Centrum Wiskunde & Informatica

CWI

Strategic plan

2019 - 2024

Preface

This strategic plan describes CWI's course for the period 2019-2024. In it, the developments in mathematics and computer science are addressed, as well as CWI's ambitions and the choices regarding research themes and topics we will focus on.

Over the years, CWI's research is highly regarded and has consistently been evaluated as excellent. CWI feels encouraged by the praise we received from the most recent international evaluation committee and is confident that our research for the years 2019-2024 will be equally rewarding and successful.

But these are challenging times for science. Science is increasingly called upon to tackle big issues in society. With the ongoing digitization of all aspects of daily life, mathematics and computer science are expected to help explore, interpret and explain phenomena which shape the digital society. CWI intends to further develop and broaden its role as a guide in the digital world. We feel we are well placed to do so because of the interdisciplinary collaboration between the mathematicians and computer scientists within our institute.

CWI is a compact and non-hierarchical institute. We intend to retain these characteristics, even as we aim for growth in the coming strategy period, expanding and extending our research, in order to continue to fulfil the whole of our mission in the coming years.

In addition to describing CWI's choices concerning our research, the Strategic Plan also sketches the way in which we will continue the valorization policy we successfully initiated in the past strategy period.

As one of the nine national research institutes under the wing of the Netherlands Organisation for Scientific Research (NWO) we are pleased to recognise important elements of CWI's mission in the recently published NWO Strategy

2019-2022. What CWI sets out to achieve in the coming years follows naturally from the ambitions we share with NWO:

- to perform groundbreaking research;
- to nurture and facilitate talented people;
- to connect with others in science and society;
- to share and valorize our knowledge.

Last but not least, the plan also addresses the optimal environment and facilities we try to provide to CWI's researchers and supporting staff, as I am very much aware that it is the people at CWI that make the institute a success.

Jos Baeten
General Director

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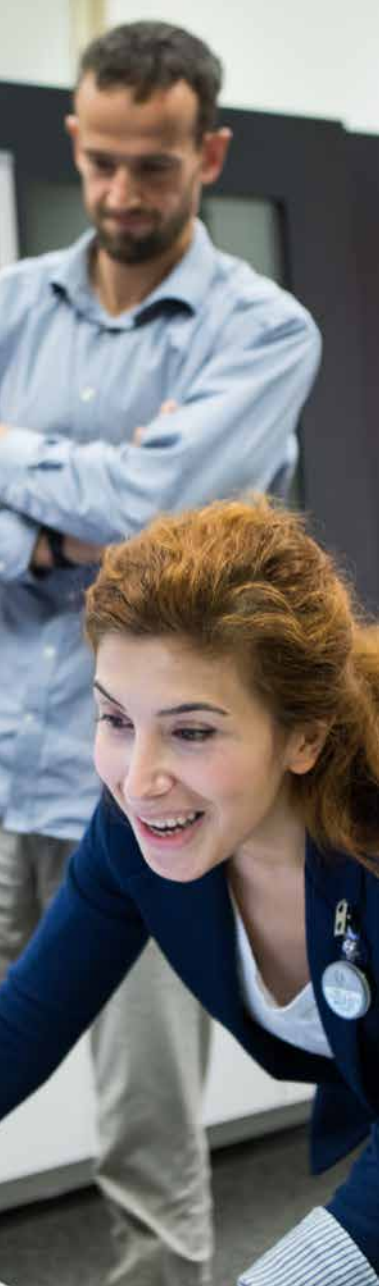


MILESTONES

CWI has a long-standing tradition of excellence in research that is both fundamental and societally relevant. CWI's track record includes building the first computer in the Netherlands, computing the dike heights for the Dutch Delta Works, connecting Europe to the internet, developing the Python programming language, computing the train timetables for the Dutch Railways, breaking factorization records of RSA encryption for internet security and developing the open source database system MonetDB. Recent highlights include showing the practical vulnerability of the SHA-1 standard for internet security, developing proactive planning methods for emergency services and launching the QuSoft research centre for quantum software.

1 Mission

Centrum Wiskunde & Informatica (CWI) is the Dutch national research institute for mathematics and computer science. 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.

Vision

Fundamental, curiosity-driven research is the basis 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, health and climate.

Ambitions

While fulfilling its mission to generate new knowledge in its fields, CWI also aims to broaden its role as a guide in the digital world. A shift to the digital domain is taking place throughout science and society. Digitization has a far-reaching impact on daily life, e.g. in communications, logistics and healthcare. New digital services and technologies are being developed at a high pace – and there is an urgent need for a fundamental understanding of these developments. CWI can contribute by offering new knowledge and solutions from our expertise in mathematics and computer science research. Based on the high quality of our research, our excellent network with universities and other knowledge organizations, public and private partners, and the fact that CWI's research is both fundamental and application-oriented, we feel that we are in the right position to do so.

In 2019-2024, our intention is to retain the present excellent quality of our research and to invest specifically in two topics with a high societal and scientific impact: Artificial Intelligence, and Privacy & Security. At the same time, we intend to continue our contributions in areas in which we are known to have a strong scientific tradition and a worldwide leading position, such as quantum algorithms, cryptology, data management and computational imaging. We will further strengthen our well-established strategic themes: Computation, Data, Software, Networks and Quantum, connect them on overlapping topics, having added Artificial Intelligence as our sixth theme, and will develop Privacy & Security as a new pilot theme.

We expect that this renewal and expansion of CWI's research will lead to a greater volume of high-quality scientific output as well as to an increase of collaboration opportunities with other knowledge organizations, industry and societal partners. We are already stepping up our knowledge sharing (valorization) efforts. In addition, we intend to strengthen our ties with other

RESEARCH GROUPS

CWI currently has fifteen research groups, which each contribute to one or more of CWI's strategic research themes. Many of these groups consist of both mathematicians and computer scientists. A brief description of each research group is given in Appendix B.

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

institutes from the Netherlands Organisation for Scientific Research (NWO) and the Royal Netherlands Academy of Arts and Sciences (KNAW). A specific issue that CWI can contribute to is a challenge that scientists across all fields are facing today: managing scientific data with their explosive increase in both size and complexity. CWI can provide answers to scientific data management questions and develop new data science techniques, thus supporting other institutes.

In this document we elaborate on CWI's course for the coming years and discuss the opportunities for CWI to contribute to science and society in the best way possible. Part of our course will also be the effort to expand CWI's research activities by trying to increase the number of permanent staff positions at our institute. When growth of the institute should become financially possible, we would be able to realize our potential to the full and substantially enlarge our societal impact. The 2017 evaluation committee endorsed our intention to grow, noting that "due to its unique constellation, CWI is also best placed to take up a natural leading role in important developments and platforms in the Netherlands (and beyond, on European level) […]. Given the fast digital evolution, a unique institute as the CWI is destined to become even more important."

GOVERNANCE

On 1 January 2018, CWI merged with the NWO institutes organization, the Netherlands Foundation of Scientific Research Institutes, or NWO-I for short. CWI is now governed by the foundation board of NWO-I with respect to operational management and by the NWO Executive Board with regard to policy-related issues. The boards form a personal union. One board member advises and monitors CWI's general director on operational issues and another board member on policy-related issues. CWI's general director continues to be responsible for the CWI mission, for the day-to-day management of the institute, for the appointment of CWI personnel and for the implementation of (research) policies. The NWO-I office provides CWI and the other institutes with a dedicated liaison officer, and supports them in e.g. payroll administration and in legal matters.

2 CWI's role in a changing world

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. One of the other distinguishing characteristics of CWI is that the institute encompasses fundamental and application-oriented research, a rare combination in our field. We safeguard fundamental research as the basis of our work, both at the core of mathematics and computer science, and at the intersection between the two fields. CWI can invest in long-term lines of fundamental research, bringing high-risk topics into development, without the pressure for short-term impact that characterizes applied research laboratories. Therefore, trailblazing research is at the core of CWI: the institute is a birthplace and accelerator for new research fields in the Netherlands. At the same time, our research is continuously inspired by real-life issues. Over the years CWI has proved itself to be a responsive and dynamic organization, anticipating on major developments in science and listening to society's needs, and adequately and timely opening up new avenues of research. With this fairly unique set of characteristics, CWI has several roles in the national and international research landscape:

2.1 Centre of excellence and expertise

CWI is one of the leading institutes in its fields worldwide. We have a unique expertise in the Netherlands in a broad range of subjects, for example, quantum algorithms, cryptology, data management, and computational imaging. Our research is of high quality: judged excellent in a series of external evaluations. Therefore CWI has an advisory role with regard to major societal developments in our fields to government agencies, NWO-I and NWO. CWI shares its expertise by collaborating with universities and other knowledge institutions in big research projects and consortia, by providing teaching in specialist topics, and by valorization.

2.2 Birthplace of new research areas

CWI invests in promising, long-term research and is therefore a breeding ground for new research areas. For example, we started research into quantum computing in the nineties, as one of the first worldwide. In time, many of the new research lines that start at CWI and are successful, are transferred to universities, to spin-off companies and to society. CWI is compact and non-hierarchical and can act decisively. For instance, we transform, without much delay, existing research topics into a new strategic theme, or combine researchers into a new research group, shifting focus to where we expect CWI can contribute most effectively to emerging scientific and societal issues. And we speedily attract new talent when a colleague retires or moves on to a full time professorship at a university. Two examples of shifting focus and combining strengths are the current research groups Life Sciences & Health and Computational Imaging.

