eliminated, these questions are highly relevant for a host of pressing societal concerns. Examples include the optimal deployment of limited resources when information is incomplete or noisy, risk assessment to safeguard critical infrastructures, and taking informed and rational decisions in the face of global challenges including resource security, climate change and extreme events such as tsunamis or nuclear accidents, that - although unlikely to happen - would have a huge impact if they do.

By framing these questions related to the nature and quantification of uncertainty in an overarching scientific knowledge context, precise answers become possible. As uncertainty affects every aspect of our lives, these investigations are therefore key to forging a future in which science and society can continue to thrive in the face of an unrelenting increase in complexity and its accompanying risks.

Cross-cutting themes

Our research can be clustered in five broad, societal-relevant themes that are of strategic importance and give focus to our efforts. The research themes also provide guidance and transparency to our collaborations with external partners.

Software

Software is everywhere: not only on our computers and smartphones, but also in TVs, cars, hospitals, banks and countless other products and services that are vital to our lives and society. The more we rely on this software, the more important it is that it is secure, robust and respects our privacy. We need to understand our complex software systems to guarantee their quality and to be able to efficiently develop new software.

Software is also a key enabling technology for the competitiveness of the Netherlands and Europe: software is power. Innovative research is essential for the Netherlands to preserve its standing as a software exporting country.

CWI investigates various aspects of software quality, including understanding complex systems, programming languages, software development, verification of correctness and software security.

Data

In the last two years more data was collected by humankind than in all previous years, and this is likely to remain true for the near future. Users on WhatsApp and Messenger sent over 60 billion messages per day, 300 hours of new video material was uploaded to YouTube every minute and radio telescopes registered gigabytes of measurement data per second. Information derived from this data is the driving force for innovation and scientific breakthroughs.

Through data collection and analysis, underlying processes can be understood and subsequently controlled, predicted and optimized. A large part of CWI's research is focused on managing volume (very large databases), velocity (high-speed processing and analysing), variety (integrating data from various sources) and veracity (generating reliable information) of big data. Research areas include database management, data analytics, machine learning and data visualization. In all these, steps transparency is vital to ensure that the results do indeed reflect conclusions that can be drawn from the data.

To strengthen our network of problem owners and data providers, CWI is a partner in national and European organizations, including Amsterdam Data Science (ADS), Amsterdam Centre for Business Analytics (ACBA), Big Data Value Association (BDVA), Data Science Platform Netherlands (DSPN) and the Big Data Alliance (BDA).

Networks

It is fair to say that networks constitute the backbone of our modern society. More than ever we depend on transportation, logistics, communication and energy networks to fuel our daily lives. The more we rely on these complex networks, the better we need to understand them.

Understanding how networks can be designed and used more efficiently, and how congestion or even breakdown can be prevented, is of fundamental importance for the functioning of our society now and in the future. This is a challenging task due to fact that networks are inherently complex.

CWI researchers are studying mathematical and computational models of networks in order to better understand, control and optimize them. To this end, they draw on insights from optimization, stochastics, dynamic systems, capacity planning, risk analysis, cryptology and security.

Currently, CWI researchers play a leading role in NWO programmes concerning logistics networks and energy networks. We are a member of a major NWO Gravitation research programme, NETWORKS, that will enter its second phase in 2018.

Computation

Thanks to rapid progress in computer technology, computation has emerged as the third pillar of scientific discovery next to theoretical science and experimental investigations. Researchers in computational science and engineering develop detailed computational models and simulations, using sophisticated algorithms and powerful computing hardware. It allows them to tackle hitherto intractable, complex problems in numerous fields ranging from physics and biology to sociology and finance.

Researchers at CWI contribute to these efforts in two ways. On the one hand, they design new algorithms that extend computational capabilities, e.g. to distributed networks or quantum computers. On the other hand, they are applying computational methods to investigate urgent questions in various application domains, including systems biology and computational neuroscience, multi-agent systems, weather and climate forecasting, multiscale modelling of non-linear physical phenomena, and quantification of financial and systemic risks.

Quantum

Quantum computers hold great promise as the next generation of hardware. They are based on counterintuitive phenomena from quantum mechanics. For specific problems, quantum algorithms can massively outperform classical algorithms. There are many ideas for applications, but the question of what exactly quantum computers can achieve is largely open. CWI investigates quantum software and applications of the few-qubit platforms that will become available in the near future, including cryptography in a quantum world.

CWI's quantum research is concentrated in the QuSoft research centre, which was founded with the University of Amsterdam and VU University Amsterdam in 2015 to investigate quantum software. It is complementary to the QuTech institute at the Delft University of Technology, which is developing quantum hardware. Quantum technology is a major topic on political innovation agendas, both nationally and internationally. The EU recently announced a 1 billion dollar flagship programme in Quantum Technology. As of 2017, CWI coordinates the Gravitation funded Quantum Software Consortium (18.8 M€).

Application domains

The last and most pragmatic level of our valorization strategy is that of the application domains. Our application domains demonstrate the various topics that CWI can contribute to. This list provides industrial partners with an overview of (potential) application areas that follow from our research. Because our research is fundamental at its core, our application domains cover a wide and diverse spectrum. For a list of CWI's application domains, please refer to appendix J.

J Application domains

At CWI we conduct pioneering research and make it available to industry and society. Our scientific investigations can be applied in a wide variety of application domains and industry sectors.

Blockchain
Blockchain is an innovative new technology that allows distributed digital ledgers in peer-to-peer networks. CWI's challenge is to design better blockchain core protocols that provide even stronger security guarantees, do not require enormous amounts of computational power and therefore energy, and are secure against future quantum attacks.

Computational methods for climate and weather forecasting
Climate research and weather forecasting both rely heavily on simulations using numerical models. CWI develops new numerical algorithms and computational methods that can be used by climate and weather modellers to increase the computational speed and accuracy of their simulations.

Computational social science and digital humanities
CWI designs transparent algorithms that explicitly include a 'human in the loop', so users and machines can interpret large quantities of data together. Our research brings the established tradition of historical source criticism into the digital age.

Cybersecurity
CWI's research aims to deliver efficient digital signature forgery detection algorithms, state-of-the-art security assessments of deployed and proposed cryptographic systems, as well as designing new candidate cryptographic standards that are secure against quantum attackers. Research results can be applied to a broad range of scientific and industrial investigations.

Data integration and information
CWI models the complex user interfaces of modern search engines in the context of the properties of the content searched and the tasks of its users. This provides content owners and search-engine developers with deeper insights about how users interact with large data collections, and which factors play a role in successful interactions.The tools we develop allow organizations to monitor global search-engine performance.

Deep 3D imaging
By using a broad range of mathematical techniques from analysis and scientific computing, CWI creates algorithms that can compute accurate images of the interior of objects from highly limited measurement data. There is a real need for such solutions in science (for improved imaging of materials and biological specimens), industry (for more flexible deep interior quality inspection), and medicine (reducing harmful radiation dose in scans). CWI develops fundamentally new algorithms for 3D-image reconstruction and turns these into open software that is used by academic users in the application fields, as well as by companies for integration into commercial products.

Digital marketplaces
CWI researches economic risk models, evolutionary game theory and multi-agent learning, in order to understand the uncertainties and interaction dynamics, especially in settings with both competitive and cooperative elements.The outcomes of this research include risk estimation algorithms for energy markets, coordination mechanisms for establishing fair and efficient outcomes, and algorithms that are able to interactively represent end-users by learning from experience and feedback.

Emergency logistics
Central to the scientific challenge of researching emergency-service processes is the omnipresence of the phenomenon of uncertainty. CWI's research leads to a better understanding of the stochastic behaviour of these processes, and to algorithms for demand prediction and for smart location and relocation of emergency resources (vehicles and personnel), both at the strategic and the operational level. In our research, we collaborate with ambulance service providers, the fire service, police and roadside assistance.

Financial risk management
Since the worldwide financial crisis, new risk measures are prescribed by the financial regulator and are currently being implemented by the industry. They are based on mathematics and computations. CWI's research in this area is focused on the development of mathematical models and numerical-solution techniques in the domain of financial and insurance risk management, aimed at reducing risk.

Genomic data science
CWI participates in the 'Genome of the Netherlands' project, which is concerned with analysing more than 750 Dutch individuals amounting to 100 terabytes of data. Algorithms developed by CWI have enabled the detection of genetic variants that were notoriously hard to detect before. The result is a catalog of systematically arranged genetic variants, prevalent in the Dutch population, which is invaluable in genetics and personalized medicine studies.

High voltage technology
CWI research concerns experimental techniques and industrial applications for long-distance electricity networks. We develop numerical models of discharge growth on several scales of space, time and energy, and systematic model reduction between the models on different scales. These micro-based and hence quantitative models can predict a growing range of phenomena and replace experiments that are expensive or impossible, and contribute to understanding and using spark processes in high voltage technology.

Immersive media
CWI's research into the connected ecosystem of devices, in which users consume digital content whenever and wherever they want, takes a full-stack approach. Our research primarily targets the creative industries and cultural heritage, while it indirectly influences other sectors based on mediated communication, such as healthcare and education. Our work so far has influenced worldwide standardization bodies such as W3C, ITU, and MPEG.

Industrial tomography
CWI develops advanced image processing and image reconstruction methods that are capable of detecting defects from a limited number of sensor measurements, and are fast enough to be used in an online factory environment. In low-cost, high-volume sectors such as the food industry, our techniques can be used to effectively detect product defects, while in high-cost, low-volume sectors our methods will lead to adaptive industry processes, allowing the repair of defects as early as possible in the production process.

Lightning phenomena and lightning protection
How do thunderstorms generate the X-rays, gamma-rays and antimatter observed from satellites, ground and aircraft? How do lightning leaders propagate? And where and how do they attach to objects and cause damage? Our research showcases fascinating lightning phenomena for the interested public, while our models contribute to the lightning protection of structures such as wind turbines, airplanes, helicopters, high buildings, railways, ships and industrial compounds.

Medical informatics
CWI's research focuses on questions that, when solved, enable improved (decision) support for medical practitioners. A particular focus is on the design of multi-objective optimization algorithms, i.e. with several conflicting goals with an inherent trade-off between them (for example, maximizing radiation delivered to tumour cells versus minimizing radiation delivered to healthy cells). Moreover, by using machine-learning algorithms our research contributes to moving toward patient-specific medicine, by learning from the data of previously treated patients the likely good solutions for new patients.

Model-driven software engineering
The goal of model-driven software engineering is to bring the code of software systems back to a size and shape which can be managed by human software engineers. The challenge is to make it effectively available to all specialized contexts. Bridging the knowledge about the specific domain context to the general software technology is an intrinsic part of CWI's approach. With language workbenches, such

as Rascal Metaprogramming Language and Ensō, we support software engineers in building their own model-driven software engineering solutions.

Multiscale biosystems modelling
Simulations of living organisms must keep track of processes occurring, in parallel, at the molecular scale, the cellular scale, and the tissue level scale. This is a tremendous computational challenge as well as a major scientific challenge. CWI develops new mathematical and computational models and tools to unravel the counterintuitive dynamics of multiscale biological systems. The insights and methodology derived from our research are applied to basic experimental research in cell and developmental biology, to preclinical research in the pharmaceutical sciences, and to nutrition research.

