

Self-evaluation 2005-2010



CWI

Centrum Wiskunde & Informatica

Self-evaluation 2005–2010



General director

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CWI

Centrum Wiskunde & Informatica is the national research institute for mathematics and computer science in the Netherlands. It is part of the Netherlands Organisation for Scientific Research (NWO). CWI is a founding member of ERCIM, the European Research Consortium for Informatics and Mathematics. The institute is a member of the World Wide Web Consortium (W3C) and it manages the W3C Office in the Benelux. CWI is located at Science Park Amsterdam.

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Glossary

AMOLF	FOM Institute for Atomic and Molecular Physics
ASTRON	Netherlands Institute for Radio Astronomy
BRICKS	Basic Research in Informatics for Creating the Knowledge Society
BSIK/FES	Besluit Subsidies Investerings Kennisinfrastructuur/Fonds Economische Structuurversterking (Netherlands fund for reinforcing the economic structure)
CNRS	Centre National de la Recherche Scientifique
ECCOMAS	European Community on Computational Methods in Applied Sciences
EIT	European Institute of Innovation and Technology
ERICM	European Research Consortium for Informatics and Mathematics
ERCOM	European Research Centres on Mathematics, a committee of the European Mathematical Society
EUR	Erasmus Universiteit Rotterdam
EURANDOM	European Institute for Statistics, Probability, Stochastic Operations Research and its Applications
FOM	Stichting voor Fundamenteel Onderzoek der Materie <i>Foundation for Fundamental Research on Matter</i>
GMD	Gesellschaft für Mathematik und Datenverarbeitung (German foundation for mathematics and computer science, now part of Fraunhofer Institute)
INRIA	Institut National de Recherche en Informatique et en Automatique (French national institute for research in computer science and control)
KNAW	Koninklijke Nederlandse Akademie van Wetenschappen <i>Royal Netherlands Academy of Arts and Sciences</i>
KWG	Koninklijk Wiskundig Genootschap <i>Royal Dutch Mathematical Society</i>
NFI	Nederlands Forensisch Instituut <i>Netherlands Forensic Institute</i>
NIKHEF	Nationaal Instituut voor Subatomaire Fysica <i>National Institute for Subatomic Physics</i>
NIOZ	Koninklijk Nederlands Instituut voor Onderzoek der Zee <i>Royal Netherlands Institute for Sea Research</i>
NKI	Nederlands Kanker Instituut <i>The Netherlands Cancer Institute</i>
NWO	Nederlandse Organisatie voor Wetenschappelijk Onderzoek <i>Netherlands Organisation for Scientific Research</i>
RUG	Rijksuniversiteit Groningen
RUN	Radboud Universiteit Nijmegen
STW	Stichting Technische Wetenschappen <i>Technology Foundation</i>
TUD	Technische Universiteit Delft
TUE	Technische Universiteit Eindhoven
UvA	Universiteit van Amsterdam
UvT	Universiteit van Tilburg
UL	Universiteit Leiden
UM	Universiteit Maastricht
UT	Universiteit Twente
UU	Universiteit Utrecht
VUA	Vrije Universiteit Amsterdam
W3C	World Wide Web Consortium

The Institute

1 Making complexity manageable

1a Vision, mission, objectives, strategy

Check the weather forecast, search with Google, navigate with TomTom, catch a train, or buy online: behind the myriad daily actions we take for granted, a complexity is hidden that can only be managed using results from mathematics and computer science. These disciplines have become vital to the efficient functioning of our society. This often goes unseen: the results are *invisible*, tucked away in society's engine compartment. And they are *universal*, applying always and everywhere. Yesterday's research for designing train timetables allows us to determine DNA profiles today.