2.3 Breeding ground for talent

CWI is a breeding ground for both top researchers and young talent. Since its foundation in 1946, around 200 of its researchers have become full professors. The majority of its current senior researchers have a part-time full professorship at one of the Netherlands' universities, and teach and supervise students in mathematics and computer science. Also non-permanent staff, in particular those with a tenure track appointment, teach and supervise students. Our researchers include a Spinoza Prize winner, thirteen researchers who currently hold an NWO Innovational Research Grant, four ERC Grant holders and three KNAW members. Almost 10% of CWI's PhD students receive their doctorate cum laude or win a prestigious prize. In addition, CWI is able to attract (inter)national talent thanks to its excellent reputation. The institute offers a stimulating working environment for its researchers of over thirty different nationalities.

CATEGORY	SOME EXAMPLES OF PARTNERS
Industry	e.g. Databricks, ING, NXP, Oracle, ORTEC, Philips, ProRail, Shell, Software Improvement Group (SIG), Tata Steel and several SME's
Higher education organizations	TU/e, TU Delft, UvA, VU, UU, EUR, RU Nijmegen, RUG, LEI, UT, UM, Tilburg University, WUR, AMC, HvA
National research consortia	NETWORKS, Quantum Software Consortium
Dutch National Research Agenda	Routes: Big Data (9), Logistics and Transport (16), Energy Transition (17) and Nano and Quantum (19).
Alliances	e.g. QuSoft, Amsterdam Data Science, Dutch Blockchain Coalition, Commit2Data, mathematics clusters DIAMANT, STAR and NDNS+, Big Data Alliance
Amsterdam	e.g. Amsterdam Economic Board, Amsterdam Science Park, Stichting Science and Business
Research and applied research institutes	e.g. NWO- and KNAW-institutes, TNO, KNMI, RIVM, eScience Center
Societal partners and government	e.g. ABP, Belastingdienst, Koninklijke bibliotheek, GGD, Rijksmuseum, Ministerie van EZ, Ministerie van BZK, Rijkswaterstaat
Mathematics and computer science organizations	e.g. Platform Wiskunde Nederland, ICT-onderzoek Platform Nederland, Data Science Platform Nederland, Vierkant voor Wiskunde, Koninklijk Wiskundig Genootschap, Pythagoras, Vereniging Software Engineering Nederland (VERSEN)
International	e.g. Inria, LIAMA, EIT Digital, ERCOM, ERCIM, Informatics Europe, IFIP, MathOA, FOAA, Schloss Dagstuhl – Leibniz Center for Informatics, Oberwolfach Research Institute for Mathematics, Dutch Flemish Scientific Computing Society
Standards	W3C, Moving Picture Experts Group (MPEG)

2.4 Partner of academic and non-academic parties

CWI maintains close ties to all Dutch universities. In 2018, 33 out of the 44 senior CWI researchers with a permanent position hold a part-time full professorship at ten of the universities in the Netherlands. In research programmes, consortia and alliances, CWI partners with universities, other national knowledge institutions, and public and private organizations, both nationally and internationally. Some examples are the Gravitation programmes NETWORKS and the Quantum Software Consortium, the Data Science Platform Netherlands, the Big Data Alliance, and the Dutch Blockchain Coalition.

CWI facilitates several long-standing (inter)national academic and non-academic organizations in mathematics and computer science, providing housing, support and chairing roles, and has initiated new (inter)national organizations. CWI is a

NWO STRATEGY

Considering our roles, CWI strongly recognizes itself in most of NWO's cornerstones, as defined in the NWO Strategic Plan 2019-2022:

- Nexus role (connecting agendas, science and society);
- People (perspective for researchers);
- Research (collaboration for excellence and innovation);
- Knowledge sharing (effective use of knowledge through co-design and co-creation).

Although we have recently invested in the FleX-Ray CT scanning lab, NWO's fifth cornerstone, Infrastructure, is not as relevant to CWI's mission as it is to some of the other institutes.

prominent partner in many of the international networks in our fields, and is a core partner in EIT Digital. As of November 2017 CWI hosts the Dutch EIT Digital Innovation Space on its premises.

2.5 Driver of valorization

CWI transfers knowledge and expertise to society through collaborations with public and private parties. CWI research regularly leads to innovative software of production-quality and to international web and (multimedia) standards. This too contributes to the societal impact of the institute, especially in the case of open source software or when software contributes to high-quality employment opportunities in the region. In addition, CWI makes a direct contribution to the economic activity of the Netherlands by generating spin-off companies, ranging from an energy consultancy firm to a company that minimizes the response time of ambulances with mathematics. CWI's valorization strategy is described in more detail in section 3.3.

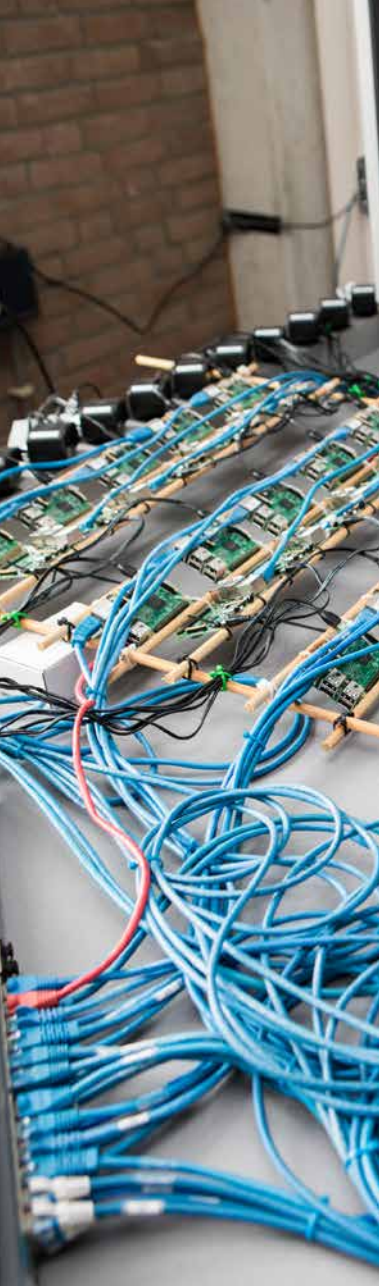
3 Scientific goals
a guide in the digital world

A shift to the digital domain is taking place throughout society. This digitization impacts the daily life of every citizen through the development of new digital services, technologies and applications. A fundamental understanding of digital developments is essential to ensure that, as a society, we get a grip on this revolution and are able to anticipate the risks. To achieve such an understanding, mathematics and computer science research are of crucial importance. CWI offers new knowledge and solutions. As a scientific expertise centre, CWI already plays a guiding role in a number of areas at the core of the digital society. Our ambition to further develop this guiding role, we feel is justified by the high quality of our research, our interdisciplinary collaborations, and the balance between fundamental and application-oriented research.

In the words of the 2017 evaluation committee: "Due to its unique constellation, CWI is also best placed to take up a natural leading role in important developments and platforms in the Netherlands (and beyond, on European level) […]. Given the fast digital evolution, a unique institute as the CWI is destined to become even more important."

3.1 Six strategic themes and one pilot theme

Our research is organized into cross-cutting strategic themes that reflect both CWI's strengths and major developments in science and society. Each of CWI's research groups contributes to at least one strategic theme and each of CWI's strategic themes is contributed to by at least two research groups (for an overview see Appendix B). The strategic themes are also helpful 'labels' to our expertise for potential partners from industry and society at large.

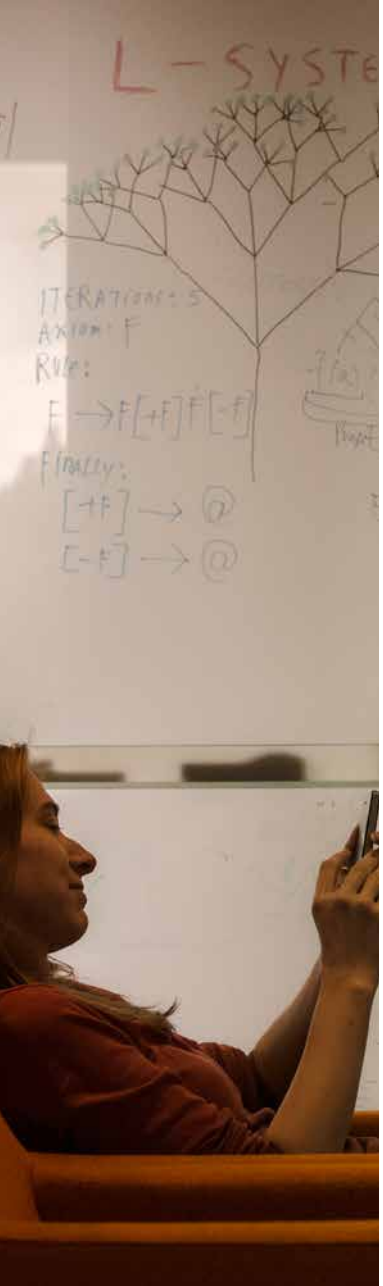


We will invest along the lines of the themes to nurture our future research efforts. The themes also serve as a guiding principle in our hiring policy. Anticipating developments in both science and society, in 2018 we 'elevated' a research area that has been part of CWI's scientific activities for a long time to become a strategic theme: Artificial Intelligence (AI). CWI now has six themes: Computation, Data, Software, Networks, Quantum, and Artificial Intelligence. Developments and intended research directions in these themes and in a seventh 'pilot' theme Privacy & Security, are described below.

Computation

Computation has a long and successful tradition within CWI, and has continuously been a basis for bringing new algorithms and models to science and society. At CWI, we develop computational methods for a variety of real-life phenomena and for complex systems. Examples are climate, weather and energy, biological and economic processes, transportation, communication, logistics and smart cities. We recognize a great societal need for efficient computational methods and algorithms, for instance for assisted decision-making and operation of complex systems and networks.