Network analysis and optimization
The analysis and optimization of networks is a difficult task because of their complexity. Through mathematical modelling, CWI extracts the relevant key characteristics of the network and represents them in a concise way. We combine mathematical modelling with sophisticated techniques from discrete optimization, stochastic optimization and algorithmic game theory, and thus the analysis and optimization of such complex networks can be done efficiently. Examples of application domains include railway networks, urban mobility, freight transportation, supply chains and emergency services. The algorithmic tools that we develop to tackle network analysis and optimization problems generally outperform the existing standard solutions in terms of solution quality and/or efficiency.

Neuroprosthetics
Understanding the signals that the central nervous systems emits, and also understanding how to encode external sensory signals so that the brain can understand them, are key issues to biocompatible interfacing. Biologically compatible models of neural-signal processing are thus central to efforts ranging from cochlear implants (invasive hearing aids) to artificial retinas to artificial limbs. The spiking neuron models developed by CWI directly model the behaviour of real neurons while demonstrating an efficient neural coding model. Work underway is, for instance, improving our understanding of how the hearing nerve encodes information, and promising to better the efficacy of cochlear implants.

Plasma technology
The key to energy saving in plasma-chemical processing is to accelerate electrons in an electric discharge to high energies while the gas stays essentially cold. CWI develops numerical models that contribute to understanding and using pulsed plasma technology.These micro-based and hence quantitative models can predict a growing range of phenomena and replace experiments that are expensive or impossible.
Power-efficient autonomous AI
Energy-efficiency in Artificial Intelligence is for many applications of paramount concern. Spiking neural networks approximate the sparse and power-efficient computation that biological brains achieve. Applications range from ‘always on’ AI on cell phones to highly power-efficient intelligence in drones. Future autonomous automotive solutions are likely to similarly benefit from power-efficient deep neural networks. CWI delivers novel deep-spiking neural networks that compute deep neural networks with very few computational and power resources.

Quantum crypto
The research groups at CWI work on design and implementation of new quantum cryptographic primitives, like unbreakable location-verification involving realistic amounts of entanglement, as well as on the analysis, design and implementation of classical cryptographic primitives secure against quantum attacks. Ultimately, our research will make cryptography ready for the quantum age and improve the privacy of individuals, companies and public administration.

Resilient networks
Contemporary society is built on a rapidly expanding number of complex networks, e.g. in logistics, energy, information and social networks.The behaviour of individual agents in these networks becomes hard to predict and control. CWI’s research effort is focused on characterizing global network parameters or performance in terms of the underlying dynamics and topology at the node-level. Simulations generate extensive data sets that need to be mined using data analytics and machine learning to uncover

interesting patterns. The results can then be translated into better engineering decisions to assist in the design and control of such networks. Our research therefore finds applications in network-related problems in smart industry and the optimization of critical infrastructures.

Revenue management and dynamic pricing
Revenue management centres around the increase of revenue by asking the right customer for the right price at the right time. The scientific challenge lies in the development of smart pricing strategies that balance the need to make profit and learn consumer behaviour. Complicating aspects are competition, demand uncertainty, and strategic consumers. CWI's research leads to a better understanding of the effectiveness of pricing strategies, and to the development of smart, 'optimal' pricing strategies.

Route planning and scheduling
The challenge in route planning and scheduling is that there is a vast number of possible routes from which an optimal one has to be chosen. Many side constraints have to be taken into account such as time windows, resting, driving and transition time regulations and travel time uncertainties. By combining mathematical techniques from operations research, combinatorial optimization and discrete choice modelling, optimal routes can be computed in an automated and efficient way for road, rail, air and ship traffic, as well as personalized travel advice. While practitioners usually spend weeks on constructing feasible routes, the new algorithms that CWI develops can compute routes with a provable optimality guarantee within seconds.

Sequential prediction
Electricity companies routinely use predictions of the electricity supply of wind-, solar- and conventional sources to decide whether or not to generate extra electricity. Classical approaches are based on mathematical models, and sometimes the predictions of human experts are also available. CWI focuses on new ways of combining the predictions of such models and experts. It turns out to be possible to do this in a way guaranteed to predict at least as well as the best candidate model or expert, and in many cases even substantially better. The combined prediction algorithm is very robust, and automatically adapts to constantly changing sources. The methodology is also useful for a variety of other problems such as predicting ad-clicking behaviour and even learning to play games.

Smart energy systems
CWI's research models the strategic conflicts of interest arising in energy systems as they are structured today, drawing on tools from multi-agent learning, game theory and mechanism design. We develop strategies for individual stakeholders to maximize their profit in the face of uncertainty and potentially adversarial opponents. In addition, we evaluate alternative regulations of the participants' interactions that promote favourable collective outcomes. The need for research addressing the principles to intelligently orchestrate the future smart-energy system is recognized by the Dutch National Research Agenda in the Topsector Energy and Energy Transition Route (Energietransitie), and the European programmes of Horizon 2020, including Secure, Clean and Efficient Energy.

Societal statistics
Today the p-value based hypothesis test ('$p < 0.05$ means significant result'), a standard method from the 1930s that has several major flaws, is still used almost universally. CWI is developing new, more robust testing methods that are much more reliable and that have proven optimality properties that are much stronger than those available with the standard hypothesis test. This testing method can be relevant for applied scientists, but also for government agencies.

Software maintenance
The great challenge in software engineering is maintenance. The technology for improving software maintenance is relevant for all domains which develop and apply software technology, such as high-tech embedded software systems and finance. One important aspect is diagnostics for hard-to-maintain software and remedies for it, the other key aspect is preventing maintenance issues. CWI has produced the Rascal programming language and eco-system for constructing source code analysis tools. With Rascal, software engineers can rapidly construct their own software tools to help their maintenance tasks.

Space weather
Forecasting space weather events is relevant for technological systems, such as satellites and electric-power networks. They can be severely damaged in case of enhanced fluxes of energetic particles. CWI develops forecasting algorithms for space weather based on machine learning. The abundance of freely available satellite and ground-based data makes the use of modern machine learning techniques an ideal way to tackle the problem of space weather forecasting.

Transportation and mobility systems
Real time coordination and optimization of daily personal activities and businesses processes is fast becoming feasible. With our interdisciplinary approach involving data fusion, data management, data analytics, service provisioning and long-term prediction, CWI's research aims at developing new models, methods and tools for improving the efficiency of logistics processes for human mobility and freight transport. These tools can then be used by the target groups for policy and decision support.

Wearable technology
CWI explores the use of wearable sensors as a source for collecting reliable and quantified data about everyday life experiences. We have created wearable sensors, networking infrastructure and customized algorithms, that collect and analyse fine-grained rich sensor data about users. The environment is customizable for different application domains, and can provide tailored visualization mechanisms. Our first focus has been the creative industries (for example music concerts and theatre plays), but we are interested in expanding our reach to other application domains such as television, advertising, music and FMCG industries.

K Narrative

To illustrate the diverse and perhaps surprising ways in which CWI's research has meaning and value outside the field of mathematics and computer science, and indeed, outside academia, to organizations, companies and society in general, we provide six short stories about our work.

Cryptanalysis research contributes to a safer internet
CWI has a long history in cryptography and cryptanalysis. An impressive example of cryptology research and its major impact on society can be found in the work of Marc Stevens. While working as a PhD student at CWI, Stevens succeeded, through in-depth theoretical analysis, in breaking the MD5 internet security standard for https. After obtaining his doctorate at the Mathematical Institute of Leiden University, Stevens continued his research at CWI, first as a postdoc and tenure tracker, and currently as a tenured researcher. With advanced mathematics, Stevens exposed more weaknesses of cryptographic functions and has shown that the widely used SHA-1 security standard is no longer secure. He collaborated with an international team from Inria in France and Nanyang Technological University in Singapore. In 2015 they made their findings public.

The SHA-1 industry standard is used worldwide for digital signatures, which secure credit card transactions, electronic banking and software distribution. The most recent work of Stevens was focused on corroborating his theoretical analysis in real life. He joined forces with Google's anti-abuse research team, realizing cryptanalytic attacks against SHA-1 with Google infrastructure. The result was that in early 2017 Stevens and Google successfully broke SHA-1 using a so-called collision attack. Looking back, Stevens' research has accelerated the phasing out of SHA-1 and has contributed substantially to a safer internet.

The scientific impact of this research is illustrated by several articles at top publishing venues by Stevens and co-authors, one of which is in the top fifteen list of CWI publications (see appendix F), and a number of invited lectures at conferences. He was honoured for this research with prizes both from science and industry.

Stevens' research has received worldwide media attention, including coverage in the New York Times, WIRED and the Wall Street Journal. As to the broader impact of his research, Stevens says: "My research is completely aimed at protecting the internet from cryptanalytic attack. This is why I also made two cross-platform software tools available open source that can detect these kinds of attacks real-time."

Formal methods used to analyse and repair bug in widely used sorting algorithm
The Formal Methods research group at CWI focuses on the development and application of mathematically founded methods for the design and analysis of software. In February 2015, Formal Method researchers repaired a bug in TimSort: the default sorting algorithm used in major programming languages (e.g. Java and Python) and platforms such as Android. The number of computers, cloud services and mobile phones that use TimSort is well into the billions.

As postdoc researcher of the Formal Methods group Stijn de Gouw attempted to prove the correctness of TimSort. But then he discovered that the bug that had already been known from 2013 was never correctly resolved. The bug causes programs to crash when used on certain inputs. Together with an international team of researchers de Gouw used the state-of-the-art verification tool KeY in the correctness proof of an improved version which is therefore guaranteed to be free of bugs. A bug report with this improved version was immediately met with a positive response. The researchers engaged in discussions with the developer communities, and shared their work process. A corresponding blog post on this topic was viewed 70,000 times on its publication day, and well over four million times in the following months.

Frank de Boer, group leader of the Formal Methods group: "This correctness proof was one of the hardest ever of an existing Java library. It required more than two million rules of inference and thousands of manual steps. But it illustrates the importance of formal methods as a means of putting state-of-

the-art software to the test and improving it." Stijn de Gouw adds: "Formal methods are sometimes perceived by practitioners as irrelevant or impracticable. Without a formal analysis and the help of a verification tool software that is used by billions of users every single day is bound to contain bugs."

The proposed correction has been adopted by Python and Android; Java followed another approach on the basis of a worst case analysis of this bug.

This can(not) be a coincidence - judges learn lessons in statistics

Peter Grünwald, senior scientist at CWI and professor of Statistical Learning at Leiden University, lectured on the use of statistics in court for an audience of Dutch judges and public prosecutors. What inspired him to do this was the flawed use of statistics in a highly controversial legal case in the Netherlands in 2003, when a nurse was sentenced to life imprisonment for a number of murders and attempted murders of patients in her care. The court based its verdict largely on a statistical analysis of the relation between the deaths and this particular nurse being on duty at the time of the deaths. After an outcry among scientists and in the media, the case was reopened in 2008. Re-investigation of the evidence, and in particular re-investigation of the statistics, made it very plausible that no murders had been committed at all. After seven years of imprisonment, the nurse ultimately was acquitted by the Dutch Supreme Court.