Centrum Wiskunde & Informatica (CWI) is the Netherlands national research institute for mathematics and computer science. It is part of NWO, the Dutch Science Council. Since its inception in 1946, the mission of CWI has been to conduct pioneering research in mathematics and computer science, generating new knowledge in these fields and conveying it to society at large, and to trade and industry in particular. Quality is a guiding principle in realizing this mission. To achieve it, CWI has formulated four *objectives*:

1. to conduct advanced research of the highest level, in particular
 - to initiate new lines of research,
 - to tackle hard questions of scientific and societal relevance, and
 - to carry out innovative contract research for industry;
2. to nurture a talent pool of academic staff and young researchers and be a meeting place for scientific discourse;
3. to establish contacts between the academic world, industry and government;
4. to accept a leadership role in science policy in the fields of mathematics and computer science.

In 2007's *A fundamental difference*, CWI outlined its strategy for the period 2007–2012. The main component of this strategy is the identification of four themes of high societal relevance that showcase CWI research to the general public, as outlined in §1d. The strategy emphasizes that, in order to stay true to its mission, and contrary to societal trends towards short-term focused research, CWI must remain committed to fundamental research with medium to long-term impact. It also should intensify already strong contacts with industry, general public, media and other leading organizations for applied and fundamental research.

CWI has a long-standing tradition of excellence in research that is both fundamental and societally relevant. Its track record includes building the first Dutch computer, computing the wing for the Fokker Friendship and dike heights for the Dutch Delta Works, connecting Europe to the internet, developing the Python programming language used by Google, computing the Dutch train timetables, and breaking factorization records of RSA encryption codes. CWI builds on this tradition as a center of excellence in mathematics and computer science. Scientific quality of the highest level is the best basis for true innovation, and it remains our highest priority.

1b Disciplines

CWI research is mathematics inspired by computer science, directed at modeling, analysis, simulation, and optimization; and computer science inspired by mathematics, such as complexity and algorithms, software technology, and database architecture.

Disciplinarity is embodied in four research clusters collected around applied analysis, combinatorics and stochastics, software engineering, and information systems. The broad disciplines within these clusters, such as numerical analysis, discrete optimization, concurrency, and database organization, are enduring. Yet they regularly give birth to new, more specific areas. For example, during the last five years CWI has started research on several new topics at the interface of mathematics and computer science, including cryptography, algorithmic game theory, machine learning, multi-scale modeling, the life sciences, energy, and visual software analysis.

1c Methodologies

Interwoven with the disciplinary organization, CWI research is united by two universal methodologies that pervade present day scientific efforts: *computational science* and *data-intensive research*.

Computational science is the *third pillar* of science, which has grown to complement experiment and theory following the advent and proliferation of computers in the latter half of the 20th century. Computer modeling is increasingly used in physics, biology, linguistics, cognitive science, sociology, and economics.

On the heels of computational science and enabled by e-science, a *fourth paradigm* is emerging in the form of data-intensive research, driven by the need to make sense of and the desire to capitalize upon the massive amount of digital data that is currently being generated and made available. The emphasis is not on models but directly on data, which are analyzed using tools from machine learning and data-mining.

1d Societal themes

Mathematics and computer science as practiced at CWI are instrumental to developments in other disciplines, and are able to provide insight and powerful analytical and computational techniques for tackling the problems at the forefront of public concern in our times. To this end the institute identifies themes of high societal impact to serve as a source of inspiration for CWI research and as a showcase of its results. In 2007, four themes were chosen: *earth and life sciences*, *the data explosion*, *societal logistics*, and *software as service*. CWI stimulates institute-wide attention to these themes through internal project initiatives. Whereas the scientific disciplines are enduring, the strategic themes are dynamic, reflecting the current research interests of a significant share of staff, motivated by societal needs and prioritization by funding agencies. Indeed, when CWI outlines a new strategy in 2012, some of the themes will evolve (see §8).

The meta-theme common to research at CWI is *making complexity manageable*. Complexity is to be understood here in a broad sense, including complexity of data and systems, complexity of technology and, more importantly, societal complexity. This key topic at the intersection of mathematics and computer science not only plays a central role in the four themes identified above, it underlies the vision that inspires all of CWI's activities.