Increasing model accuracy We will increase the accuracy of our physical, engineering and economic models and results, aiming to mimic the occurring phenomena in applications in an even more realistic way. The presence of multiple scales in time and/or space, with relevant processes on all scales mutually connected via nonlinear couplings, poses an important challenge for the modelling of many real-world phenomena. Inevitably, an increase in model complexity will lead to more expensive computations.
We have seized opportunities in computational life sciences and computational imaging, in particular in developing mathematics and algorithms for real-time adaptive 3D imaging. We invested in hardware for computational imaging, most notably the FleX-ray CT scanning lab, which was developed in collaboration with our sister institute Nikhef, and was opened in 2017.



By combining our efficient algorithms with real-time, data-driven systems, we create interactive systems where various agents (humans or artificial) can interact, communicate and make complex, well-informed decisions. We develop new paradigms for involving the user in such complex computing systems.

Uncertainty quantification In many of our application areas we encounter uncertainties in e.g. input data, model parameters, the model itself or boundary conditions. We already put a lot of research effort in developing robust and efficient numerical techniques and computational algorithms to handle these uncertainties. The overarching method of stochastic partial differential equations is another step towards dealing with uncertainty, in which we would like to put additional research effort.

Reducing computational time by incorporation of data CWI's Computation and Data themes are strongly connected. As the interaction between simulation, data and uncertainty is of increasing importance in science and engineering, CWI aims to take an internationally leading position in this area. For the near future, the development of efficient algorithms for incorporating data into computational models is important. Making our algorithms which are characterized by detailed, highly informative output much more efficient is a core challenge, and a prerequisite for a successful transfer of these methods and models to society. Our current research already includes learning from data, data handling, and development of the corresponding algorithms (that are based on optimization techniques, convolutions, GPU computing). We want to recruit additional researchers who aim to deeply understand and thus improve the performance of the corresponding algorithms.

In the area of quantum computation, the development of algorithms for quantum computers is a very active field of CWI research. As soon as implementation of the advanced algorithms on quantum hardware becomes feasible, in terms of stability, operating system, compilers, etc., we will increase our research effort in this direction.

As new application areas we envisage specifically Digital Finance and Digital Twin (see also section 3.2).

All disciplines of research increasingly depend on collection and analysis of data, a phenomenon called the 'fourth paradigm' of scientific discovery (following theory, experimentation and computation). CWI has delivered award-winning fundamental data research over the past decades that has impacted society and industry, and has generated multiple spin-offs. CWI continues to invest in data research along three paths.

'Core' data research In terms of big data, volume and velocity of data is continuously increasing, demanding more processing capability from generic data processing systems. This can be obtained either using parallel cluster computing, especially in the cloud, or by depending on faster future hardware. Hardware is still evolving but is steering away from simply faster processors to highly diverse processors: graphical processors, programmable hardware (FPGA) and special purpose (ASIC) devices such as tensor processors – all integrated into standard chips. An important question CWI will study is how this jungle of hardware can be used automatically by data processing systems to empower big data users. Adaptive optimizers, new compressed representations of data, and just-in-time query compilers are relevant directions of research. Beyond volume and velocity, big data poses variety and veracity challenges. CWI will continue to invest in responsible data science, especially studying how to identify, quantify and visualize bias and uncertainty in data. Solutions for this would be especially useful to automatically provide context that enables people to better interpret the veracity of news and social media messages. CWI aims to improve the way people access media and communicate, using novel human-computer interaction techniques to present data in immersive environments, also taking the human context into account. This context includes data gathered with sensors such as wearable technology and smart textiles.

Data-guided techniques for other research themes The Data theme plays an increasingly important role in CWI's other strategic themes. In connection with AI, CWI will work on the formal modelling of limitations of machine learning

methods, investigating how to quantify these limitations along dimensions that are relevant for specific kinds of data, and how to convey these limitations to data users. There are further connections in defining more efficient deep learning algorithms that avoid the creation of huge matrices, pushing learning into a database system. Connections to the Computation theme are in reducing the complexity of simulations using properties derived from data, and in improving and constraining (predictive) simulations using data. Connections to the Networks theme are in devising efficient algorithms for analyzing graphs, also by exploiting data properties. Connections to the Software theme are in studying domain-specific languages suited for compiling and optimizing queries for heterogeneous hardware. In connection with Privacy & Security, CWI is studying personal data management architectures that provide users with the ability to trace which of their data is used by third parties. A research domain that is of specific interest is life sciences: CWI is moving into big data analytics with pan-genomics, the study of large collections of sequenced DNA, for example to develop personalized medicines. This demands more efficient algorithms that discover and take advantage of commonalities in the genomic data.

Data science in collaboration with NWO sister institutes Finally, CWI intends to start an initiative into scientific data management in collaboration with other NWO institutes. CWI can contribute to data management research questions from other scientific domains; while at the same time helping our NWO sister institutes in managing their data, which continuously increase in size and complexity. For more information, see section 3.4.
As new application area connected to the Data theme we specifically envisage Earth observation (see also section 3.2)

Software

CWI is the birthplace of fundamental software science. Part of CWI's legacy is the build-up to and creation of Algol68 in the 1960s and the introduction of formal syntax and formal semantics to programming languages. Our mission

is to fundamentally understand software and software engineering better; to simplify software and software engineering in order to better predict and control software quality aspects such as maintainability, safety, energy consumption and information security which have a high societal impact. Topics of interest are verification, certification and research on software usage, design and transformation. We intend to further develop our research in privacy of software, software language engineering, software analysis, programming environments, and formal methods.

Software and privacy Privacy is one of the key problems of the coming decade. There are new research challenges in terms of finding, analyzing, and solving privacy issues in existing software, as well as how software development, and in particular programming languages or domain specific languages, can be improved to avoid privacy leaks in the future (privacy by design). These issues are both urgent and hard, since the software landscape is becoming more and more diverse. This situation is all the more urgent because of the increasing popularity of blockchain and smart contract technology.

Software language engineering We approach the software engineering challenges from the software language perspective. Programming languages and domain specific (modelling) languages are our objects of study and design. We combine reverse analysis with forward analysis: studying and improving tools for existing languages and software systems as well as designing and implementing new languages. As a rule, we strive to produce high quality prototypes of tool and language implementations as output of our research efforts.

Software analysis We aim to invest in language engineering to better understand software engineering in context. Software analysis is becoming increasingly context dependent: it is not just code that needs to be analyzed, but the whole ecosystem surrounding software development, including version histories, frameworks, APIs, mailing lists, configuration files, issue trackers etc. This means that off-the-shelf tooling does not suffice, and that powerful meta tooling (tools to build tools) is crucial. We plan to consolidate and disseminate

these tools in a scientific software infrastructure to answer fundamental empirical questions about software engineering, like how and why does software grow and become more complex.

Next generation programming environments We further see an increased diversity in how organizations are developing their software. There is a trend in moving beyond traditional programming languages: dedicated domain-specific languages, highly tailored software environments, low-code platforms, and end-user programming make up the future software engineering landscape. We will further research software language engineering principles and techniques to develop programming systems beyond the traditional compiler.

Timed data and interaction We study domain specific languages and infrastructures for modelling and controlling complex collections of media objects (including real-time media and sensor data), which are interactive and distributed in time and space. The fundamental interest is on how the 'time', 'distributed' and 'interactive' aspects influence the creation, distribution and delivery of complex content in a customizable manner. The final goal is the development of optimization mechanisms for interactive systems centered around the user.

Formal methods Throughout the history of computer science, a major challenge has been how to assert that software is free of bugs and works as intended. The general approach of formal verification is to give precise, mathematical proofs of correctness of software, with respect to specifications of the intended behaviour expressed in formal logic. Formal verification can fully guarantee correctness of software (as opposed, for instance, to testing) but can be challenging in practice, as it typically requires significant effort. Our aim is a systematic verification of mainstream libraries as provided by popular programming languages like Java. Software libraries are the building blocks of millions of programs, and they run on the devices of billions of users every day. Therefore, their correctness is of the utmost importance.
Our overall objective is to establish programming as a scientific engineering discipline by the integration of formal verification methods and tools into the

practice of software engineering. We plan to extend and apply our expertise on formal modelling, verification and development methodologies to security and privacy software and cyber-physical systems.

Networks

Networks form the backbone of many physical or abstract complex systems in a broad range of application areas including transportation, logistics, energy, communication, life sciences, database architectures and software. CWI has a strong research track-record in networks, rooted from the early years in the fields of operations research and stochastics, and encompassing both fundamental and applied research. CWI researchers are involved as PI's in the NWO Gravitation NETWORKS consortium, which will enter its second phase in 2019. We will continue and expand our research activities along the following lines, in synergy with the other strategic themes:

Understanding networks An overarching direction is gaining fundamental understanding of networks, aiming to improve their resilience, performance, operation and control. For instance, we work towards making better predictions (such as disruptions in logistic networks), achieving synchronization in noisy networks (such as frequency variations in energy networks), improving the reliability and performance of communication networks, and obtaining efficient coordination mechanisms in decentralized systems such as traffic networks and sustainable energy markets. We expect a new generation of societal networks, involving multiple-level intertwined networks (e.g. 5G technology). Monitoring the emergence of self-organization in such complex multi-agent systems relates directly to the Artificial Intelligence theme. Networks are also indispensable in life sciences: we use metabolic networks to understand symbiosis in microbial communities and phylogenetic networks to explore genetic relations within such communities.