Between 2011 and 2014 Grünwald gave lectures on the use of statistics in court, as part of the programme 'Sciences and Law', co-ordinated by the Training and Study Centre for the Judiciary (a joint training institute of the Dutch judicial system and the Public Prosecution Service). In several cities throughout the country, criminal judges and prosecutors thus acquired relevant knowledge to better assess contributions of expert witnesses in court, e.g. on drugs and toxic substances, and DNA.

Grünwald: "When something unexpected happens, people tend to think: 'there is such a small chance of this happening, it cannot be coincidence, something must be behind this'. Statistics teaches us, however, that this reasoning is wrong: sometimes it really can be coincidence. Establishing whether the unexpected is just a coincidence or not can be difficult. The faulty reasoning 'small chance means no coincidence' is an instance of what statisticians call the 'prosecutor's fallacy'. As the name indicates, it unfortunately happens all too often in court."

CWI collaborating with creative business in constructing a 'sixth sense'

A chance meeting between CWI's director Jos Baeten and a 'textile innovator' during the October 2014 China mission of the mayor of Amsterdam, led to an mutually beneficial collaboration in innovative research. Borre Akkersdijk attended an informal breakfast talk by Baeten, who had traveled to Beijing to sign an agreement with China's online news service company Xinhuanet. Akkersdijk and Jos Baeten got to talk about their respective work, and discovered a common interest. The following June, at 'CWI in Bedrijf', CWI's industry networking event, the Distributed and Interactive Systems group (DIS) collaborated with Akkersdijk in a presentation on the development of 'wearables'. Their collaboration was further shaped into a public-private partnership, and this led to DIS creating a wearable 'sixth sense' to enhance and explore everyday environments.

An immersive club experience was staged on October 20th and 21st during the 2016 Amsterdam Dance Event. While the guests' senses were enveloped in music and scent, the research system, designed by CWI for this event, was seamlessly gathering and processing data from the 450 clubbers. With several of his colleagues, project leader David Ayman Shamma, senior scientist at CWI and past director of the USA HCI Research Group at Yahoo and Flickr, had developed the necessary sensors, network infrastructure, and artificial intelligence. These captured the energy levels of the crowd and fed them in real time to a visualization engine and to a room where the multisensory stimuli were altered to inversely match the activity levels inside the club.

Shamma reflected in a December 2016 blog: "It was quite a three months adventure, starting from scratch, to achieve technology connecting the senses throughout the curated club. In total, we collected some 50 BLE (Bluetooth Low Energy) million packets across the two nights and we are working on some scientific publications in Human Computer Interaction (HCI), Data Science, and AI."

The data gathered during the event were carefully anonymized, scrubbed, and further analysed, to better understand human activity recognition, social behaviour, and the interplay between technology and the environment. A number of scientific publications have since been accepted for publication and an open data set is available for the research community. Shamma has been invited to talk about the results to the Intelligent Valley Forum in Nanjing in November 2016, organized by Xinhuanet, and at the Delft University of Technology seminar on Data Science and Smart Culture in January 2017. Cesar gave the keynote speech at the Sense of Contact Conference in December 2016 on this topic and will also deliver his keynote at the 2017 International Conference on Physiological Computing Systems on this project.

Looking back, Pablo Cesar, group leader of DIS, concludes: "It was a unique opportunity to bring our research outside the lab. In this event we could test our work on network resource optimization techniques and human activity understanding algorithms in realistic testing grounds, which is in general not so easy to achieve. I am unaware of any previous research work supporting the collection of such massive amounts of data using BLE, while analyzing and processing it in real-time."

Watch the video This is the Future by Red Bull TV.

CWI online lectures popular with young and old

The 'Universiteit van Nederland' is a virtual university that presents academic topics to a wide audience. It is based on a concept that is as simple as it is effective: the best, most appealing professors in the country are invited to give a talk about their research to the general public. Two of CWI's senior researchers have been selected so far: computer scientist Harry Buhrman and mathematician Rob van der Mei. Stochastics researcher Rob van der Mei gave a talk on emergency planning: how ambulance services can get to the emergency location faster. Harry Buhrman's five lectures are on one of the most promising technologies of the 21st century: quantum computing. Buhrman introduces viewers to the basic concepts of classical computation, quantum mechanics, and cryptography, discusses the developments in quantum computing and quantum software and explains the do's and don'ts of quantum computing.

The Universiteit van Nederland lectures are recorded in an Amsterdam club in front of a live audience, and are made available online for free. Each week there is a new professor, each working day there is a new lecture. The obvious comparison is to the well-known TED Talks. Universiteit van Nederland started in 2013; up until now around 500 lectures are online. The lectures are almost universally favourably received and in 2015 the three initiators were awarded the national 'Eurekaprijs' for science communication by NWO and KNAW.

The reach of the videos is impressive, the top ten lectures are viewed between 40,000 and 230,000 times. Over 66,000 people subscribe to the YouTube channel, and half of these subscribers are under the age of 34. The concept of the short lectures is geared to the habits of users of online clips. They differ from online courses (MOOCs) in that they offer a short and snappy introduction on an often highly specialized topic to a broad public, without cutting corners on content. As far as design and pace are concerned, the lectures are a form of 'edutainment': instructive as well as entertaining.

Recently, the Universiteit van Nederland organization published fan reactions. A 13 year old fan said: "I think I watch some fifteen lectures a month. Sometimes they come in handy for school assignments, but more often I just watch them before I go to sleep or something. The things you learn in school are all right, but Universiteit van Nederland is more interesting and that is super cool!" This child plans to 'do something with computers' when he grows up, and the lectures on artificial intelligence and internet law are therefore among his favourites. "As a preparation for university, kind of. But I find other subjects interesting too!" A much more senior fan shared: "Now that I am 78, I realize, partly because of these lectures, how much knowledge I missed out on. That's why I'm such a keen 'student' now. To watch the lectures on YouTube I put everything else aside, and I view some of the lectures a second time. Being partly deaf, I use my tablet and wireless headphones to watch them on a big television screen". Regular viewers all have one thing in common, says Universiteit van Nederland. In the words of a father who took his primary school aged children to several of the lectures: "You must be interested in knowledge and science, you must want to grasp why things are the way they are. If that is the case, Universiteit van Nederland is for you."

Both Rob van der Mei and Harry Buhrman acknowledge that they invested a lot of time in the lecture preparations with the editors of Universiteit van Nederland, but that they found it was worth their while. The format compelled them to formulate precise and sharp information, and the editor's suggestions were useful. Buhrman adds: "It's convenient that I can now point interested people to my online lectures for a quick introduction to the field. And of course, I hope that the videos will motivate some of the younger viewers to study and eventually embark on research in quantum computing".

Watch the Universiteit van Nederland lecture by Rob van der Mei.

Watch the Universiteit van Nederland lectures by Harry Buhrman.

Diverse audiences experience Turing's legacy through CWI exhibition

Alan Turing (1912-1954) was one of the first people to foresee what automation would come to mean to society. As a research institute, CWI owes a lot to Turing. To reach out to the general public during the Turing centenary, CWI organized an exhibition called 'Turing's Legacy'. The exhibition told the story of Turing as a World War II hero and founding father of computer science and artificial intelligence. Among the objects displayed were an original WWII Enigma machine, a demonstration of Turing patterns and an X1 computer from 1958.

A highlight of the exhibition was a functioning LEGO Turing machine, built by CWI researchers Davy Landman and Jeroen van den Bos, that demonstrated Turing's famous 1936 theoretical model for a computing machine. The machine caught the attention of researchers and media, both within the Netherlands and worldwide. It was subject of a viral web video that has been watched over half a million times. The video featured on numerous blogs and websites, such as WIRED, geek.com, io9.com and slate.com. The machine also found its way to various educational programs at universities. National media coverage abounded: for instance, in December 2012, CWI Fellow Paul Klint explained the Turing machine on Dutch national television, in the popular science programme 'Labyrint'.

The exhibition opened on June 14 2012, when over 200 software engineers, students, industry contacts, researchers and other relations met for a CWI Lectures event. It was so popular that the exhibition period was extended by six weeks, to 30 November 2012. High school groups could combine a visit to the exhibition with a cryptology workshop organized by 'Stichting Vierkant voor Wiskunde', an organization that coordinates maths activities for children. A total of 40 tours were given to more than 1,000 visitors, including the mayor of Amsterdam and ERC President Helga Nowotny. This number includes the public that came to CWI's Open Science Days in October. During the Open Science Days, CWI provided the public with additional talks on Turing and on recent developments in computer science and mathematics, and invited children to programme their own computer games.

Although CWI took the initiative, many partners and relations contributed to the 'Turing's Legacy' exhibition. Most of the machines on display were on loan from Edo Dooijes, who initiated the Computer Museum of the University of Amsterdam (UvA). Support came from Science Park neighbours Nikhef, the Informatics Institute (UvA), the Institute for Logic, Language and Computation (UvA) and the Korteweg-de Vries Institute (UvA). Support also came from the Municipality of Amsterdam, IOS Press, King's College Cambridge, LEGO Netherlands, TNO, and the Delft University of Technology Library.

Watch the video of the LEGO Turing machine.

Gender diversity and the challenge to overcome unconscious bias

While other narratives describe the relationship between CWI's research and society, CWI's work floor has its own societal microcosm. In this narrative we look more closely at gender diversity within this microcosm.

Lynda Hardman is a member of the CWI management team and a part-time professor of Multimedia Discourse Interaction at Utrecht University. She was the first non-Dutch person and the first woman on the CWI management team. As a young researcher at the University of Edinburgh, she was puzzled that

there were so few women in computer science. Gradually she became aware that the misconception girls have about this field -- that it just isn't for them -- is at least partly due to the lack of female role models, both in real life and in the media. Only much later in her career did she become aware that unconscious bias also plays a role, for women as well as for men. Now that she holds influential positions in academia, being a member of CWI's management team and the current president of Informatics Europe, Hardman wants to reduce the gender gap because she feels computer science and maths is losing out on potential talent.

Gender bias starts early. In the Netherlands, girls tend to be less interested in technical and mathematical topics even at primary school. Girls need female role models who are comfortable with science in order to encourage them at a young age. This is why Lynda participated in the introduction of a special maths programme ('Rekentijger', math tiger) at her children's primary school, and attended small group sessions once a week to stimulate the kids with maths problems their teachers had difficulty with. She also gives talks to encourage and inspire a new generation of female IT talent, and encourages young women to participate in networking events. Networking is a valuable tool, as the 'old boys' have known for centuries, but it requires both effort and practice. And as far as the media are concerned, Hardman is happy to see that more awareness is developing and that mainstream movies are beginning to portray positive role models of the 'techie heroine'. As a board member of Informatics Europe, she founded the Women in Informatics Research and Education working group as a European-wide platform to further raise awareness and to stimulate colleagues from university departments and research institutes to learn from each other's best practices.

Hardman: "I am delighted that CWI has committed itself to an active gender diversity policy, and we are making headway in hiring and promoting women. Nevertheless, our collective unconscious bias leads us to prefer male leadership and most probably influences personnel appointments. This may not be what we really want, and I think we will all benefit, men and women alike, if we at least understand that we have our own unconscious preferences."