1e National and international positioning

National positioning. CWI is one of eight NWO institutes spanning the spectrum of science in the Netherlands. As such it fulfills a distinguished role in the Dutch research landscape, developing new technologies for future research, providing a significant concentration of researchers in an



Figure 1. Management structure.

interdisciplinary field of science, providing continuity through long-term investment in the research infrastructure, and serving as a national headquarters for international cooperation and facilities. CWI staff have recently chaired the writing committees for some important national research policy documents.

CWI distinguishes itself from a university department. Its staff need not provide a broad university curriculum, but instead concentrates its research in a few select branches of mathematics and computer science. This makes CWI a compact, flexible and agile organization that can afford to be opportunistic. New topics are brought into development and conveyed in a timely manner. Within such topics, there is always room for high-risk research, without the pressure for short-term impact that characterizes applied research laboratories.

CWI serves as a meeting place for researchers from the Netherlands and abroad, and as a unique talent pool for university staff. Since its founding, it has produced 180 full professors (see also §7a). Most senior staff members hold a part-time chair at a university. On average twelve CWI-trained PhD students receive their degrees at universities each year, with a high of twenty in 2009.

CWI takes part in national consortia such as EURANDOM and ICTRegie, as well as large national programs such as BSIK/FES, based on income from the country's natural gas reserve. CWI staff serve on the boards of three of the four national mathematics clusters.

International positioning. The symbiosis achieved by accommodating mathematics and computer science under one roof and through a careful balance of fundamental and applied research leads to a unique position in the international research landscape.

CWI's scientific level measures up with that of the best universities world-wide. CWI is a national research institute similar to the Max Planck Institutes in Germany, the INRIA institutes in France, and the National Laboratories in the U.S., but at a smaller scale in keeping with the size of the Netherlands (and its science budget).

CWI is a founding member of ERCIM, the European Research Consortium for Informatics and Mathematics, and a long-term participant in ERCOM, European Research Centers on Mathematics. CWI houses the Benelux office of the World Wide Web Consortium (W3C), the organization responsible for setting standards on the web.

For more details about CWI's positioning, see §7 on *combining forces*.

2 Composition

2a Organization

Management structure (see Figure 1). CWI's Governing Board consists of five members appointed by NWO. The

General Director reports to the Board and, together with the Management Team, is responsible for the strategic, administrative and day-to-day management of the institute. The Management Team consists of the leaders of the research clusters and the managers of the support departments (see below). In 2008 the General Director established a Scientific Advisory Committee to advise in matters of strategy and long-term planning. The Works Council has a legal responsibility to advise and approve matters of personnel policy.

Research structure. The research dynamics at CWI springs from the perceptivity and curiosity of the researchers. They form the most important element of the institute. The researchers are organized into *research groups* (labeled *themes* until April 2007) on the basis of scientific discipline. The implementation of the institute's research policy is realized at the group level. Each group leader is responsible for the quality and coherence of the group's scientific output, for its financial health, and for its interaction with other groups. The fifteen research groups are managed within four *clusters*.

2b Research clusters

Each research cluster consists of three or four groups and is primarily an organizational entity managed by a senior staff member, who represents the groups in the Management Team. We give a broad overview of the research clusters here. See Part 2 of this document for a detailed evaluation.

PNA—Probability, networks and algorithms (leader until 2010 Bert Gerards, presently Rob van der Mei). Motivated by each of the four strategic themes (see §8), research of PNA is positioned on the interface between mathematics and computer science. The cluster pursues fundamental topics in discrete and probabilistic analysis, modeling and optimization, complexity and cryptology, and their societal applications. PNA currently hosts four groups.

SEN—Software engineering (leader Paul Klint). Research of SEN focuses on software technology, evolutionary systems, and multimedia applications. Typical research questions are the analysis and transformation of software systems, component-based development, competitive agents, and multimedia players. The ambition is to cover the whole range of activities from fundamental concepts and prototype implementations to their validation in practice. SEN currently hosts four groups.