Computational complexity Networks are at the core of fundamental questions in computational complexity, at the interface of mathematics and

computer science. Whether efficient algorithms exist for scheduling and routing (such as the travelling-salesman problem) is the famous 'P versus NP' problem. Understanding the possibilities and limits of efficient computations, both from theoretical and practical viewpoints, also within the realm of the upcoming quantum computer, is a major inspiration for our research. On the one hand we work on designing faster algorithms. On the other hand, with the security of cryptographic protocols being based on the assumption that no fast algorithms exist for certain computational tasks, we explore new post-quantum computational primitives that can resist both classical and quantum cryptanalytic attacks. The link to the Quantum theme is twofold: designing quantum algorithms for network problems, and using classical optimization tools to quantify the advantages that quantum devices may have over classical ones.

Networks and optimization Network optimization problems are typically nonlinear, with discrete and continuous decision variables, and data uncertainties. We will develop more efficient algorithms for such problems through a deeper theoretical understanding of the practical behaviour of the current computational tools and through harnessing links between the discrete and continuous paradigms. With many network problems needing real-time answers and being data-driven there is a growing need for optimization tools that are able to cope with very large scale problems and are robust to data uncertainties, still aiming at high quality solutions. If we can recruit the right talent, large scale data-driven optimization and stochastic control are promising areas where we want to strengthen our research capacity. We also see opportunities in increasing our networks research in combination with machine learning in data science, in particular through exploring deeper connections between statistical and online learning and advanced optimization techniques.

Networks and data Networks research provides promising new methods for the processing and analysis of large heterogeneous data sets, for instance of pangenomic data. Recently graph-based data structures have been proposed, assuming that intrinsic network structures can be exploited for fast exploration and tracing back provenance. The development and operation of such data

structures are focus points of the Data theme. Apart from life sciences, it has numerous other possible applications, such as large social networks and cultural heritage data.

Quantum

CWI is a long-term pioneer in quantum computing, an area which is quickly gaining momentum. In 2015 CWI launched the research centre QuSoft, together with the University of Amsterdam and Vrije Universiteit Amsterdam. QuSoft is a central player in quantum computing worldwide, shaping the quantum software landscape. Its main goal is to find more applications for the future quantum computer.

Quantum algorithms Quantum computers can solve certain computational problems much faster than any classical computer could, though we do not yet know many examples of such problems. CWI works on the design and analysis of more algorithms that give quantum speed-up, in areas such as optimization, networks, machine learning, computational science, and others. Conversely, we also study the ultimate limits of such quantum algorithms.

Quantum communication Networks of quantum computers can solve certain distributed problems with much less communication than classical networks. CWI studies such problems, which could eventually lead to a 'quantum internet'.

Quantum cryptography Based on effects like entanglement and Heisenberg's uncertainty relation, quantum communication also enables more secure and/or private communication. CWI works on the 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.

Particular attention is given to applications that could be run already on the first small to medium-sized quantum computers (up to 100 qubits) that are

becoming available now. Initially such examples of 'quantum supremacy' will involve artificial computational problems, but slightly bigger quantum computers will subsequently be able to handle much more practically important problems, for instance in quantum chemistry. In addition to the development of such applications, the research also involves broader computer-science questions of compilers, architectures, fault-tolerance, and testing and verification of quantum software. These overarching research lines embody CWI's 'quantum' theme, putting CWI and QuSoft at the forefront of current quantum computing developments.

Other themes There are many connections to other research themes within CWI, e.g. using classical optimization tools for quantum problems and developing quantum algorithms for optimization; and using quantum mechanics for better cryptography and protecting classical cryptography against quantum adversaries. We aim to continue and strengthen these collaborations in the coming years. In the near future, we also expect collaborations with the AI theme, both on quantum machine learning and on using classical machine learning for quantum problems.

Beyond CWI We expect increased academic collaborations on the topic of quantum chemistry with the UvA's Sustainable Chemistry, VU's Chemistry, and AMOLF. QuSoft plays a leading role in the national Quantum Software Consortium which was awarded an 18.8 million euro grant in the NWO Gravity programme in 2017. Our long-standing European collaborations will be strengthened substantially by the new European Commission Quantum Flagship. In addition, we expect opportunities emerging from the Dutch government's National Digitization Strategy ('Nationale Digitaliseringsstrategie') and increased industry involvement as quantum computing is extending from academia into industry at a fast pace. In the next few years, we and our partners aim for a strong growth of QuSoft, possibly leading to a more independent form of organization such as an Advanced Research Centre involving universities, CWI and private parties. In such a case, CWI will consider transferring its quantum software research activities to this new organization.

The importance of artificial intelligence (AI) as a research topic has grown immensely in the past few years, and AI techniques have become an essential part of computer science. AI holds great promise for industry areas such as technology, finance, manufacturing, energy, gaming and health, and will impact our society, for example in virtual assistants, image- and speech recognition, and self-driving cars. AI research is firmly embedded at CWI, as CWI was involved in AI, especially machine learning research, from the early beginnings of the field. In the coming years we aim to expand AI as a strategic theme, by expanding our current research activities through hiring new tenure track researchers or senior researchers and by extending our AI research into new areas.

CWI focuses on topics that concern (long-term) fundamental research, with an eye on current and future applications. Our focus is on fundamental, monodisciplinary AI research as well as fundamental multidisciplinary research between AI and other scientific disciplines.

Mono-disciplinary AI research A thorough understanding of the fundamentals of AI is more important than ever, for designing, using, understanding, and ultimately relying on AI techniques.
Fundamental insights in not only how machine learning (deep learning) works, but especially also why it works, have become essential. This is important for both designers as well as users of AI, who want to understand what happens and like to have some form of control over the process. Explainable and accountable AI as well as complexity issues are important topics of investigation. Related to the above topic is our investigation of biological plausible neural networks, which is unique in the Netherlands. Important current topics concern computational simulation and learning rules, neuromorphics, and theoretical aspects like mathematical models and bounds, and optimal coding mechanisms. Furthermore, the design of (model-based) evolutionary algorithms form an important field for complex single- and multi-objective optimization, as well as

for machine learning, especially when black-box optimization -or at least a grey-box optimization- is required.
In addition, fundamental insights in the behaviour of complex systems of multiple learning agents or diverse subsystems that interact with each other or in uncertain environments, become more and more important. Important aspects are multi-agent learning, both cooperative and non-cooperative or even antagonistic, and the development of agent strategies, planning approaches with uncertainty, preference elicitation techniques, and agent coordination mechanisms. This also concerns the security, reliability and privacy aspects of (multiple) operational systems using AI, as well as how to keep people in control over (multiple) operational systems using AI.

Multidisciplinary research with AI The current developments in AI mean promising opportunities for new approaches together with other scientific disciplines. These multidisciplinary research topics yield new AI challenges and research directions. Important current examples are research with

- electrical engineering, which combines future electricity system paradigms and agent-based coordination and operations;
- management science, dealing with decentralized transportation logistics and agent-based management;
- cognitive computational neuroscience, where simulation and investigation of biological neural networks come together;
- Human Computer Interaction (HCI), combining symbolic and statistical AI, explainable and accountable AI, and assessment methods for AI methods by users; and connecting AI methods in vision, emotion, speech and language processing with future real-world user interaction paradigms and machine perception of human activity.

Upcoming opportunities are for AI in combination with

- computational imaging, where new machine learning architectures are needed that are targeted to the challenges of the novel, advanced 3D imaging problems;

- continuous optimization techniques in deep learning approaches for high-dimensional problems, where learning and optimization comes together;
- scientific computing, for learning of and sampling from high-dimensional probability distributions and models, where underlying models are learned from noisy data or based on physics models (physics-based deep learning); and for addressing the challenges of multi-scale modelling and simulation by data and learning techniques;
- geophysical and space-physical systems, where machine learning techniques are developed in combination with state-of-the-art simulation techniques (currently for space weather).

Most of these new fundamental opportunities typically can take place within CWI, where the research of mathematicians and computer scientists is strongly interwoven; for other research directions, we will intensify cooperation with external research groups.

AI applications. CWI continues and extends its activities on application of its research results in context, for both mono-disciplinary and multi-disciplinary research. Examples of current and future applications are data science applications; health care applications in ambulance planning and radiation oncology, such as automated treatment planning, deformable image registration and 3D dose reconstruction; information processing systems, smart energy systems, data integration and information, resilient networks, etc., where activities are or will be performed in context, together with companies and societal organizations.

Privacy & Security (pilot theme)

The ever-growing use of digitized services poses formidable security and privacy challenges for society-at-large, especially considering the near-omnipresence of digitization, increased networking between services, and surveillance technology, in combination with novel, powerful AI techniques. Almost inevitably, this means

that nearly all areas in computer science will turn out to have privacy and security issues at their core, and that for many of the challenges an integrated approach is called for.

In the coming years CWI will explore the possibility of introducing the new strategic theme Privacy & Security. Aspects of privacy and security have been part of CWI's research for a number of years, but in order to become a strategic theme, both the volume and diversity of the research need expanding.

We are already investigating privacy and security through cryptology, e.g. quantum-safe crypto (including cryptanalysis, construction and standards), cryptographic aspects of blockchain technology and foundations of cryptology. We are exploring the possibilities for a broader research approach that includes various other cybersecurity techniques. We will invest in the area of applied cryptography, with a focus on privacy preserving technology. Topics are encryption, digital signatures and secure computation, applied to social media systems or apps.

Private data management There is a strong connection between this theme and the data theme. Desired investments are in the area of private data management. For instance: how can citizens regain a degree of oversight and control over the private data that third parties collect on them? A data management infrastructure can be envisioned where citizens can monitor data usage and take action to restrict permissions of use. The research area should focus on the intersection between data management systems architecture and privacy methods. A possible application field is networked health data.