L Public-Private Partnerships

List of CWI Public-Private Partnerships (PPPs) in 2011-2016:

Research group	Industry partner	Period	Description
N&O/ST	Rovecom/Lanting Reizen	2015 - 2017	Route planning and scheduling
ST/N&O	CTVrede	2016 - 2019	Optimization container planning
ST	Trinité automation	2014 - 2017	Traffic flow optimization
ST/SWAT	ING	2014 - 2018	Software quality analysis (performance and robustness)
ST	Gemeente Amsterdam	2016	City logistics and Mobility
ST/IAS	Engie (formerly Cofely)	2016 - 2017	Modelling and optimizing production processes (smart industry)
ST/DA	BZK	2016 - 2020	Big data analytics
SC	DNV GL (formerly KEMA)	2015	Intelligent Energy Networks
SC	Exxon Mobile	2014 - 2016	3D imaging nanomaterials
FM	SDL Fredhopper	2014 - 2016	Monitoring techniques for cloud applications
DIS	Xinhuanet	2015 -2016	User experience lab; sensor technology
DIS	ByBorre	2016	Wearable sensors for data driven experience
DA	AAA	2016 - 2020	Real time financial data analytics
CR	NXP	2016 - 2017	Future cryptographic standards
MD	ABB	2016 -2017	Multiscale modelling of discharge growth
LS	SysBioSym	2016 -2017	Multiscale biosystems modelling

M List of CWI's spin-offs

Throughout the years, CWI has spun off the following start-up companies and initiatives. Next to the logo, the founding year, the current status of the company (e.g. existing, ended or (partially) sold) and the area of business has been provided. Furthermore, it is mentioned from what area of work in the institute the company has been incubated. Spin-offs that were launched in the evaluation period, are highlighted.

CWI supports spin-off initiatives with its CWI Incubator BV. CWI Inc. is a dedicated company with the aim of providing an ideal environment for researchers to measure their abilities in the business world with minimum early risk, and for successful ventures to accelerate on a firm footing into the mainstream of world commerce.

swat•engineering Software engineering, 2017, existing (SWAT group)	seita energy flexibility Energy consultancy, 2016, existing (IAS group)	Stokhos emergency mathematics Emergency math, 2015, existing (ST group)	monetdb Database consultancy, 2013, existing (DA group)	spinque Knowledge retrieval, 2010, existing (IA group)
vectorwise Database technology, 2008, sold to Actian (DA group)	monetdb Open source DB, 2008, existing (DA group)	SAFIRO Software design, 2007, existing (N&O group)	personal space technologies 3D environments, 2005, existing (CI group)	Podiceps Cancer detection 2004, ended (CI group)
adaptive planet Software composition, 2002, existing (FM group)	EPICTOID Digital avatars, 2001, ended (Graphics group)	Financiële Wiskunde Amsterdam Financial training, 2000, ended (FinMath group)	SIG Software consulting, 2000, existing (SWAT group)	development b.v. oratrix Multimedia creation, 1998, ended (DIS and IA groups)
EIDETICA www.eidetica.com Search systems, 1998, sold to Filtercontrol (IA group)	UniPay Digital currency, 1997, ended (CR group)	SIDN .nl top level domain, 1996, existing (IT department)	Can Math software vendor, 1995, existing (IT department)	Data Distilleries driving e-business personalization Data mining, 1995, sold to IBM-SPSS (DA group)
GENERAL DESIGN internet solutions Webdesign, 1994, sold to Satama/LBI (IA group)	DigiCash™ Digital currency, 1990, tech sale to eCash (CR group)	NLnet Internetprovider, 1989, existing (IT department)	sara Dutch supercomputer, 1971, existing (IT department)	ELECTROLOGICA Computer builder, 1956, sold to Philips (IT department)

N CWI software products

CWI develops software, and makes it available to others: researchers, industry and society. A number of our software tools is aimed to be used by a wide audience and is intended to become the reference software in its area. CWI has contributed to new industry standards in multimedia, internet security, database management systems and the development of programming languages. Please find a list of selected software products below:

Afivo: A framework for adaptive mesh refinement with geometric multigrid methods
Afivo, short for Adaptive Finite Volume Octree, is a framework for adaptive mesh refinement on quadtree (2D) and octree (3D) meshes with shared memory parallelization (OpenMP) and geometric multigrid.

Amalgame: Managing alignments in large vocabularies
Amalgame, short for AMsterdam ALignment GenerAtion MEtatool, is a Semantic Web tool for finding, evaluating and managing vocabulary alignments, i.e. relating corresponding concepts in different vocabularies. The commercial service is developed by Spinque and hosted by Beeld en Geluid.

Ambulant: An open media player for SMIL presentations
The Ambulant Open SMIL Player is an open-source media player with support for SMIL, a W3C XML standard to describe multimedia presentations.

ASTRA Toolbox: Commercial-class software for tomography imaging
The ASTRA Toolbox is a MATLAB and Python platform providing scalable, high-performance GPU primitives for 2D and 3D tomography, including building blocks for advanced reconstruction algorithms.

Bio-Signal Data Processing and Visualization Suite: The full cycle
The Bio-Signal Data Processing and Visualization Suite supports the full cycle of collecting, processing, analysing and visualizing data from physiological sensors. Closed source.

CLEVER: Ultra-fast search for genetic variants in human DNA
CLEVER, short for Clique-Enumerating Variant Finder, implements an extremely fast methodology for discovering genetic variants in genome fragment data.

Counter-Cryptanalysis: detecting forged digital MD5, SHA-1 signatures
The Counter-Cryptanalysis project provides a drop-in replacement for the existing cryptographic hash functions MD5 and SHA-1.

Derric: finding more digital forensic evidence in a faster way
Derric is a domain-specific language created to simplify and speed up the development of file format validators, i.e. software components being able to identify the type of a file or data structure.

Extensible Coordination Tools: plug-ins for the Eclipse platform
ECT: The Extensible Coordination Tools consist of a set of plug-ins for the Eclipse platform to facilitate development of concurrency protocols and distributed applications based on the coordination language Reo.

HashClash: A framework for studying the weaknesses of MD5 and SHA-1
HashClash is a software framework for cryptanalysis of the MD5 and SHA-1 cryptographic hash functions, and for Chosen-Prefix Collisions for MD5.

Invisible XML: parsing any format into XML
Invisible XML is based on the idea that data in any parsable format can be treated as XML - a format that is readable by machines as well as humans - without the need for markup.

MonetDB: high-performance query processing against very large databases
MonetDB is a relational database management system (DBMS) providing high performance on complex queries against large databases.

MP3DG: A development framework for point cloud compression algorithms
MP3DG is a software framework for the design, implementation and evaluation of point cloud compression algorithms. It has been developed as an extension of the open Point Cloud Library (PCL).

NewHope: Fast implementation of a quantum-resistant key exchange
NewHope is the reference implementation of a quantum-resistant key exchange protocol.

PumpKin: Analysing complex chemistry models
PumpKin, short for Pathway Reduction Method for Plasma Kinetic Models, is a tool for post-processing results from zero-dimensional plasma kinetics solvers.

QoE Testbed: Performing quality studies on video-conferencing systems
The QoE Testbed is a set of tools for conducting Quality of Experience (QoE) studies for video-conferencing.

Rascal: one-stop shop for metaprogramming
Rascal is a general metaprogramming language, facilitating programmers in analysing, transforming and generating source code.

Rebel: A domain-specific language for product development in finance
Rebel is a domain-specific language (DSL) targeted at the financial sector.

SAGA: A run-time verifier for Java programs
SAGA is a run-time verifier for single-threaded as well as multi-threaded Java programs.

Squint: Experimenting in Prediction with Expert Advice problems
Squint provides a codebase to perform numerical proof-of-concept experiments in learning theory, particularly in Prediction with Expert Advice problems, a core problem in learning theory.

VideoLat: Measuring end-to-end delays in A/V systems
VideoLat is a toolset to measure the delays of audio-visual pipelines, such as teleconferencing systems.

VirtualLeaf: a modelling framework for plant tissue morphogenesis
VirtualLeaf is a computer modelling framework for the simulation of plant tissue morphogenesis, i.e. the biological development of an organism's shape.

O Update CWI Strategy 2017

Contents

1 Introduction

In 2012, we composed the 'Strategisch Plan 2013-2018': a strategic plan for CWI to maintain our excellent status, to better align ourselves with our changing environment and to tackle the issues brought up by the evaluation committee in 2011. We have made progress in realising our strategic goals, and we are facing new changes in our environment, such as the transition of NWO, the ongoing digitization of our society and economy, the 'Nationale Wetenschapsagenda' (National Research Agenda) and the upcoming portfolio analysis of Dutch research institutes. By updating and reformulating our strategy, we aim to better equip ourselves for the coming years.

This document can be considered a preliminary version of the strategy that will go into effect in 2019 (Strategic Plan 2019-2024). We will later incorporate the recommendations that follow from the evaluation in the new strategic plan, and the strategic plan will be agreed upon by our governing board before it comes into effect.

In section 2.1 and 2.2, we evaluate our accomplishments in reaching our strategic goals so far. We discuss external developments in the past years, and what we expect for the coming years. This section is based on the yearly updates on the progression in realizing of our strategic goals as recorded in our Institute Plans, as well as recent discussions on CWI's ambition for the coming years. In section 2.3 and 2.4 we use this evaluation to update our SWOT analysis and formulate updated strategic issues. In chapter 3, we further develop these strategic issues and propose actions for the upcoming years that will assist us in tackling these issues.

2 Analysis

2.1 Analysis Strategic Plan 2013-2018

In our Strategic Plan 2013-2018 we formulated five strategic issues:

1 take advantage of available funding opportunities to anticipate the changes in research funding and the research landscape;
2 determine and exploit new strategic, societal themes to guide our research;
3 intensify valorization to emphasize the societal relevance of our research;
4 strengthen our role as national institute and centre for mathematics and computer science;
5 optimize our internal organization to be able to effectively implement strategic decisions.

For each strategic issue we formulated an action plan. Each year in our Institute Plan, we updated and reflected upon this action plan to monitor our progress. This is our progress up to 2016:

2.1.1 Take advantage of available funding opportunities to anticipate the changes in research funding and the research landscape

Progress

- Funding opportunities are now discussed regularly in various meetings. The monthly meetings of the theme coordinators ('themaoverleg', redeployed in 2016 as 'valorisatieoverleg') are dedicated to discussing funding opportunities and new partnerships. CWI's project administrator is now part of the directorate team instead of the financial department, in order to keep a closer eye on projects and funding.
- The financial system has been changed to create more incentive for generating additional funds. Groups and individual researchers can be rewarded for obtaining grants, by dedicating extra funding to successful groups and researchers. Also, the ability to obtain external funding is now an explicit criterion in reviewing tenure trackers applying for tenure.
- We have created two support positions dedicated to valorization and new partnerships. The Manager R&D is responsible for setting up new partnerships. As of 2015, the Manager R&D is supported by a valorization officer.
- In 2014 and 2015, we dedicated CWI funds to accelerate new public-private partnerships. This resulted in various new contracts with industrial partners.
- To increase our success rate in personal grant applications, we support our researchers in their application process. In 2016, we formed a Proposal Guidance Committee, which better coordinates these efforts and provides support and coaching to our researchers throughout the grant application process. Two external parties that are specialized in grant applications also advise our researchers on how to write better proposals.