MAC—Modelling, analysis and computing (leader until 2007 Jan Verwer, from 2007 until 2010 Arjen Doelman, presently Barry Koren). Research in MAC rests on three pillars: scientific computing, dynamical systems, and system and control theory, with a growing interest in discrete and stochastic systems. The research approach ranges from fundamental to applied. Application areas include earth and life sciences, fluid and plasma dynamics, computational finance, and discrete tomography. MAC currently hosts four groups, including a cross-disciplinary group devoted to the life sciences.

INS—Information systems (leader until 2011 Martin Kersten, presently Lynda Hardman). Research of INS focuses on information systems, covering the complete software stack from hardware to user experience. Leading research questions are self-organizing data structures and query processing paradigms in database systems; information extraction in (semi-) structured sources; model-driven visualization; and human-centered interface design. There is a strong empha-

sis on quantitative and experimental validation. At the end of 2010 INS hosted three groups.

See the Appendix for the total number of seniors, tenure trackers, postdocs, PhD students, and guests.

2c Support departments

CWI has four service departments that provide administrative, technical and production support. Service department managers are also members of CWI's Management Team.

C&I—Communication and information. C&I handles internal and external communications, including press and institute documents. The department includes an internationally renowned library.

P&O—Personnel and organization. P&O supports employees in their career paths: selection, evaluation, and outplacement. The department also helps PhD students and postdocs secure temporary housing and handles residence and work permits for foreign employees from over 30 countries.

PFC—Projects, finances and control. PFC handles institute financing, accounting, and project administration. PFC acts as financial coordinator for various national and European projects and activities in which CWI is involved.

ITF—Information technology and facilities. ITF is responsible for the work environment including the building, workspaces, lecture rooms, security and computing facilities. ITF also maintains a printing office.

See the Appendix for the total number of employees in the support departments.

2d Funding

CWI's operating budget derives from a direct grant from NWO, complemented by external funding via program competitions and contract research. The funding model ensures that the base funding covers the salaries of permanent staff plus fixed overhead. Temporary staff is paid from respective project funds. See the Appendix for CWI funding and expenditures over the evaluation period.

Base funding. The base funding averages 10.5 M€.

External funding. To strengthen the knowledge transfer aspect of its mission and expand its non-tenured staff, CWI ambitiously pursues acquisition of funding from existing as well as new, emerging sources. Forming alliances is an element of increasing importance in CWI's acquisition strategy. With the funding landscape in a state of flux, acquisition is a tough challenge. The BSIK/FES program was an important source of income since 2004. These projects ran out at the end of 2009. Their successor will be funded at a much lower level than anticipated.

Bonus funding. In 2006 NWO awarded CWI a one-time bonus of 2.25 M€ for the evaluation of 2005 with 'excellence' as a result. Subsequently, in 2009, there followed a one-time impulse of 2.7 M€ as a reward for the institute's earning power (see §5) and collaborative and unifying spirit (see §7). The bonus funds have largely been invested to establish a new life sciences group (MAC4) and to stimulate internal collaborative projects that contribute to CWI's mission and strategy, and increase cohesion in the institute.

Change of funding policy. In 2008 there was a significant change in the allocation of research funding by the Ministry of Education, Culture and Science. Since 2008, direct funding of Dutch universities was cut by 100 M€. In return, there is now more grant-based funding available for talented individual researchers. The NWO institutes were not directly affected. Yet, in the Netherlands, when applying for indi-

vidual grants, computer scientists have to compete with mathematicians and astronomers, and it is an empirical fact that applied computer scientists are less often successful. Thus, while CWI welcomes the pursuit of individual excellence, too narrow a focus in this respect may affect funding of groups with an applied computer science component.