AI systems In order to be secure in their operation, cyber-sociophysical AI systems, like decision and control systems or market-based systems, should be robust against malicious attacks. How to ensure these AI systems cannot be tampered with? How do we deal with the inevitable perspective of change and growth? Also, data-driven detection of security breaches is necessary.
Another topic is AI systems, where the threats lie in the intrinsic learning and

knowledge capabilities. It needs to be explainable how such systems learn (machine learning and general AI algorithms) and behave, in interactions with humans, in controlling devices (e.g. cars or medical devices) or in complex interactions between AI systems themselves.

Software Security needs to be addressed at various levels when designing and maintaining software systems, also in software-intensive embedded systems. Research topics of interest are software engineering, usability engineering, system design and modelling, distributed design. Our formal methods research enables provably secure systems.

We expect increased collaboration with TNO in the area of applied secure multiparty computation. To investigate the impact of security measures on the privacy of citizens, we will seek collaboration with our sister institute NSCR (Netherlands Institute for the Study of Crime and Law Enforcement).
As new application area connected to the pilot theme Privacy & Security Data theme we specifically envisage Digital Finance (see also section 3.2).

3.2 Emerging application areas

We identify a number of upcoming, new application areas to which CWI aims to contribute in the coming years, such as humanitarian logistics, wind energy and data analytics software. Three specific areas that we want to invest in are:

Digital Finance Digital Finance aims to automate finance. Payments, financial and insurance contracts, risk computations and management could all be dealt with fully automatically, online and in real-time, based mainly on financial and personal data. In addition, there are initiatives to design alternatives to the regular payment systems and to financial contracts by means of cryptocurrencies. Blockchain technology may form the data platform foundation on which many novel financial applications will run. Possible downsides are the vulnerability of a rapidly developing novel system and privacy issues.

Mathematics and computer science can be of great help in ensuring the sustainability of this emerging field. CWI aims to contribute to the development of decent risk management, protection of privacy and accurate handling of data. This fits well into CWI's pilot theme Privacy & Security, and there are strong connections to the Data theme as well.

We propose a combination of mathematical and computational approaches to tackle potential risks. CWI's expertise in smart contract negotiations, in machine learning for financial applications, in fast and robust algorithms in computational finance, in cryptography and blockchain, may all contribute successfully. It is the right place and right time, given the Netherlands' highly active fintech sector, the many initiatives that are currently developing in Amsterdam, and the 2017 launch of the EIT Digital Innovation Space at CWI.

Digital Twin An example of a new application domain within the Computation theme is digital twins: a simulation model which is essentially the intelligent counterpart to an actual, physical object. Such a real-world-based model accompanies a big data model. One of the many possible industrial applications would be a pipeline in operation: a living model could be created of this physical asset which is continuously calibrated using data collected from sensors. Preferably in real-time, the simulation model augments and clarifies the physical features that the data model displays. For this purpose, computations of the highest efficiency are required. CWI's aim is to develop algorithms that would be suitable in the context of such a digital twin.

Earth observation The increased spatial resolution of satellite instruments is considered a game-changer for climate science: it opens up new avenues for studying air pollution and climate change, and it entails an increasing demand on computing power. CWI intends to work with earth observation researchers to transform existing earth observation software, in order to exploit the high computational capabilities of modern hardware elements, including graphics (GPU) and tensor (TPU) processors. Earth observation fits well within CWI's Data theme.

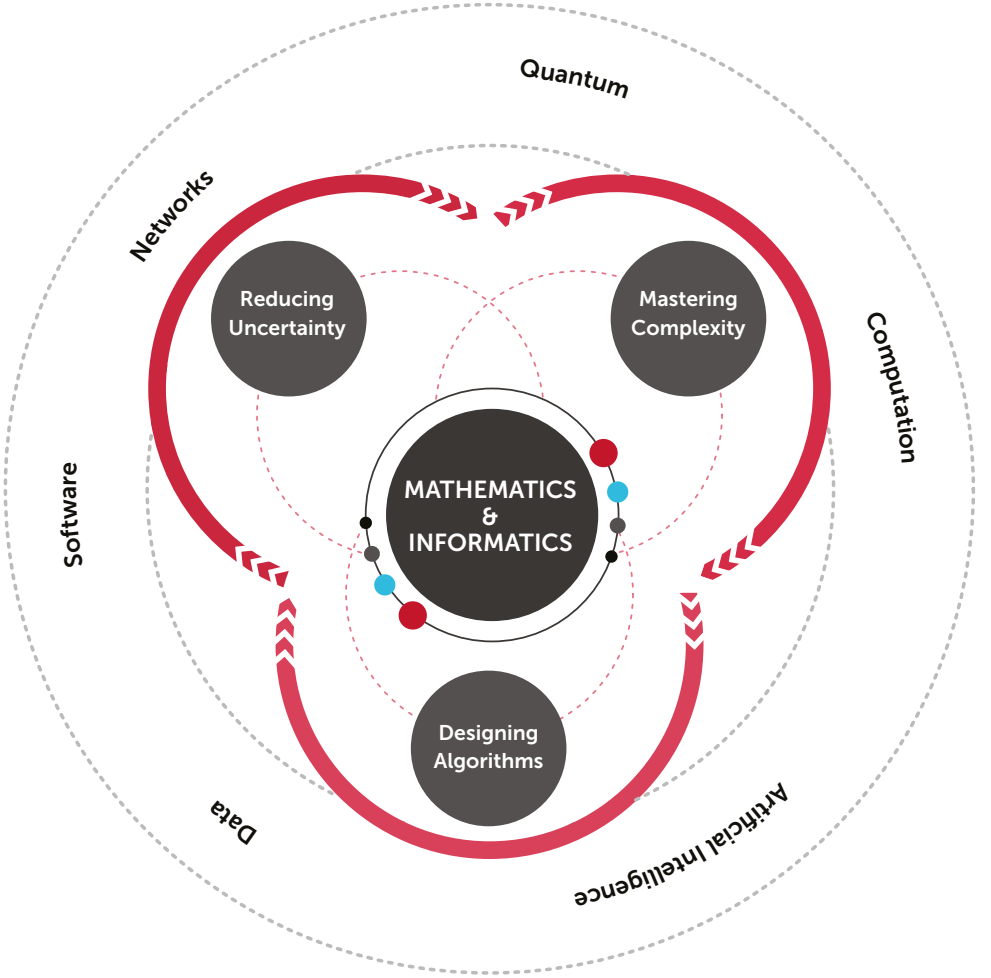
3.3 Valorization

Proactive approach of valorization

CWI research is driven by challenges in science and society. From our strong fundamental research basis, we will continue our activities to share knowledge, and increase valorization and visibility of research results. To help seize valorization opportunities at all levels of CWI, the valorization team provides support to our research staff. We actively explore opportunities to work with partners from society and industry, in order to transfer knowledge to industry and society at large. Strategic public-private partnerships, realizing spin-off companies and creating and disclosing software tools to the outside world will continue to be our main focus. The 2017 evaluation committee noted that industrial uptake can be enhanced, among others through further involvement of software engineering companies to go 'the extra mile'. We will focus our strategic cooperation with industry through PPP's, as opposed to direct contract research, because PPP's offer better opportunities for long-term research with industry engagement. In all forms of research cooperation with external partners our guiding principle is that the research must be of scientific value for CWI.

VALORIZATION TEAM

The launch of the valorization team in 2016 and its valorization strategy has resulted in an increase in public-private partnerships. The valorization team currently consists of four scientific staff members among whom CWI's manager research & development, and two coordinators partnerships & transfer. They are supported by a valorization manager, to consolidate valorization efforts within CWI and to strengthen contacts with potential industry partners and government agencies.


Quantum
Networks
Computation
Software
Data
Artificial Intelligence
Reducing Uncertainty
Mastering Complexity
MATHEMATICS & INFORMATICS
Designing Algorithms

To increase our visibility amongst potential industrial stakeholders, the communication department and the valorization team will collaborate to further develop our outreach strategy to industry partners (see also section 5.2). Thus CWI lays a broad foundation on which to further professionalize its technology transfer, adequately answering to industry's need to be in touch with modern R&D and to be part of scientific knowledge exchange. CWI will make choices bearing in mind the adage quality over quantity. CWI's valorization team will assess which existing industry contacts within CWI's groups can be broadened by involving other topics and researchers within CWI.

MULTILEVEL VALORIZATION STRATEGY

In 2016 CWI introduced a multilevel valorization strategy, aimed at securing knowledge transfer to industry and society-at-large. Key to this strategy is increasing the visibility and transparency of CWI to potential partners, showcasing how our knowledge can contribute to their future innovations. We target a broad scope of potential industry partners, from corporate R&D centres to high-tech SME's and public organizations. Depending on their level of involvement in scientific research, we use one of three levels to offer insight into our expertise:

1 core activities (designing algorithms, mastering complexity and reducing uncertainty);
2 strategic themes that cross-cut all CWI research (see section 3.1);
3 application domains and techniques, illustrating the wide range of issues of industry interest that CWI can contribute to (see section 3.2. for emerging application areas and Appendix C for an overview of the current ones).

CWI's offer to industry partners

The valorization team is currently identifying new target companies and branch organizations that might be interested in longer term contact with CWI. We will proactively approach possible new partners for a customized Research to Business meeting at CWI. CWI's Unique Selling Points will be brought across: CWI is a small-scale institute with a wealth of research relevant to industry and with a pivotal role in national and international research (organizations).