Analysis: Thanks to our efforts we have been able to keep our research volume intact, in spite of increased competition for limited fundamental research funds. Most prominently, we have achieved an increase in public-private partnerships. We aim to continue on this track and keep increasing funding through external partnerships. Acquisition, partnerships and external communication need to remain our priorities to be able to realize this. Furthermore, we will devote extra attention to personal grants. Although we have been successful in NWO's 'Vernieuwingsimpuls' (Innovational Research Incentives Scheme), by 2016, we had not yet achieved our ambition concerning European personal grants (ERC Grants). However, we feel that the quality of our researchers is competitive, and that by providing more professional assistance with proposal-writing, our success rate can increase substantially. Recently, in March 2017, CWI's Ronald Cramer was awarded an ERC Advanced Grant.

2.1.2 Determine and exploit new strategic, societal themes to guide our research

Progress

- From 2013 to 2016, five theme coordinators were responsible for exploiting the themes Software, Information, Life Sciences, Logistics and Energy. They met monthly in the 'Themaoverleg' (theme meeting) to discuss new funding and partnerships opportunities, and they internally mobilized researchers to act upon these opportunities.
- New tenure track positions at CWI were scheduled around the research themes, to increase investments in these topics. This led to the appointment of new researchers in research areas closely related to the themes.
- In 2016, the research themes were updated to Computation, Data, Software, Networks and Quantum to better reflect the changes in CWI's focus and our environment, most prominently the shift in focus from the top sectors to the National Research Agenda. The five theme coordinators were replaced by three Coordinators Partnerships & Transfer that are not explicitly linked to the themes, in order to streamline the internal coordination and organization.

Analysis. The use of themes successfully focuses our attention on societal relevance, and it provides guidelines for strategic appointment of new researchers. The recent update of our societal themes allows us to better align ourselves with the National Research Agenda and to extend our role as birthplace for new mathematics and computer science fields in the Netherlands. We aim to keep updating the themes once every few years to adapt to circumstances and developments in our fields.

2.1.3 Intensify valorization to emphasize the societal relevance of our research

Progress

- The renewed attention to create spin-off companies has resulted into the launch of four new companies: MonetDB Solutions (2013), Stokhos Emergency Mathematics (2015), Seita Energy Flexibility (2016) and swat.engineering (2017). More ideas for new companies are under development.
- We increased attention to societal relevance of our research by putting it on the agenda of various internal meetings, see section 2.1.1.
- Focus on external communication has resulted into better visibility of CWI's research. This includes numerous publications in newspapers, television and (IT) magazines. Our industry outreach event 'CWI in Bedrijf' (CWI in Business) has been revitalized to provide an opportunity for our researchers to meet potential industrial partners.
- We are involved in the National Research Agenda, in that we strongly contribute to several routes: Big Data (route 9), Logistics and Transport (16), Energy Transition (17) and Nano and Quantum (19). We also see opportunities in contributing to varying extents to the routes Personalised Medicine (1), the Origin of Life (4), Building Blocks of Matter (5), Between Conflict and Cooperation (7), Brain, Cognition and Behaviour (8), Smart Industry (10) and Smart Cities (11).
- We are involved in the open access movement, and aim for 100% open publication of all our research products, including papers and software. By providing our products free of charge, we can improve utilization of our results. CWI, as one of the first Dutch institutions, started to build an institutional repository in 2004. In 2013 it was made mandatory for our researchers to deposit each publication in the repository upon publication, preferably a gold open access version; if need be a post review version. The number of open access journal articles and proceedings has since steadily increased from about 60% in 2013 to almost 100% in 2016. The contents of our repository are harvested by NARCIS (national Dutch repository), OpenAire, Google Scholar and others. CWI uses part of a former NWO bonus to fund article processing charges ('publication fees') for articles that are not published as part of an NWO or EU project. To be eligible for these funds, publication in a gold open access medium is required. Considering software, we are working on an online platform for disclosing our software products, and making them available for downloading. Finally, CWI is involved in creating an open access foundation for mathematics, MathOA, with the aim of promoting Fair Open Access.

Analysis. We are satisfied with our success in new partnerships, visibility of our research, the creation of new spin-off companies and our progress in open access publication. Awareness for societal relevance has grown within the institute and has resulted in several new partnerships and applications (see 2.1.1). We realize that we must keep up these efforts, as societal relevance remains an important focus for our institute, both as part of our mission and because of external expectations by society. We acknowledge that developing ties with society and industry doesn't come naturally for all groups, so we need to keep our focus. In short, we aim to continue with full force on the road we set out on.

2.1.4 Strengthen our role as national institute and centre for mathematics and computer science

Progress

- As national research institute, we aim to be on the forefront of new developments in mathematics and computer science, and initiate new research fields in the Netherlands. This has become a major focus in strengthening our national role. In 2015, we founded the QuSoft research institute for quantum software together with the University of Amsterdam (UvA) and the VU University Amsterdam. QuSoft is housed at CWI. In 2016, we also founded two new research groups in Machine Learning and Computational Imaging, in order to provide new focus in these fields. We

are investigating new, similar initiatives, including research lines in computational social sciences and social machines, and blockchain technology.

- We took the initiative to unite the Dutch academic software engineering community by launching the VERSEN association. CWI is the administrative home of VERSEN, and houses its annual conference.
- We house several external parties in mathematics and computer science, including the national platform for mathematics 'Platform Wiskunde Nederland' (PWN), COMMIT/ (up to 2014) and the Royal Dutch Mathematical Society ('Koninklijk Wiskundig Genootschap'). We frequently host meetings of these and other external parties, thus welcoming a large portion of Dutch mathematics and computer science researchers and policymakers throughout the year.
- We aimed to create a sabbatical programme for researchers at Dutch universities, but had to abandon this plan due to a lack of interest. Instead we shifted our focus to the exchange of researchers on a part-time basis, including new part-time professorships.
- We have invested in expanding our ties to the Dutch universities. This resulted in new ties to universities through part-time professorships of CWI researchers, including the University of Twente and the University of Groningen. The total number of CWI senior researchers affiliated with a Dutch university has increased: at the end of 2016, 34 senior staff members held a professorship, at 11 Dutch universities. Of these, 32 held a part-time full-professorship and 2 held an associate professorship.
- On an international level, we strengthened our ties with the French institute Inria, and signed a new, broader cooperation agreement in 2016. We also joined the European-Asian cooperation LIAMA, and continued our efforts in ERCIM, W3C, EIT Digital, Informatics Europe (for which we currently provide the president) and other international networks. We are aiming to house a satellite of EIT Digital in our building, related to our research in blockchain technology with several banks.

Analysis. We have made progress in expanding our role as national institute and centre for mathematics and computer science activities in the Netherlands. However, as an institute without major national facilities, we are not widely known by all stakeholders and potential partners. Therefore, we want to increasingly invest in our role as accelerator for mathematics and computer science and as a birthplace for new fields. By investing in new, promising lines of research, we can strongly contribute to the position of the Netherlands in the research landscape.

2.1.5 Optimize our internal organization to be able to effectively implement strategic decisions

Progress

- As of 1 January 2013, we eliminated the research clusters, making research groups the main organizational units in our institute. The Management Team (MT) members have adapted to function as advisors. They supervise group leaders based on a managing role, rather than from a research content point of view, thus removing the ties to the old research clusters.
- We revised the management bodies at CWI. To make MT meetings leaner, the Management Team meets two-weekly and the meeting no longer includes the managers of the support departments. Acquisition, partnerships and funding are discussed in the new 'Valorisatieoverleg' (valorization meeting).
- We have revitalized our strategic cycle to improve our strategic awareness. We monitor the execution of our Strategic Plan in our annual Institute Plans. We also monitor the performance of individual employees in performance interviews, which are now mandatory for all personnel. Also, we selected a new Scientific Advisory Committee (SAC) consisting of international experts in our fields, and we consult them on an annual basis on strategic topics.
- NWO has undergone a major transition in the period 2015-2018, leading to a clustering of all research institutes in one institute organization. In the NWO Transition, we argue for flexible and decisive institutes. To be able to fulfil their mission, NWO institutes should be able to make their own strategic decisions in scientific autonomy, such as forming strategic alliances with other institutes or companies, investing in promising research areas and launching spin-off companies. We were able to secure these values within the new NWO institute organization. This means that we maintain control over our policy, i.e. how to fulfil our mission, with the investments and support we think necessary.

Analysis. We have been able to reach most of our goals for this target and are overall satisfied with the results. We believe our institute is now better equipped to implement strategic decisions, and we are glad that we will remain flexible and decisive within the new NWO institute organization.

2.2 External developments

- Digitization of society and economy will steadily continue so there will be a crucial role for mathematics and computer science in the Netherlands. A broad coalition of societal and industrial parties have urged the government to take leadership to transform the Netherlands into a successful digital society and economy. The Manifesto for a Sustainable Digital Society, signed by a large number of parties from society, industry and large corporations (including KNAW, VNO-NCW, VSNU, TNO, PostNL, ANWB, the Port of Rotterdam, LTO Nederland, the Nederlandse Vereniging van Banken, Schiphol Group, MKB-Nederland), argues for extra investment in digital education and innovation. Informatics Platform Netherlands (IPN) has developed a Five Point Plan ('Vijfpuntenplan') for various governmental organizations, that urges for extra investments to keep the leading position of the Netherlands in IT and digital science. Also, the new COMMIT2DATA programme, the successor of COMMIT/, underlines the importance of computer science for the Netherlands.
- In 2018 there will be a portfolio analysis of Dutch research institutes, where the portfolio of all NWO and KNAW institutes will be analysed and balanced. We expect this to lead to an increase and redistribution of research funds. We aim to prove the need for extra funding for mathematics and computer science, in line with the call for extra investments from societal and industrial parties mentioned above.
- The trends of increased competition for fundamental research funding and the growing importance of societal relevance of research results has continued. Funding opportunities like those in NWO's Open Competition have decreased. Researchers from all disciplines compete for the same funds. Also, the success rate of personal grants like the 'Vernieuwingsimpuls' (Innovational Research Incentives Scheme) and ERC have shrunk. However, the Knowledge Coalition ('Kenniscoalitie') has presented an investment agenda of €1 billion (Spankracht and Daadkracht), which we expect will result in both additional basic funding and project funding opportunities.
- For the upcoming years, we expect an increased role for the 'Nationale Wetenschapsagenda' (the National Research Agenda) in determining both research agendas and funding. We strongly contribute to several routes: Big Data (route 9), Logistics and Transport (16), Energy Transition (17) and Nano and Quantum (19). We also see opportunities in contributing to varying extents to the routes Personalised Medicine (1), the Origin of Life (4), Building Blocks of Matter (5), Between Conflict and Cooperation (7), Brain, Cognition and Behaviour (8), Smart Industry (10) and Smart Cities (11).
- As a result of the NWO transition, the CWI Foundation will be ended per 1 January 2018 and join the NWO institute organization (NWO-I). The consequences for CWI personnel seem to be limited. The transition is expected to lead to a better cooperation within NWO (better connection between the institutes and the granting domains) as well as an increased cooperation between CWI and the other NWO institutes, and possibly the KNAW institutes.
- Research in quantum computing will get an extra boost through the EC Flagship Programme of €1 billion that is expected for 2018, and a Gravitation grant (18.8 M€), which was awarded in May 2017. This will open up possibilities for further investments in our quantum software research, led by the QuSoft institute.
- IT industry in the Netherlands is expected to keep expanding, with a growing need for more technical personnel. For CWI this will on one hand lead to an extra challenge to recruit talented researchers in computer science, and on the other hand provide opportunities for increased cooperation with IT companies.
- We play an active part in the national and international open access movement. We expect the open access movement to really get off the ground, with open access journals becoming more influential.