3 Quality and scientific relevance

We quote a few examples of CWI research of high visibility. For more highlights over the evaluation period, we refer to §6, §8, and the contributions of the research groups.

The work by Martin Kersten and his group on database architectures successfully bridged the gap between long-term research and product dissemination. The MonetDB product suite grew from 800K to 2,000K lines of code, positioning it in the top ten largest open-source projects worldwide. The open-source distribution grew from about 3K in 2005 to about 200K in 2010.

After 55 years, CWI resumed its work on mathematical models for height control of dikes, at the request of Dutch governmental institutes. Dedicated numerical methods and portable software were developed. Research by Ute Ebert on modeling electrical discharges explains the transition from halo to sprite discharge high above thunderclouds and the interaction of discharge channels. The results were widely covered by the media.

The work on software technology has resulted in several textbooks on topics ranging from verification of concurrent programs, multimedia authoring and computational semantics, as well as well-cited papers on universal co-algebra, grammarware engineering and computational intelligence. Software systems for meta-programming (Rascal), coordination (Reo) and multimedia authoring (Ambulant) are finding wide acceptance.

The cryptanalysis of the MD5 hash function by Marc Stevens and colleagues led to a successful attack strategy on the Secured Lock Layer, causing the world-wide withdrawal of MD5 from the internet. New algebraic techniques for combinatorial problems led to new bounds for the kissing number problem. Also, stronger upper bounds on the fault-tolerance threshold for quantum computers were obtained. Its precise value will to a large extent determine if large-scale quantum computing will ever become feasible.

The group on learning theory developed the switch distribution, extending Bayesian model selection and converging at an optimal rate while retaining the Bayesian consistency properties. In applied probability, a powerful theory was developed to derive simple heavy-traffic limits for multi-queue single-server models that satisfy a branching structure. This breakthrough in the field finds applications in logistics and computer-communication.

4 Scientific output

See the Appendix for a summary of CWI's scientific output over the evaluation period. CWI also publishes open source software. The number of downloads is more than 30,000 per year.

5 Earning capacity

Figures 2 and 3 give an indication of CWI's earning capacity in terms of the funding for external projects over the period 2005–2010. These projects are mostly funded by NWO, BSIK/FES, the Technology Foundation STW, EU and direct contract research with private parties. Many external pro-

jects involve private-public consortia, in which companies and technological institutes participate to set a joint research agenda and anchor knowledge transfer.

The earning power over the whole period was relatively stable at 50% above the base subsidy from NWO, as was the percentage of funding for external projects obtained from the various sources. CWI's earning power is typical for an institute of its kind but is comprised of prestigious programs. CWI has a Spinoza Prize winner and an ERC-SIG recipient. Twenty-one CWI researchers were awarded an NWO Innovational Research Grant: three Vici, eight Vidi, ten Veni. CWI coordinated the BSIK/ FES project BRICKS, with a budget of 24 M€. Having a history of involvement in EU programs, it currently serves as coordinator for four EU projects.

While the level of base funding has remained stable, the financial position of the institute has improved due to success in obtaining external funding, two one-time stimuli from NWO (see §2d), and careful financial management. The fraction of the budget spent on support and overhead continues to decrease. The financial buffer of the institute, which was negative in 2004, has grown to a healthy size.

6 Academic reputation

CWI's research is recognized at many levels.

Alexander Schrijver was awarded the Spinoza Prize 2005 'for his extraordinary, pioneering, and inspiring research in the field of combinatorics and algorithms'. Vici grants were awarded to Harry Buhrman in 2004, to Ronald Cramer in 2006, and to Peter Grünwald in 2010. Krzysztof Pietrzak received an ERC Starting Investigator Grant in 2010. Young talent that chose for CWI includes PhD student Floor Sietsma (starting at age 18, social networks), postdoc Nitin Saxena (co-author of the proof that primality is polynomial), and tenure-tracker Joost Batenburg (discrete tomography).