To accommodate industry's wish for short-term innovation projects, CWI is exploring partnerships with high-tech SME consultancy companies to join forces in academic knowledge exchange. In such a cooperation the commercial party can provide the human resources while CWI is able to reach out to potential partners in the role of scientific knowledge supplier. The desired effect for CWI is that this type of innovation projects will be the stepping stone to longer lasting partnerships and that they may also be financially rewarding.
CWI will also broaden its activities in the domain of public private partnerships. CWI is exploring new ways to accommodate academic staff in public private partnerships, e.g. in industrial doctorate programmes.

Finally, CWI intends to stimulate public private collaboration by offering its industry partners a wider range of activities and services in partner programmes at a fee. CWI's offer includes various partner programmes with tailor-made packages: from an introduction programme to intensive executive programmes. Typical programme components are access to scientific meetings, research results or CWI events, in-house company training, and joint master projects.

Software and standards as output

One of the pillars of CWI's technology transfer activities is developing software and making this available to researchers, industry and society. Dissemination

of our software products takes place through open-source platforms, in collaborations with industrial partners, and through the establishment of spin-offs. CWI's software output is known for its high impact contributions to internet security, database management systems, and to the development of programming languages. We also contribute to the development of standards, such as web and multimedia standards and standards for digital publishing.

CWI will continue to develop software packages and standards, and make these available to nonscientific stakeholders. This will be further boosted by the intended recruitment of scientific software engineers (see section 4.3) and by offering consultancy services around software tools of commercial potential, whether or not in collaboration with third parties.

3.4 Connecting to other institutes

In the 2019-2024 period, we envisage a connecting role towards other national research institutes (NWO sister institutes and KNAW institutes) and with applied research institutes. Notably, our expertise can contribute to the managing and solving of data problems in their fields. CWI will start an initiative into scientific data management focused primarily on earth observation and astronomy. This builds on existing relationships around LOFAR with ASTRON, and CWI will initiate cooperation with SRON and KNMI on the Tropomi satellite and its successors. The scientific purpose will be to elicit data management research questions from these domains and to develop new data science techniques to answer these; while at the same time helping our NWO sister institutes in managing their data that continuously increases in size and complexity.
We also see a possible collaboration between CWI and ARCNL on computational plasma modelling, a subject that several CWI research groups can contribute to. The same goes for our research into the digital aspects of other natural phenomena, e.g. in sustainability, climate, and energy, where other research institutes are in the lead (e.g. DIFFER).
With TNO we expect more collaboration in the area of applied secure multiparty

computation. And in order to investigate the impact of security measures on the privacy of citizens, we will seek collaboration with our sister institute NSCR (Netherlands Institute for the Study of Crime and Law Enforcement).
Finally, on the intersection of our fields with social sciences and humanities, we are strengthening our ties with several KNAW institutes, e.g. Huygens ING, IISG and NIOD.

At the European level, CWI continues its strategic alliances and research collaborations in the coming years, e.g. in its CWI-Inria International Lab. Regarding global cooperation, in the coming five year period we will strengthen our collaboration with China through LIAMA (Sino-European Laboratory in Computer Science, Automation and Applied Mathematics), as well as our ties to Silicon Valley in the USA through our partnership with EIT Digital.

3.5 Connecting to the National Research Agenda

CWI is involved in the Dutch National Research Agenda ('Nationale Wetenschapsagenda', or NWA), a programme for innovative and societally relevant research, which consists of 25 'routes'. Consortia develop knowledge for scientific breakthroughs with respect to societal challenges. This means involvement of the entire knowledge chain, from universities of applied sciences, universities, university medical centres, (applied) research institutes and government knowledge institutions through to societal partners, public and private. CWI is currently involved in several routes: Big Data (9), Logistics and Transport (16), Energy Transition (17) and Nano and Quantum (19). In the strategy period 2019-2024, CWI will seek opportunities to contribute to other 'routes', e.g. Personalized 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).

4 Organizational goals
requisites for excellent science

4.1 Creating an optimal research environment

To maintain the excellent quality of CWI research, we need the best researchers and we need to provide them with the optimal research environment.

We will continue to 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 aim to maintain the right balance between good supervision and respect for autonomy, which the evaluation committee noted our PhD candidates appreciate.

Support for our researchers includes support in writing research proposals, obtaining personal grants, getting into contact with external research partners, collaborating in multidisciplinary projects with other institutes or universities and publicizing research results. In 2016, we formed a Proposal Guidance Committee, which provides extensive (writing) support and coaching to our researchers throughout every personal grant application process.

Training courses that are offered to PhD students are e.g. 'scientific writing' and a research ethics course that also includes responsible data management. Issues concerning ethics are regularly discussed in management meetings, and we promote an open culture where integrity issues can be freely debated.

Specifically tenure-track researchers are given ample support during this often challenging step of their career. In 2016, we initiated a mentoring programme for all tenure track researchers. We will explore the possibility of further extending this programme to include postdocs and PhD students. In addition, for all our employees, we will structurally offer professional guidance towards career opportunities.

To make sure our PhD students gain a broader work experience and can explore their career options, we offer our students an additional academic training (teaching), an industrial training (working in industry), or a research management experience (for instance participation in conference organization). This is in line with a recommendation by the evaluation committee. To offer interested PhD students a more thorough industry experience, we will encourage our research group leaders to utilize and create industrial PhD positions in collaboration with their industry partners.

A requisite for facilitating high-quality support is the continuous high quality of our support departments. We recognize that the increased cooperation with NWO and the other NWO institutes provides an opportunity to further improve the support for our researchers, for instance through the exchange of best practices and through jointly organized courses and workshops.

4.2 Diversity

CWI is highly multinational, with researchers of over thirty nationalities. However, with regard to gender, there is still a large gap between the number of male and female researchers on all levels, a common issue in our fields. CWI works

PERSONNEL

At the start of the past strategy period, the research staff of CWI made up 151 fte (full-time equivalent), of which a little over 40% were PhD students. There were 6.7 fte worth of visiting researchers, and the support staff consisted of some 40 members (38.2 fte). The situation per January 2018 was 168.9 fte research staff, 8 fte visiting researchers and 34.6 fte support staff, which illustrates a growth in scientific personnel and a slight decrease in support staff.

towards a better representation of women in mathematics and computer science on the whole, and in our institute in particular.

In 2010 CWI signed the Charter 'Talent to the Top', committing to ambitious gender diversity targets for 2016: 35% female PhDs, 20% female postdocs, 25% women in the sub top and 10% women in the top of the institute. In particular the number of female PhD students, postdocs and women in the sub top is not yet as desired. Our efforts in attracting female talent continue to be much-needed. In 2018, we will set new gender diversity targets, in close collaboration with NWO and its other institutes.

Also, translating these efforts into concrete action, CWI will reserve funds specifically for recruiting female talent in tenure track and tenured positions, in addition to the NWO WISE programme.

In recent years, our focus has broadened from gender diversity to an inclusion policy that considers gender, age, ethnic and cultural background, sexual orientation and disabilities. This inclusion policy is in development, with CWI adopting best practices from across the field of science.

In 2018, NWO adopted a new Diversity Policy implementation plan, to which CWI is an active contributor. CWI's HR manager is coordinating the implementation of the NWO-wide personnel management policies.

Amongst the actions that NWO and CWI aim to undertake are:

- improving recruitment and selection procedures;
- continuing the WISE (Women in Science Excel) programme;
- raising awareness of implicit bias;
- establishing a network for the LGBT+ employees;
- becoming a member of Workplace Pride;
- creating more job opportunities for people with disabilities.

The 2017 evaluation committee recommended organizing visits of female master

students to the institute, and talks by (influential) women scientists at various stages of their careers. CWI will put effort in organizing these meetings.

Our outreach strategy also aims to enhance CWI's climate of diversity and inclusion, e.g. by ensuring that the language and imagery used in our recruitment and corporate communications is consistently inclusive, and by organizing outreach events aimed specifically at female students.

4.3 Scientific software engineers

CWI is well known for producing high-impact software products, e.g. Python, MonetDB, Rascal, the ASTRA toolbox and CleverSV. Creating software products such as these is not a goal in itself, but the natural consequence of our research. However, production-quality software has a high impact and a high valorization value. We therefore intend to recruit a number of scientific software engineers, to offer our research groups structural technical support, and to ensure the step towards software 'beyond the lab' is taken more frequently. In order to offer these software engineers an attractive career path and continuous development of their skills, we are seeking collaboration and exchange with neighbouring institute Netherlands eScience Center.

5 Beyond the institute
science for everyone

5.1 Research integrity and open science

CWI will continue its research integrity awareness procedures and activities, striving to optimize an open scientific culture in terms of research integrity, open access and open data. Regarding open science, CWI also takes an active role on the national and international level. We are active in the foundation MathOA, part of the Fair Open Access Alliance, which aims to 'flip' journals from subscription models to Fair Open Access, and we play a leading role in ERCIM efforts to boost Open Access.

Our open science policy is in line with developments in our research fields, where open access journals are becoming increasingly important, and with a broader movement in the Netherlands that was initiated by the Ministry of Education, Culture and Science, NWO and the Royal Netherlands Academy of Arts and Sciences, which encourages open access of publicly-funded research results.

In the coming years, CWI will increasingly contribute to NWO's data management policy, including replication of research results, and will align policy and procedures on scientific integrity with the partners in the NWO institute organization. Following up on the recommendation of the evaluation committee to take the lead in this area, CWI will be alert on emerging opportunities, e.g. for participating in developing an OA framework for research data, and storage and invocation of software.

To ensure transparency and public accountability, and to give the general public insight into our research, we will also continue to invest in external communication to a broad audience, most notably through the Dutch and international media as intermediate (see section 5.2).