2.3 Update SWOT analysis

Following the discussion in the past sections, we update our SWOT analysis from 2013 to the following:

Strengths	Weaknesses
• the synergy between mathematics and computer science; • scientific excellence and high quality of research staff; • applicability of research results in a wide range of areas; • dynamic research organization with high-quality facilities and support; • close ties to all Dutch universities.	• internal communication and coordination between the different parts of the institute (i.e. directorate, research groups and support departments) can be improved; • due to our focused portfolio and limited size, we are not yet known by all societal potential partners and stakeholders; • we have not yet achieved an overall culture of diversity within the institute.
Opportunities	**Threats**
• increasing importance of mathematics and computer science due to the digitization of society and economy; • chance to show our value in portfolio analysis of Dutch research institutes; • strategic partnerships on a regional, national, European and global level.	• fundamental research is under pressure; • continuing increase in competition for limited research funds; • (inter)national 'war for talent'.

Assessing both CWI's internal strengths and weaknesses and the external opportunities and threats that we are dealing with, provides insights into the issues that are the most relevant for the successful implementation of CWI's strategy and the priorities we are setting for the coming years.

Opportunities vs strengths (enterprising)

- CWI as an institute is exceptional in that it is home to researchers in both mathematics and computer science. This allows us to exploit the synergy between the two fields, as well as to promote the increasing importance of both mathematics and computer science research in a digitizing society and economy.
- Our scientific excellence and the quality of our research staff, combined with the increasing importance of mathematics and computer science, gives us the opportunity to demonstrate our value in the portfolio analysis of Dutch research institutes and to argue for growth of the institute.
- The applicability of our research and the growing importance of our research fields provide excellent opportunities to set up new (public-private) partnerships.
- CWI provides an environment that stimulates growth of talented researchers to full professors. The appointment of CWI staff as full professor further strengthens our ties to the Dutch universities, which reinforces strategic partnerships on a national and international level.

Threats vs strengths (defensive)

- Researchers from all disciplines, from cancer research to astrophysics, compete for the same funds. Although our scientific quality makes us competitive, we often start from a less favourable vantage point in this competition because of the less demonstrable nature of our type of research and results.
- Thanks to the wide applicability of our research, a shortage of fundamental research funds can be partly accommodated by initiating more contract research and public-private partnerships.
- By consistently proving our scientific excellence and strategic position, we can argue for an increase of our basic funding from NWO.
- Fundamental research is under pressure. Firstly, because there is a shift in funding towards thematic programmes. Secondly, industrial partners expect short-term results, and do not readily invest in long-term work (but are interested in talent development). CWI's added value in the national research landscape is in maintaining the balance between fundamental and application-oriented research, in mathematics, computer science, and in the intersection between the two fields. We cover (new) research fields that will benefit the Netherlands as a whole.
- There is an (inter)national 'war for talent', and we experience increased competition with industry for personnel. Whereas industry can offer high starting salaries, in academia, young researchers are often confronted with an uncertain career path. However, CWI is a successful competitor in attracting talent

in the academic world. We strive to be a very attractive employer, offer career planning support, and we provide an excellent, dedicated research environment for young researchers.

Opportunities vs weaknesses (reform)

- We see opportunities to increase our strategic partnerships. However, we are not yet widely known by all of our potential societal partners. We must further increase attention to branding and external communication.
- By improving our internal coordination, e.g. by more effectively communicating management decisions to our researchers, we facilitate the CWI community to act more as a strategic and coherent research organization. This can also contribute to forging new alliances with potential strategic partners.
- We expect that the increased societal importance of mathematics and computer science will stimulate an increased participation of currently underrepresented communities. This should lead to an increase in the diversity of our talent pool, which, combined with our efforts to create a culture of diversity and inclusion within our institute, will lead to a better representation of minorities and women in our workforce.

Threats vs weaknesses (get by)

- An improved culture of diversity and inclusion within our institute will contribute to a stronger position in the 'war for talent'. Improvements will make for a more pleasant working environment, and an even higher research quality.
- Internal communication and coordination within CWI can be improved. Better internal coordination would allow us to better exploit all funding opportunities.
- The lobby for an increase of (long-term) funding will be more powerful if CWI aligns its efforts with other knowledge organizations and with industry. It is therefore important that we make ourselves better known to all potential partners and stakeholders.

2.4 Update strategic issues

Using the SWOT analysis and the report on our progress in the five strategic issues from 2013 in chapter 2.1, we update our strategic issues to the following five issues:

1 explore new, promising research areas;
2 increase our research volume through extra funding;
3 safeguard the balance between fundamental and application-oriented research;
4 create an optimal research environment;
5 optimize research integrity, open access and open data.

We explore these issues in more detail in the following section.

3 Strategic issues and actions

3.1 Explore new, promising research areas

To further advance our role in the Dutch research landscape as birthplace and accelerator of new research areas in the Netherlands, we invest in novel, promising lines of research. We hire tenure track researchers in new areas whenever a position becomes available, and we aim to accelerate this process by creating new positions. In line with developments in (inter)national research policy, our core strengths and to redress the balance of fundamental and application-oriented research, we have selected the following cross-cutting themes, and will invest along these lines:

Computation. Computational science is often called the third scientific paradigm, next to theory and experimentation. With our extensive history in numerical analysis and large-scale computation, CWI

can play a leading role in this field. We will invest in computational science for circular economy and sustainability, including the transition to renewable energy and smart cities. We also see opportunities in computational plasma and high voltage technology, computational life sciences and computational imaging. In 2016, we launched a new research group that focuses on the latter and we invested in hardware for this field, most notably the FleX-Ray CT Scanning Lab which was opened in May 2017.

Data. Big data is a crucial part of science and society. As one of the early pioneers in data science, CWI has a continued commitment to this theme. CWI invests in fundamental research into algorithms, systems and methodologies needed for data science. We research novel data systems architectures that help data scientists perform large-scale data analytics. In 2016, we launched a research group dedicated to Machine Learning. We strive to strengthen the connection between data and computation through big data simulation, and we see opportunities in social machines research and in applying a big data approach in life sciences.

Software. The quality of software is increasingly important to society, as software becomes a crucial aspect of our daily lives and is often the driving force behind innovations. CWI is the birthplace of fundamental software science. We currently work on verification, certification and research on software usage, design and transformation. We intend to further develop our research in software analytics, legacy problems, domain-specific programming languages and model-driven engineering.

Networks. CWI can provide a fundamental mathematical and computer science contribution to network research. Currently, CWI researchers play a leading role in NWO programmes concerning logistics networks and energy networks. We are also a member of a major NWO Gravitation research programme, NETWORKS, that will enter its second phase in 2018. We are going to develop our research in various types of networks, including logistics networks, enterprise networks, biological networks and software-defined networks. We will work on e.g. the analysis and optimization of large networks and network security.

Quantum. We are a long-term pioneer in the area of quantum computing, which currently puts us in the position to play a leading role in the quantum revolution. We aim at growth for QuSoft, the research centre for quantum software that CWI launched together with the University of Amsterdam and VU University Amsterdam in 2015. We strive to develop QuSoft into an Advanced Research Centre and are working on external funding to achieve this, including an EC Quantum Flagship and public-private partnerships. In May 2017, a Gravitation grant (18.8 M€) was awarded to a CWI-led research programme, the Quantum Software Consortium.

Under the umbrella of these cross-cutting themes, we plan to invest in the following upcoming research topics:

- **Digital finance and blockchain technology**. Blockchain technology will be a disruptive technology. CWI has the potential to become a major international player in blockchain technology research. We have assembled a multidisciplinary group of experts on this topic, and we have initiated collaborations with several banks.
- **Control theory**. Control theory is of great importance to the high tech industry. In the Netherlands, current research in this field is mainly of an applied nature. This is especially the case for hybrid systems (cyber-physical systems). CWI could provide a substantial contribution with our fundamental research approaches, for instance in the study of hybrid systems by combining control theory research with our formal methods research.
- **Security and privacy**. The ongoing digitization of services makes security and privacy issues increasingly relevant. We are already investigating this topic through cryptography, and are exploring the possibilities for a broader research approach that includes various other cybersecurity techniques.

Actions:
- hire excellent tenure track researchers in promising areas;
- create a new research group starting from researchers of different current groups;
- in exceptional cases, create a new tenured position for an exceptional talent.

3.2 Increase our research volume through extra funding

Mathematics and computer science are the essential tools to master and improve the increasingly complex digital world. The need to increase knowledge in these fields is widely acknowledged, on a European level by the Horizon 2020 Work Programme 2018-2020, and on a national level by the 2014 Deloitte report 'Mathematical Sciences and their value for the Dutch economy', as well as the Five Point Plan (Vijfpuntenplan) developed by the Dutch IT research platform (IPN) which urges extra investments to keep the top position of the Netherlands in IT and digital science. To match the growing importance of our research areas, we aim to accelerate the growth of mathematics and computer science in the Netherlands. We will do this by continuously demonstrating the significance of these disciplines, creating extra research positions, and attracting and developing (inter)national talent.

In light of the upcoming portfolio analysis of Dutch research institutes, and an anticipated increase in governmental spending on research, we will demonstrate the increasing role of mathematics and computer science. We aim at an increase of basic funding, as well as personal grants and public-private partnerships. To increase our success rate in personal grant applications, we support our researchers in their application process. In 2016, we formed a Proposal Guidance Committee, which better coordinates these efforts and provides extensive (writing) support and coaching to our researchers throughout the grant application process.

In line with our intended growth we will continue to apply ourselves to attracting research talent, for instance by closely collaborating with universities, and through the efforts of CWI researchers offering education courses at universities and in inter-university research schools.

Actions:

- prepare for a successful evaluation and portfolio analysis;
- make our case for an increase in our basic funding;
- keep working to increase our project funding;
- increase our success in personal grants, most notably the ERC Grants programme.

3.3 Safeguard the balance between fundamental and application-oriented research

We will continuously safeguard the balance between application-oriented and fundamental research. Curiosity-driven and long-term research has an intrinsic value and is essential for bringing about ground-breaking innovations. Therefore, CWI will continue to have fundamental research at its base. We ensure that our researchers can commit to a long-term research strategy, without being forced to meet pre-determined application targets. However, we will also continue our efforts to increase valorization and visibility of our research results. To seize valorization opportunities at all levels of our institute, we provide valorization support to our research staff through the valorization team that we established as part of our current strategy. We will continue to explore opportunities to work with partners from society and industry, to provide software tools, to transfer knowledge and to found spin-off companies. To ensure transparency and public accountability, and to give the general public insight into our research, we will continue to invest in external communication.