Prizes. ICTRegie Award (Boncz 2006, CWI spin-off Software Improvement Group 2008), John von Neumann Theory Prize (Schrijver 2006), ECCOMAS Best PhD Thesis Award (Wackers 2007), Franz Edelman Award (Maróti-Schrijver-Steenbeek 2008), Erlang Prize (Zwart 2008), ACM CHI Lifetime Service Award (Pemberton 2009), Van Dantzig Prize (Grünwald 2010).

Fellows. Royal Netherlands Academy of Arts and Sciences (KNAW) (Schrijver), The Young Academy (Cramer), Royal Holland Society of Sciences and Humanities (Ebert, Hemker), Nordrhein-Westfälische Akademie der Wissenschaften (Schrijver), Deutsche Akademie der Naturforscher Leopoldina (Schrijver), Academia Europaea (Apt, Schrijver), INFORMS (Lenstra), SIAM (Schrijver).

Media attention. CWI research received media attention in the form of interviews and press releases. The institute came under the spotlight through radio and television (e.g. TELEAC) and Paradiso-lectures (Buhrman, Schrijver). Subjects receiving attention included the Dutch train timetables, twenty years of internet, lightning, the kissing number, cracking RSA512 and MD5, MonetDB, diffusion of euro-coins, forensic statistics (Lucia de B. case), quantum computing, identification of whale-fins, Spinoza Prize, tumor cell diagnosis, classification of music pieces by self-learning algorithms, identification of the SARS virus, secure multi-

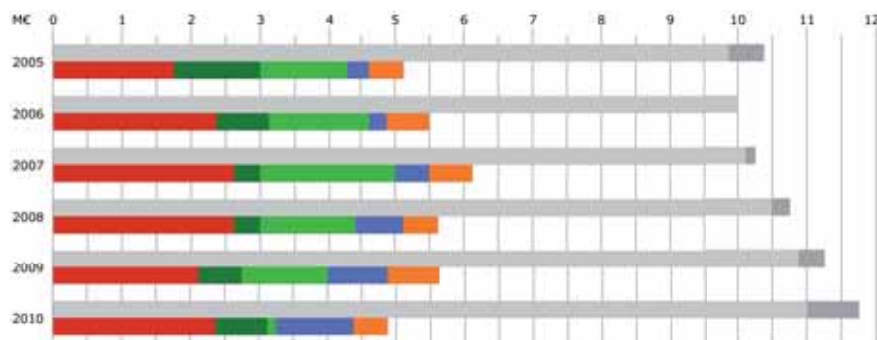


Figure 2. Base funding and project income.

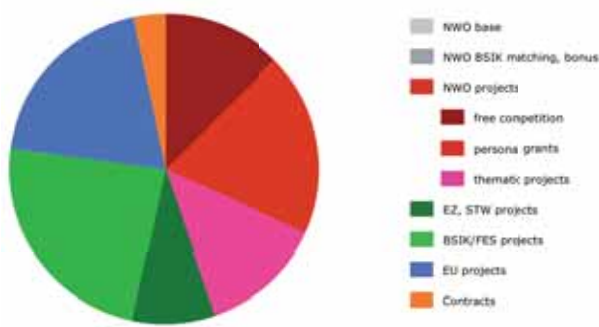


Figure 3. Project acquisition 2005–2010.

party computation, energy and smart grids, and the KNAW report on mathematics teaching in primary schools.

Benchmarking. In the recent SIR World Report 2010 ranking of institutions (see <http://www.scimagoir.com>), CWI's normalized impact factor of 1.79 ranks 149 out of 2,278 institutions worldwide in the physical sciences. CWI compares favorably with other institutions in the report such as:

- US National Labs: Lawrence Berkeley (2.02), Sandia (2.02), Lawrence Livermore (1.77), Oak Ridge (1.55), Los Alamos (1.53);
- Institute for Advanced Study (2.28), Santa Fe Institute (2.13);
- Max Planck Gesellschaft (1.74), Weierstrass Institute (1.33);
- INRIA (1.82), CNRS (1.33);
- Dutch universities: RUG (1.82), UT (1.71), RUN (1.70), TUE (1.64), UL (1.61), UU (1.61), VUA (1.56), TUD (1.55), UvA (1.55), EUR (1.44), UvT (1.29);
- Dutch labs: AMOLF (2.25), NIOZ (2.12), NIKHEF (1.82).