5.2 Outreach

Today, our responsibility to conduct outreach is more important than ever. The ongoing digital revolution impacts every industrial sector, and indeed the life of every citizen, on a daily basis. Topics such as artificial intelligence, cybersecurity, privacy, big data and digital finance are hot issues, and considering their large societal impact, a broad understanding of these (and other) topics is desired. Moreover, outreach is an important pillar in the role we foresee for CWI as a guide and a national centre of expertise in the digital society. We aim to disseminate new knowledge in our fields, but also to give insight in how research 'works', and in how it impacts society. To this end, we will continue to reach out to relevant target groups, including the general public, the media, industry and decision-makers. We make high-impact research outcomes readily available, especially for the media and industry, by creating accessible and usable (written and audiovisual) content. Our digital presence continues to increase, e.g. on all relevant, major social media networks.
Furthermore, the Communication department increasingly takes up a role as the 'enabler' of outreach, by training scientists who are willing and able to fulfil an active outreach role – and thus serve as CWI's ambassadors to an audience other than their peers. For instance, the Communication team offers researchers media training, alerts them to outreach opportunities, supports them in creating presentations for specific (non-peer) audiences, and encourages their social media presence.

Industry

One of the challenges for the coming years is to increase CWI's visibility to potential partners from industry and public organizations. The Communication department will work closely with the valorization team to develop strategies to reach new and existing industry contacts, e.g. through the use of online videos or on-site events.

6 Outlook

In the previous chapters CWI's ambitions and research directions for the period 2019-2024 have been presented. We continue on the path of generating new knowledge for science and society and we aim to broaden our role as a guide in the digital world. We have described the high level of quality we intend to maintain and the topics we will invest in, further strengthening our research themes, in particular the interplay between the existing strong research themes and the recent theme Artificial Intelligence and the pilot theme Privacy & Security.

To some degree CWI can achieve this renewal in research directions by staff mobility and the phasing out or transferring of research lines we initiated in previous periods. However, in order to address the whole breadth of research issues we are called upon to contribute to by science itself, by industry and by society, we feel the need to increase our research volume. Financial scenarios how to achieve this will be drafted at a later stage. Two interconnected aspects are briefly highlighted here, external funding opportunities and the role of permanent research staff.

The overall trend of fierce competition for funding is ongoing, with the success rate of personal grants at the national and European level having shrunk due to the ever-growing number of applications. At the European level, CWI has hopes that funding opportunities for research in mathematics and computer science will increase substantially with the acknowledgement that these fields are drivers of scientific advancement in all disciplines. The EU's 9th research & innovation framework Horizon Europe (2021-2027) is expected to include an increase in funding opportunities for e.g. Artificial Intelligence and Cybersecurity. Regarding Quantum, the EU Quantum Flagship Programme is expected to open up possibilities for further investments in our quantum software research line in the QuSoft institute. In addition, we expect that growing industry involvement in quantum computing will lead to more industry collaborations.

Given the nature of our institute, investing in CWI research means investing in research staff, no investments on a grand scale such as for large scientific infrastructures are involved. Attracting talented new researchers to CWI as well as stimulating and facilitating CWI's current research talents is key. For CWI, increasing our research volume means adding to the number of research positions. It is permanent staff that have a pivotal role in attracting grants, in designing public-private partnerships with industry and in initiating the large consortia required for major programmes and projects. Therefore part of our course for the coming years is the effort to expand CWI's research activities by an increase of the number of permanent staff positions at our institute.

APPENDICES

Appendix A

Organizational chart

Foundation Board NWO-I

Stan Gielen
Caroline Visser
Ineke Braakman
Wim van den Doel
Jaap Schouten
Jeroen Geurts

Institute Advisory Committee

Scientific Advisory Committee

General Director

Jos Baeten

Management Team

Peter Boncz
Dick Broekhuis
Han La Poutré
Monique Laurent
Kees Oosterlee

Communication
Ans Hekkenberg

Financial Administration
Edwin de Boer

Information & Documentation
Lieke Schultze

IT & Facilities
Niels Nes

Personnel & Organization
Angelique Schilder

Secretariat
Hans Hidskes

Valorization
Rob van der Mei

Research Groups

Algorithms & Complexity	**A&C**	Harry Buhrman
Cryptology	**CR**	Ronald Cramer
Networks & Optimization	**N&O**	Guido Schäfer
Stochastics	**ST**	Bert Zwart
supervised by Monique Laurent		
Computational Imaging	**CI**	Joost Batenburg
Life Sciences & Health	**LSH**	Leen Stougie
Multiscale Dynamics	**MD**	Ute Ebert
Scientific Computing	**SC**	Daan Crommelin
supervised by Kees Oosterlee		
Database Architectures	**DA**	Stefan Manegold
Information Access	**IA**	Jacco van Ossenbruggen
Machine Learning	**ML**	Peter Grünwald
supervised by Peter Boncz		
Distributed & Interactive Systems	**DIS**	Pablo César
Intelligent & Autonomous Systems	**IAS**	Eric Pauwels
Formal Methods	**FM**	Frank de Boer
Software Analysis & Transformation	**SWAT**	Jurgen Vinju
supervised by Han La Poutré		

Software
Data
Networks
Computation
Quantum
Artificial Intelligence

Appendix B

Research groups

CWI consists of the following fifteen research groups, which each contribute to one or more of CWI's strategic research themes.

Algorithms and Complexity (A&C)

A&C designs software for the computing technology of the future, especially quantum computing. Based on the laws of quantum mechanics, which tell us that systems and particles can be in multiple states at once, quantum computing is radically different from computing as we know it. Our 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. A&C is involved in QuSoft, the Dutch research centre for quantum software.
A&C contributes to the strategic themes Software, Networks and Quantum, and aims to increasingly contribute to the pilot theme Privacy & Security.

Computational Imaging (CI)

CI is developing the next generation of 3D imaging – enabling scientists to look further into objects of all kinds. Based on mathematics, algorithms and numerical solution techniques, our approach is interdisciplinary, combining aspects of mathematics, computer science and physics. We pride ourselves on the versatility of our solutions, and our algorithms can be applied to a wide range of imaging in science, medicine and industry. In Computational Imaging, it's our goal to constantly push the boundaries of research. By combining advanced image acquisition, parameter estimation, and discrete tomography algorithms for example, we are able to develop workflows for 3D electron microscopy at atomic resolution.
CI contributes to the strategic theme Computation, and aims to increasingly contribute to the themes Data, Software and Artificial Intelligence.

Cryptography (CR)

CR is concerned with digital security, an area of increasingly pressing concern for industry, government and society at large. We investigate how cryptologic methods can contribute to solving security issues, for example through encryption, digital signatures and secure computation. Furthermore, we seek to establish the reliability of current cryptologic methods, how they can be improved, and what better alternatives there might be.
CR contributes to the strategic themes Computation, Quantum and the pilot theme Privacy & Security.

Database Architectures (DA)

DA is well known as a top data systems research group, active in the broad area of data (management) systems and infrastructure for supporting data science. DA has a strong international reputation in academia and industry for pioneering column store technology, fast compression methods, vectorized query execution, on-line query-driven indexing (cracking), adaptive caching, and integration of statistical languages and analysis in database management systems. We develop, distribute and maintain the MonetDB open-source system, and we have spawned multiple spin-off companies, including Data Distilleries, VectorWise and MonetDB Solutions. DA also operates a self-built cluster, SciLens, that – unlike many other computer clusters – is bandwidth-optimized and thus better suited as a data-science infrastructure. We pride ourselves on revealing the real problems in our discipline and coming up with revolutionary solutions that are frequently ahead of their time.
DA contributes to the strategic themes Data and Software, and aims to increasingly contribute to the theme Networks and the pilot theme Privacy & Security.

Distributed and Interactive Systems (DIS)

Future multimedia systems will be intelligent and empathic, capable of understanding the user and the environment. Extending techniques from distributed networking and contextual modelling, the DIS group adapts and extends traditional research on multimedia systems from this new perspective. Our research questions not only address 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. The group enjoys a number of fruitful partnerships with companies and organizations in the areas of creative industries and smart cities.
DIS contributes to the strategic themes Data, Software and Networks, and aims to increasingly contribute to the theme Artificial Intelligence.

Formal Methods (FM)

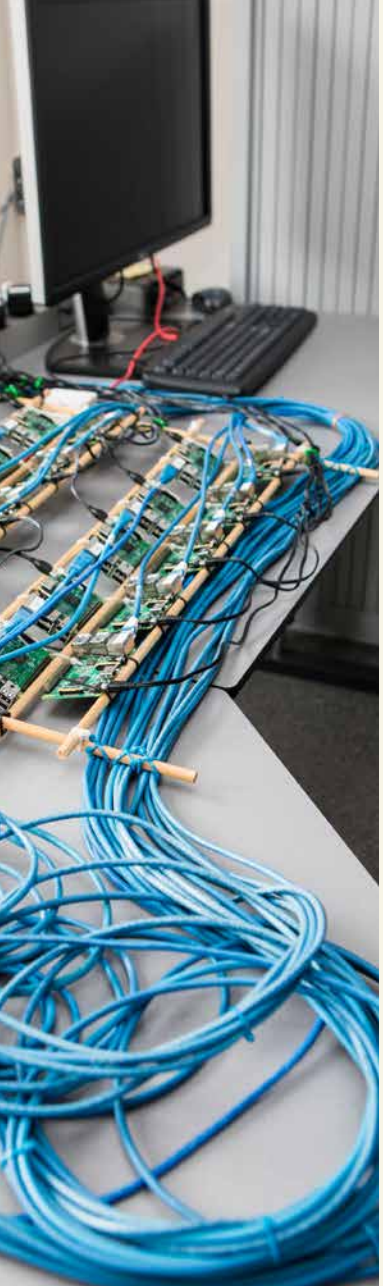
FM's research involves finding solutions to highly pragmatic real-world problems by reducing their complexity through the elegance and beauty of mathematics. We formulate problems to reveal their complexity and make them amenable to elegant solutions. Our work yields technological foundations that underpin software engineering and service-oriented computing. With everything we do, we aim to add stability and reliability to those foundations and so to the third-party applications built on them. In this way, we cut the costs of technological failure for business and society and make life easier for programmers, developers and ultimately users. FM has a rich history as one of CWI's original research groups, and our work is grounded in our collaborations with partners in business and industry.
FM contributes to the strategic theme Software, and aims to increasingly contribute to the pilot theme Privacy & Security.