Actions:

- keep realizing spin-off companies;
- create and disclose software tools for external parties;
- support all research staff to recognize and use valorization opportunities;
- keep publicizing research results to increase visibility.

3.4 Create an optimal research environment

The success of our institute primarily depends on our researchers. To be able to meet our strategic targets, we need the best researchers and we need to provide them with an optimal research

environment. A pleasant working environment is also an essential requirement for attracting a diverse research staff.

We support both our junior and senior researchers to get the most out of their job. We coach our junior researchers as they enter the challenging and demanding world of scientific research. We maintain a high quality support staff, and we continue to provide support for e.g. writing research proposals, getting into contact with external collaboration partners and publicizing research results. The increased cooperation with NWO and the other NWO institutes provides an opportunity to further improve the support for our researchers.

Actions:

- coaching junior staff, in particular tenure track researchers;
- providing support for grant writing;
- providing high-quality support and working conditions;
- cooperate with NWO and the other NWO institutes to maintain or even increase the quality of support.

3.5 Optimize research integrity, open access and open data

We play an active part in the national and international open access movement. In recent years, a broad movement, initiated by the Ministry of Education, Culture and Science, NWO and the Royal Netherlands Academy of Arts and Sciences, encourages open access of publicly-funded research results. As of December 2015, NWO requires that all publications resulting from NWO funding are open access. Within our own institute, CWI strives to optimize an open scientific culture, including research integrity, open access and open data.

Actions:

- Jos Baeten chairs and Lieke Schultze is treasurer of the foundation MathOA, which aims to flip journals from subscription models to Fair Open Access;
- Baeten and Schultze play a leading role in ERCIM efforts to boost Open Access;
- further develop the CWI repository under Artudis;
- continue to contribute to NWO's data management policy;
- align policy and procedures on scientific integrity with the future partners in the NWO institute organization (NWO-I).

P Issues raised in the evaluation of 2011

The conclusions and recommendations of the 2011 evaluation committee and the added recommendations by NWO gave rise to reflection and discussion on CWI's strategy (Strategic Plan 2013-2018 and the 2017 Update in appendix O).

Conclusions

1 **Excellent research institute**. We are very glad to hear this.
2 **Well organized, stimulating excellent research, attractive place**. We are glad to see that our efforts pay off.
3 **Cluster layer seems superfluous**. We took this conclusion to heart and worked on revising our organizational structure. The clusters have been discontinued as of 2013. The scientific members of the Management Team still supervise the leaders of five research groups, monitoring their strategic results. However, they do not supervise the content of the research.
4 **Strategic process too weak**. We worked on this and developed a new Strategic Plan with concrete actions that we monitor in our annual Institute Plans. We defined strategic themes to guide our investments and recruitment of new researchers, and set up a new Scientific Advisory Committee.
5 **Output other than scientific publications should be stimulated**. We made the improvement of valorization a major strategic issue.
6 **Societal impact should be more rewarded**. CWI is proud of its societal impact and its balance in scientific and societal output. In recommendation 3 we elaborate on improving societal impact.
7 **No fixed strategy for selecting research areas**. We started to align our selection of research areas with strategic themes. New tenure track researchers are hired along the lines of these themes. From 2013 to 2016, our focus was on the research themes Software, Information, Life Sciences, Logistics and Energy. In 2016, the themes were updated to: Software, Data, Networks, Computation and Quantum.
8 **CWI could play a more central role in Dutch mathematics and computer science research**. We worked on increasing our central role. For further discussion, see recommendation 2.
9 **The change in leadership in some groups needs attention**. We understand the concerns of the committee and paid attention to young group leaders. The groups in question have mostly been able to maintain their excellence and status. In general, we started coaching of young researchers by more experienced colleagues.
10 **Some groups are subcritical in size**. Research group size has the attention of CWI's management. Two small groups (INS3 and MAC1) were merged into larger groups (SWAT and SC). We aim to have at least three senior researchers per group.
11 **For some groups their large contribution to innovative software is not adequately taken into account in the standard measures for productivity**. The standard measure has been updated since the last evaluation, allowing more flexibility in defining research quality and productivity.

Recommendations

1 **CWI needs more aggressive and effective PR**. External communication has been a major focus in the past years and will remain to be so. We have a very active communication department which is successful in attracting attention to CWI in many ways, with a main focus on stakeholders and external partners. CWI research appeared over 113 times in major national newspapers, national television and radio. We revitalized our industry outreach event 'CWI in Bedrijf' (CWI in Business) to improve relations with industry. We are overall satisfied with our PR, but it requires continuous attention because of the less demonstrable nature of our type of research and results.
2 **CWI should have a more central and coordinating role in the Dutch mathematics and computer science landscape [also NWO1]**. Our role in the national research landscape is not always obvious to all relevant partners and stakeholders, as we are one of the few national institutes that do not maintain a national collection or infrastructure. We therefore focus on increasing our national role as birthplace of new, promising research areas in the Netherlands. As we are more flexible and adaptive than universities, we can relatively quickly take up high-risk, high-gain research areas. We also took upon us some central roles such as housing several mathematics foundations (such as KWG, PWN) at CWI, we are working on an EIT Digital dependance at CWI. Our researchers

are involved in many national programmes and initiatives, and CWI is a breeding ground for talent for universities, as we stimulate growth of talented researchers to full professors.

3 **CWI should devote more attention to developing products and services from research results. [also NWO 3]**. CWI has a long tradition of transferring knowledge to society and knows of the various problems and pitfalls for developing products and services for our type of research. Going the 'last mile' in implementing our results is not always in line with our mission. That does not mean that we never go the 'last mile', as can be seen from the following examples:

- We launched three new spin-off companies (MonetDB Solutions, Stokhos and Seita) since 2011 and have more planned.
- We invest in external relations through our industry outreach event 'CWI in Bedrijf' (CWI in Business), and through networks such as Amsterdam Economic Board, Amsterdam Data Science, Data Science Platform Netherlands, EIT Digital and various others.
- We initiated a large number of public-private partnerships, including contracts with ING Bank, Trinité Automation, SDL Fredhopper, NXP Semiconductors, ABB, Gemeente Amsterdam and many more.
- In 2013-2016, theme coordinators monitored valorization activities within the institute. In 2016, we appointed a valorization task force (Valorization Team) to signal and take action on opportunities for new partnerships and transfer.

4 **CWI should try to generate funding by making a profit on products, services and spin-offs**. This is a reasonable recommendation, but expectations should not be too high. Profit on spin-offs has happened, but is a too unreliable source of income to be included in regular budgets. As a frontrunner in open access, we are strongly opposed to patenting and trying to make a profit on software products and other products resulting from research paid for by public funds, so that is a road we do not want to take in principle.

5 **CWI should appoint personnel for valorization**. In 2013-2016, theme coordinators monitored valorization activities within the institute. In 2016, a new body, the Valorization Team (VT), was established as part of our updated valorization strategy to focus on external relations and transfer. They are supported by a dedicated Valorization Officer in the support staff. Their work is focused on improving partnerships and transfer, not products and services per se. See also our reply to recommendation 3.

6 **CWI could enter strategic alliances with other parties to use their valorization expertise**. We are involved in many networks and alliances, including Amsterdam Science Park, Amsterdam Economic Board, EIT Digital and Dutch Techcentre for the Life Sciences. The focus in these alliances is networking and cooperation, see also recommendation 3. We cooperate with TNO (the Netherlands Organisation for Applied Scientific Research), Amsterdam University of Applied Sciences (Hogeschool van Amsterdam), Amsterdam Centre for Business Analytics (ACBA).

7 **[NWO3]. CWI should get more funding from the EU**. We agree with the recommendation and have devoted much attention to obtaining ERC Grants and funding in Horizon2020. We have been relatively successful in the latter, and have obtained one Consolidator and two Advanced Grants. We developed a personal grant support committee, which provides internal and external assistance in writing good proposals.

Q Glossary

ACM — The Association for Computing Machinery is an international learned society for computing. It was founded in 1947 and is the world's largest scientific and educational computing society. The ACM is an umbrella organization for academic and scholarly interests in computer science.

ALGO — The annual ALGO congress is the leading international gathering of researchers on Algorithms in Europe.

AMOLF — NWO (former FOM) Institute for Atomic and Molecular Physics.

Andreas Bonn Medal — Five-yearly prize for original work in natural sciences and medicine, awarded by the Dutch 'Genootschap ter bevordering van Natuur-, Genees- en Heelkunde'.

ARC — Advanced Research Centre, new type of research institute with substantial industry involvement.

ASTRON — NWO Institute Netherlands Institute for Radio Astronomy

BDA — Big Data Alliance aims to promote collaboration among the leading Dutch academic institutes and industry in Big Data and Data Analytics.

Centrum Wiskunde & Informatica — See CWI.

CNRS — 'Centre National de la Recherche Scientifique', the French National Center for Scientific Research.

COMMIT/ — COMMIT/ brings together scientific research, non-profit organizations and companies in IT projects within the nine economic top sectors in the Netherlands in order to research and develop ground-breaking products and services. CWI is one of the participants.

COMMIT2DATA — To further develop the use of big data, the COMMIT2DATA programme offers a national research and innovation programme based on public-private partnership. CWI is one of the participants.

CONCUR — International Conferences on Concurrency Theory, initiated by CWI director Jos Baeten.

COST — The longest-running European framework supporting trans-national cooperation among researchers, engineers and scholars across Europe.

CWI — Centrum Wiskunde & Informatica, Dutch national research institute for mathematics and computer science. CWI is one of the institutes of NWO, the Netherlands Organisation for Scientific Research.

Deltaplan Wiskunde — Deltaplan Mathematics. In 2014 the Platform Mathematics Netherlands (PWN) published a vision document with longer-term ambitions for Dutch mathematics. The Ministry of Education, Culture and Science requested that NWO and PWN formulate a plan with concrete actions based on the vision document that would have broad support. CWI's former director, mathematician Jan Karel Lenstra, was one of the writers of the resulting Deltaplan Mathematics, presented to the Minister in March 2016.

DigiVita — Project by VHTO to encourage more girls to get engaged with IT.

DSPN — Data Science Platform Netherlands is the national platform for ICT research within the data science domain. DSPN unites all Dutch academic research institutions where data science is carried out from an ICT perspective, specifically the computer science or applied mathematics perspectives.

EC Flagships — Large-scale research initiatives addressing grand Scientific and Technological (S&T) challenges. They are long-term initiatives bringing together excellent research teams across various disciplines, sharing a unifying goal and an ambitious research roadmap on how to achieve it.

EIT — European Institute of Innovation and Technology. The EIT is an independent EU body set up in 2008 to enhance Europe's ability to innovate.

EIT Digital — EIT Digital, formerly known as EIT ICT Labs, is a Knowledge and Innovation Community of the EIT. Its mission is to foster digital technology innovation and entrepreneurial talent for economic growth and quality of life in Europe.

ERA-NET — European Research Area Network, a scheme that promotes the cooperation and coordination of research activities carried out at the national or regional level in the EU Member States and Associated States. ERA-NET is a system of cross-national collaboration that brings together national research funders (governments, institutions or individuals) and researchers.

ERC Grants — Personal grants of the European Research Council. The ERC grants comprises three grants geared to different stages in a researcher's scientific career: a Starting Grant, Consolidator Grant and Advanced Grant.