7 Combining forces

7a Links with academia

Within the Netherlands, the bulk of university research training effort is organized in interscholastic research schools. CWI participates in all research schools in mathematics and computer science and in one in physics. Additionally, starting in 2005, four national mathematics clusters have been formed to reinforce research in key areas. CWI is a partner in three of these: NDNS+ (Nonlinear Dynamics of Natural Systems), DIAMANT (Discrete, Interactive and Algorithmic Mathematics, Algebra and Number Theory), and STAR (Stochastics – Theoretical and Applied Research). The institute maintains close ties with EURANDOM, a research institute for the study of stochastics, located in Eindhoven.

Since its founding, CWI has produced 180 full professors, of whom 120 are currently active. This motivates CWI's claim to being a 'training center for professors'. Of its senior researchers, 33 currently fill professorial chairs at ten universities in the Netherlands and Belgium; see Figure 4.



Figure 4. 33 Part-time chairs at universities.



Figure 5. 33 Nationalities.

A recent NWO survey shows that CWI has ties with more universities than any other NWO institute. It gives CWI a central role both in national science networking and in the internal transfer of knowledge in Dutch science. At the same time, CWI houses many visitors on a regular basis and has recently started programs for summer internships, distinguished visitors, and Dutch sabbaticals.

CWI produces an average of twelve PhDs per year, who receive their degrees from Dutch universities. These universities in turn receive a governmental bonus for each PhD, to which CWI lays no claim, implying that CWI generates over 1 M€ per year in science funding for academia.

CWI regularly organizes events that reinforce its network with science, industry and other relations within the Netherlands. These include the annual CWI Lectures in Mathematics and Computer Science, held in May or June since 2005. The lectures focus on a research topic at which CWI excels, often highlighting the work of a distinguished CWI scientist. The program consists of an afternoon of lectures by some of the most well-known researchers in the field. Besides these lectures, groups at CWI frequently organize one-day symposia to which scientists throughout the Netherlands are invited. Each summer, CWI organizes a two-day course for high-school teachers (see §8b). In October, there is the annual open house, during which CWI and other institutions located in the Science Park Amsterdam are open to the general public. Every year in November, there is CWI in Bedrijf ("CWI in Company"), a one-day workshop in which

CWI's contacts with industry are reinforced. The theme of the 2010 workshop was energy, mathematics and computer science. Finally, once every five years, around CWI's anniversary on 11 February, CWI organizes a soiree for its network relations and former employees, during which the Van Wijngaarden awards are handed out to two distinguished scientists for their exceptional contribution to mathematics and computer science. Recipients so far are Persi Diaconis, Nancy Lynch, John Butcher, and Éva Tardos.

7b Role in other networks and organizations

CWI actively pursues its objective (§1a) 'to accept a leadership role in science policy in the fields of mathematics and computer science'. The chair of the ICT Research Platform Netherlands has long been held by CWI. CWI chaired a number of committees that prepared the national mathematics policy documents *Concentration & Dynamics* and the *Master Plan for the Future of Mathematics*, and a KNAW committee on primary school mathematics teaching. The institute is represented in the Council for Exact Sciences (TWINS) of the KNAW and played a role in the initiation of a Platform Mathematics Netherlands.