Information Access (IA)

IA develops methods and techniques to better support users in accessing information that is heterogeneous, subjective and potentially inconsistent. We focus on the information's context, using knowledge graphs to model differences in time and other relevant perspectives. We work 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. We advocate the notion of transparency in all critical use of technology to improve trust assessments.
IA contributes to the strategic themes Data and Networks, and aims to increasingly contribute to the theme Artificial Intelligence.

Intelligent and Autonomous Systems (IAS)

Increasingly, our social and technological world is organized around complex systems. These are dynamic networks of interacting nodes (or agents) that continuously exchange digital or physical resources, including data or information, energy, materials and products. The agents in these systems face real challenges, as they often only have access to partial and noisy information and need to operate in a constantly changing and uncertain environment. As a consequence, there is an unrelenting pressure to improve the network's overall performance and resilience by making the individual nodes more intelligent and autonomous. The IAS group studies generic and fundamental mechanisms that enable the emergence of various degrees of organization, intelligence and autonomy in such systems, and applies them to concrete problems of societal relevance.
IAS contributes to the strategic themes Computation, Networks and Artificial Intelligence, and aims to increasingly contribute to the pilot theme Privacy & Security.



Life Sciences and Health (LSH)

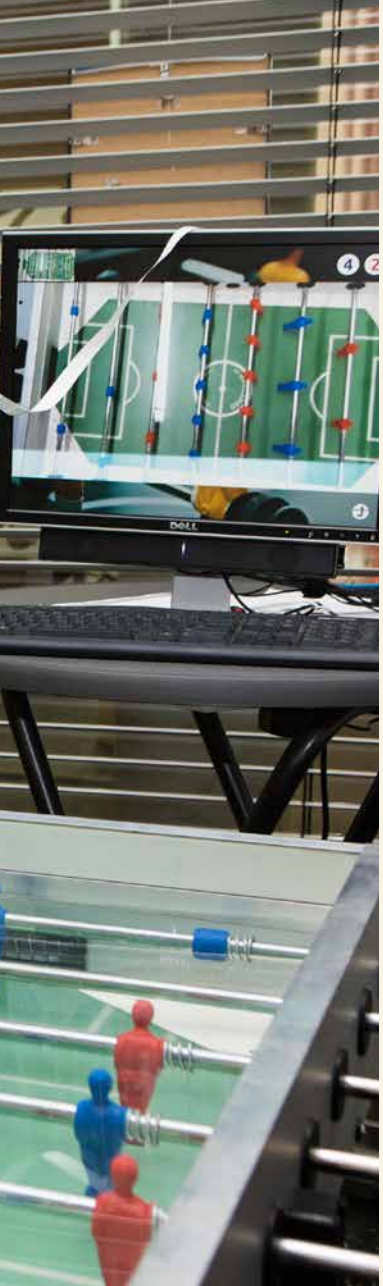
LSH creates fundamental knowledge and applied solutions in the broad field of life sciences and health. Our interdisciplinary team of computer scientists, mathematicians and theoretical biologists develops new models, theories, and decision support systems in collaboration with experimental biologists and medical experts. Driven by practical applications, LSH utilizes and extends models and algorithms from diverse disciplines such as artificial intelligence, networks, optimization and machine learning. Given the explosive growth in biological and biomedical data, we are increasing our focus on models and methods in data science and large scale computing, leading to new applications such as personalized medicine.

LSH contributes to the strategic themes Computation, Networks and Artificial Intelligence, and aims to increasingly contribute to the theme Data.

Machine Learning (ML)

ML focuses on how computer programs can learn from and understand data, and then make useful predictions based on it. These algorithms integrate insights from various fields, including statistics, artificial intelligence and neuroscience. Machine-learning applications are increasingly part of every aspect of life, from speech recognition on cell phones to illness prediction in healthcare. One common problem is extremely polluted data, for which no single model can provide adequate explanations. At CWI we address this issue with statistical machine learning based on combining predictions from different models and experts in order to achieve reliable conclusions. We also study how networks of neurons in the brain process information, and how modern deep-learning methods can benefit from neuroscience. We develop novel neural networks, like Deep Adaptive Spiking Neural Networks, and also theoretical models of neural learning and information processing in biology. Applications of our work range from low-energy consumption neural machine learning to neuroprosthetics.

ML contributes to the strategic themes Data and Artificial Intelligence, and aims to increasingly contribute to the pilot theme Privacy & Security.



Multiscale Dynamics (MD)

Nature and technology are full of dynamics, often involving multiple scales in length, time and energy. To model these processes, MD combines scientific computing with model reduction and machine learning, with particular focus on plasma dynamics in lightning and space weather, and in high voltage and plasma technology. Our research addresses questions in nature such as start and propagation of lightning strokes, terrestrial gamma-ray flashes and space weather, and closely related technological problems such as switch gear for long-distance electricity nets, air purification and disinfection with corona reactors, and protection of satellites and electricity nets from space weather. We collaborate with colleagues in applied plasma physics, electrical and mechanical engineering, atmospheric electricity, and cosmic particle and space science.
MD contributes to the strategic theme Computation, and aims to increasingly contribute to the theme Artificial Intelligence.

Networks and Optimization (N&O)

In today's society, complex systems surround us. From transport and traffic, to behavioral economics and operations management, real-world applications often demand that we identify simple, optimal solutions among a huge set of possibilities. N&O does fundamental research to tackle such challenging optimization problems by providing efficient algorithms. To come up with the best optimization algorithms, we combine and extend techniques from different disciplines in mathematics and computer science. N&O's expertise ranges from discrete to continuous optimization and applies to centralized and decentralized settings. We focus on both problem-specific methods and universal toolkits to solve different types of optimization problems. The key in our investigations is to understand and exploit combinatorial structures, such as graphs, networks, lattices and matroids.
N&O contributes to the strategic themes Networks and Quantum, and aims to increasingly contribute to the themes Computation and Artificial Intelligence.

Scientific Computing (SC)

The SC group develops efficient mathematical methods to simulate and predict real-world phenomena 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. Our work is targeted in particular at applications in climate, energy, finance and biology. In these vital areas, the ability to assess uncertainties and their impact on model predictions is of paramount importance. Expertise in the SC group includes uncertainty quantification, data assimilation, stochastic multiscale modelling and risk assessment. The availability of data to inform and improve simulations and predictions, for example through learning and data-driven modelling, plays an important role in our research.
SC contributes to the strategic theme Computation, and aims to increasingly contribute to the theme Artificial Intelligence.

Software Analysis and Transformation (SWAT)

SWAT studies software systems: their design, construction and evolution. Our mission is to learn to understand software systems and to improve their quality. In particular, SWAT studies the causes of software complexity – a major cause of technology failure in society – and investigates how complex systems can be made simpler and more reliable. We analyze and visualize software systems, transforming them into better versions of themselves. We also generate new software with the goal of simplifying it through automation and abstraction. We keep our feet on the ground by working with corporate IT departments on streamlining their software systems and making them more reliable. Putting our ideas into practice is the best way to ensure they work.
SWAT contributes to the strategic theme Software, and aims to increasingly contribute to the pilot theme Privacy & Security.

Stochastics (ST)

Many natural and man-made systems and processes are driven by random phenomena. Examples can be found in areas such as communication, energy, information, logistics, and transportation systems. In order to model, describe, and improve such systems, ST develops and studies probabilistic, operational and statistical models. Our group's analysis of these models relies on techniques from fundamental probability theory, queueing theory, stochastic scheduling, spatial stochastics and stochastic geometry. Our work with various companies in these areas, as well as with top researchers and universities across the globe, ensures our position at the forefront of every aspect of this research field.
ST contributes to the strategic themes Computation and Networks, and aims to increasingly contribute to the theme Artificial Intelligence.

CWI
Stochastics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Appendix C

Application domains and techniques

CWI's scientific investigations can be applied in a wide variety of application domains and industry sectors. They change over time and this overview reflects the 2018 situation. The list of application domains and techniques will be updated in 2019. For emerging application areas, see also section 3.2 of the Strategic Plan.

Bandits and game tree search in AI
By being smart about which data to obtain, a learning system can maximize performance and minimize cost. Such adaptive data acquisition problems arise in, for example, medical testing, recommendation, advertising and website optimization, in simulator-based planning, and in time-constrained search for winning moves in two-player board games. Existing approaches are optimal only for unstructured problems, whereas CWI studies the design of learning systems for answering structured questions.

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 modelers 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 interaction

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 analyzing 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

CWI combines mathematical modelling with sophisticated techniques from discrete optimization, stochastic optimization and algorithmic game theory, to efficiently analyze and optimize complex networks. 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 system 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 of paramount concern for many applications. 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

CWI works on the 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.

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 ecosystem 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 analyze 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.

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