- **ERC Starting Grant** — ERC grant for top researchers with 2-7 years experience after PhD, 1.5 M€ for 5 years.
- **ERC Consolidator Grant** — ERG grant for top researchers with 7-12 years experience after PhD, 2 M€ for 5 years.
- **ERC Advanced Grant** — ERC grant for established leading principal investigators, designed to allow outstanding research leaders of any age to pursue ground-breaking, high-risk projects in Europe, 2.5 M€ for 5 years.

ERCIM — European Research Consortium for Informatics and Mathematics.

ERCIM News	Quarterly magazine of ERCIM.
ERCOM	European Research Centres on Mathematics, a committee of the European Mathematical Society.
EXTREMA	CWI leads this European network of imaging specialists, which works on the next generation of imaging techniques to advance science and industrial R&D.
FOCS	Annual IEEE Symposium on Foundations of Computer Science.
FOM	'Stichting voor Fundamenteel Onderzoek der Materie', Foundation for Fundamental Research on Matter.
FP7	The European Union's Programme for funding Research and Innovation, 2007-2013.
Gravitation	'Zwaartekracht', large-scale government research funding programme, for consortia executing excellent research over a 10 year period. The programme is coordinated by NWO.
Horizon2020	Current EU's Framework Programme for funding Research and Innovation, 2014- 2020.
Horizon2020 Work Programme 2018-2020	The European Commission's proposed Work Programme 2018-2020 within the framework of Horizon 2020 promising increased attention for digital technology.
IACR	International Association for Cryptologic Research.
ICALP	The annual International Colloquium on Automata, Languages and Programming, the main European conference in Theoretical Computer Science.
IDPF	The International Digital Publishing Forum is a trade and standards association for the digital publishing industry.
IEEE	US based technical professional organization for the advancement of technology.
Informatics Europe	Informatics Europe represents the academic and research community in Information and Computer Sciences in Europe. With over 110 member institutions across 28 countries, Informatics Europe promotes common positions and acts on common priorities.
Innovational Research Incentives Scheme	'Vernieuwingsimpuls', NWO Talent Scheme for talented and creative researchers who engage in innovative research. The scheme boosts innovative research and promotes mobility within scientific research institutes. The Innovational Research Incentives Scheme comprises three grants geared to different stages in a researcher's scientific career: Veni, Vidi and Vici (see entries below).
Inria	'Institut National de Recherche en Informatique et en Automatique', the French National Institute for Computer Science and Applied Mathematics.

IPN 'ICT-onderzoek Platform Nederland', Dutch IT research platform. Published 'Een vijfpuntenplan voor Nederland, ICT - Digital Science voor de Digitale Maatschappij', A five point plan for the Netherlands, IT - Digital Science for the digital society, in 2016.

ITU The ITU Telecommunication Standardization Sector coordinates standards for telecommunications.

KHMW 'Koninklijke Hollandsche Maatschappij der Wetenschappen', Royal Holland Society of Sciences and Humanities, the oldest Dutch Learned Society for the arts and sciences.

KNAW 'Koninklijke Nederlandse Akademie van Wetenschappen', Royal Netherlands Academy of Arts and Sciences.

Knowledge Coalition The Dutch National Research Agenda was drawn up by the Knowledge Coalition consisting of the universities, the universities of applied sciences, the university medical centres, the Royal Netherlands Academy of Arts and Sciences, the Netherlands Organisation for Scientific Research, the Confederation of Netherlands Industry and Employers, Royal Association MKB Nederland and Federation TO2 (the institutes for applied research).

KPN Dutch data and IP communications company.

KWG 'Koninklijk Wiskundig Genootschap', Royal Dutch Mathematical Society.

LIAMA In 2013, CWI joined research network LIAMA, the Sino-European Laboratory in Computer Science, Automation and Applied Mathematics, as one of the founding members.

LOFAR The Low-Frequency Array is a large radio telescope located mainly in the Netherlands, operated by NWO-institute ASTRON, the Netherlands Institute for Radio Astronomy and its international partners.

MathOA CWI is involved in creating an open access foundation for mathematics, MathOA, of which CWI director Jos Baeten is president.

MPEG The Moving Picture Experts Group is a working group of authorities that sets standards for audio and video compression and transmission.

National Research Agenda The 'Nationale Wetenschapsagenda', National Research Agenda, was published in 2015 by the Knowledge Coalition as requested by the Minister of Education, Culture and Science. In the National Research Agenda, science and society together have formulated the large scientific questions on which research in the Netherlands should focus in the coming years.

Netherlands eScience Center The national hub for the development and application of domain overarching software and methods for the scientific community. The eScience Center is a joint initiative of NWO and the Dutch organization for ICT in education and research (SURF).

NETWORKS CWI is a co-applicant of the national consortium NETWORKS, which started in 2014 with funding from the Gravitation programme. NETWORKS is a consortium of 50 researchers from CWI, University of Amsterdam, Eindhoven University of Technology and Leiden University with the aim to address the pressing challenges posed by large-scale networks using stochastics and algorithms.

Ngi-NGN Dutch platform for IT professionals.

Nikhef NWO Institute (former FOM institute) 'Nationaal Instituut voor Subatomaire Fysica', National Institute for Subatomic Physics.

NIOZ NWO Institute 'Koninklijk Nederlands Instituut voor Onderzoek der Zee', Royal Netherlands Institute for Sea Research.

NWO 'Nederlandse Organisatie voor Wetenschappelijk Onderzoek', Netherlands Organisation for Scientific Research.

NWO-I 'NWO-Instituten Organisatie', the Netherlands Foundation of Scientific Research Institutes Organisation. NWO-I's role is to support the eight NWO institutes and research centre ARCNL and to closely collaborate with the research domains of NWO. Since 2017, it accommodates the former FOM Institutes AMOLF, DIFFER, Nikhef and research centre ARCNL. From 2018 onward, the remaining NWO Institutes ASTRON, CWI, NIOZ, NSCR and SRON will also be accommodated in the Institutes Organisation.

OA Open access.

OCW The Dutch Ministry of Education, Culture and Science.

PODC Annual ACM symposium on Principles of Distributed Computing.

PPP Public-private partnership.

PWN The 'Platform Wiskunde Nederland', Platform Mathematics Netherlands, was founded in 2010 by the Dutch Royal Mathematical Society and the Dutch Association of Mathematics Teachers to enhance both the scientific and societal position of mathematics in the Netherlands.

QCRYPT Annual conference on Quantum Cryptography.

QIP The international annual Quantum Information Processing series is the premier meeting for theoretical quantum information research.

QuSoft The research centre for quantum software that CWI launched together with the University of Amsterdam and VU University Amsterdam in 2015.

RDFa RDFa, Resource Description Framework in Attributes, is a W3C recommendation that adds a set of attribute-level extensions to HTML, XHTML and various XML-based document types for embedding rich metadata within web documents.

Royal Holland Society of Sciences and Humanities 'Koninklijke Hollandsche Maatschappij der Wetenschappen' (KHMW), the Royal Holland Society of Sciences and Humanities, is the oldest Dutch Learned Society for the arts and sciences.

Scientific Advisory Committee The Scientific Advisory Committee, or SAC, consists of international experts in mathematics and computer science. CWI consults them on strategic topics.

Simula Simula Research Laboratory in Norway conducts fundamental research in the fields of communication systems, scientific computing and software engineering.

SKA The Square Kilometre Array is a large multi radio telescope project aimed to be built in Australia and South Africa. The Dutch participation in SKA is led by NWO Institute ASTRON for radio astronomy.

Stieltjesprijs Annually awarded prize for the best PhD thesis in mathematics that is defended at a Dutch university. The award is made available by the Dutch 'Foundation Composito Mathematica'.

STOC Annual ACM Symposium on Theory of Computing.

STW / TTW 'NWO-domein Technische en Toegepaste Wetenschappen', Applied and Engineering Sciences domain of NWO. Formerly 'Stichting Technische Wetenschappen', Technology Foundation STW.

SURFsara SURFsara is a Dutch foundation that provides supercomputers, colocation, networks and high-end visualisation to academic institutions.

Take-off Grant NWO funding scheme to encourage commercial activities and entrepreneurship at Dutch knowledge institutions for academic entrepreneurs to bring research results to the market.

TCS+ An online seminar series in theoretical computer science.

TOP grant NWO grant for outstanding, established research groups to strengthen or renew lines of research. Module 1 is intended for senior researchers with a proven track record of significant research results in the last ten years, Module 2 is for junior researchers at the beginning of their scientific career.

Top sectors As of 2012, valorization activities of the Dutch knowledge institutes is organized by the government in the top sectors Agriculture & Food, Chemistry, Creative Industry, Energy, High Tech Systems & Materials, Logistics, Life Sciences & Health, Horticulture & Seed Stocks, Water.

UMC University Medical Centre, e.g. at Universiteit Utrecht.

Universiteit van Nederland Online lectures by prominent professors aimed at the general public.

UT 'Universiteit Twente', University of Twente.

UvA — 'Universiteit van Amsterdam', University of Amsterdam.

Vernieuwingsimpuls — See Innovational Research Incentives Scheme.

Veni grant — NWO grant for researchers who have recently obtained their PhD (within the last three years). Maximum of 250 k€.

Vidi grant — NWO grant for researchers who have gained several years of research experience after their PhD (who have obtained their PhD no more than eight years ago). Maximum of 800 k€.

Vici grant — NWO grant for senior researchers who have demonstrated an ability to develop their own line of research (who have obtained their PhD within the last 15 years). Maximum of 1.5 M€.

VERSEN — 'Vereniging Software Engineering Nederland', Dutch National Association for Software Engineering.

VHTO — Dutch national expert organization on girls/women and science/technology.

VSNU — Association of universities in the Netherlands formed by the fourteen Dutch research universities.

VU — 'Vrije Universiteit Amsterdam', VU University Amsterdam.

W3C — World Wide Web Consortium.

WIAS — The German Weierstrass Institute for Applied Analysis and Stochastics conducts research in applied mathematics and basic mathematics.

WISE — The Women In Science Excel programme provides talented female researchers with an opportunity to develop or expand their own research group at one of NWO's institutes.

Wiskundeclusters — Mathematics Clusters The four Mathematics Clusters - unique in the world - are a successful Dutch concept. They were established in 2005 to counter fragmentation of research and education. The clusters provide critical mass and focus on the mathematics research and education in the areas in which the Netherlands performs best. The four Mathematics Clusters are: DIAMANT (Discrete, Interactive and Algorithmic Mathematics, Algebra and Number Theory), GQT (Geometry and Quantum Theory), STAR (Stochastics - Theoretical and Applied Research) and NDNS+ (Nonlinear Dynamics of Natural Systems). Nine universities and CWI participate.

XForms — A W3C recommendation for creating web forms and web applications.

Zwaartekracht — Gravitation, large-scale government research funding programme, for consortia executing excellent research over a 10 year period, coordinated by NWO.

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Centrum Wiskunde & Informatica (CWI) is the national research institute for mathematics and computer science in the Netherlands. The institute's strategy is to concentrate research on five broad, societally relevant themes: Software, Data, Networks, Computation and Quantum.

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