CWI has strong presence and in many cases a leading role in a number of cooperations. It is a founding consortium member of Novay, one of four technological top institutes in the country. CWI participated in three projects within the BSIK/FES program: BRICKS, MultimediaN, and VLe, serving as coordinator for BRICKS. In 2007 CWI, jointly with AMOLF, UvA and VUA, founded the Netherlands Institute for Systems Biology (NISB); the director of CWI chairs its board. Other cooperations at the national level include Science Park Amsterdam, the Netherlands Forensics Institute (NFI), and the Netherlands Cancer Institute (NKI). CWI also actively collaborates with other NWO-institutes such as ASTRON, FOM Rijnhuizen, and NIOZ.

CWI has strong international ties, with 44% of its research staff originating abroad, representing 33 nationalities; see Figure 5.

From the inception of European-wide research support in the early 1980s, CWI has been successful in obtaining competitive funding from European initiatives from ESPRIT to FP6. This success is continued under FP7 and other current European programs.

In 1989, CWI, GMD (Germany) and INRIA (France) founded ERCIM, the European Research Consortium for Informatics and Mathematics, which currently has nineteen member organizations across Europe, representing a research community of over 12,000 scientists. CWI researchers have played an active role in a substantial number of World Wide Web Consortium (W3C) working groups. CWI's institutional commitment to W3C and to the transfer of Web technology to national industry was strengthened when the institute became the host of the national and later Benelux W3C office in 1998.

CWI is a long-term participant in ERCOM (European Research Centers on Mathematics), a subcommittee of the European Mathematical Society. ERCOM consists of the directors of 26 European mathematics research institutes, with CWI's director acting as chair from 2006 until 2010. The director of CWI is currently chair of the scientific advisory board of Digiteo, a French consortium for ICT research. CWI is shareholder in the Leibniz-Zentrum für Informatik in Dagstuhl, Germany.

CWI maintains close ties with its French counterpart INRIA. Backed by strong French governmental support for scientific research, CWI and INRIA signed a collaborative agreement

in October 2007. Its first act was the initiation of a joint research group at CWI on software engineering, which marked the first time that an INRIA group was established outside of France. The long-range vision behind this agreement extends beyond the funding of research across borders to the building of Europe.

8 Societal relevance

8a Societal themes

A key component of CWI's strategy as outlined in 2007's *A fundamental difference* was the identification of research themes of high societal relevance, which serve as a showcase of CWI research to the outside world. The four themes identified in 2007 were *the data explosion*, *societal logistics*, *earth and life sciences*, and *software as service*.

These themes are broad-scale application areas enjoying institute-wide attention. For example, the theme *societal logistics* includes optimization of ambulance services, hospital logistics, and next-generation navigation systems. Reflecting changing societal needs and interests, the themes are continually in flux. A major event is the start of the life sciences group in 2008 (MAC4, §9b-4). A new strategic plan, to be outlined in 2012, will include a decision on themes for the period starting 2013. The theme *earth and life sciences* may then split in two, focusing on *life sciences* on the one hand and *environment and energy* on the other. *Learning* is expected to figure more prominently in the *data explosion* theme. The theme *software as service* is currently shifting towards *efficiency in software engineering*, with research into multi-core architectures and visual software analysis. Figure 6 depicts the main involvement of the research groups in these themes.

CWI is well positioned with respect to the strategic themes of NWO and the priority areas of the Dutch Government; see Figure 7.

8b Knowledge transfer and utilization

CWI's primary forms of knowledge transfer are the publications of research results, the training of PhD students and postdocs and their subsequent employment in science and industry, and collaborative research with industrial partners, whether or not in the form of contract research.

From its inception, CWI has collaborated with private and public partners, from the numerical analysis of the Fokker aircraft wing to computation of the dike heights for the Dutch Delta Works and optimization of timetables for the Dutch railways. Most research projects involve collaborative consortia, with industry and technological institutes participating to ensure both anchoring and societal relevance. Though the financial crisis is making industry more reluctant to invest in research collaboration, CWI maintains links with a great many companies, ranging from multinationals to small and medium businesses; see Figure 8.

CWI is the long-term developer of one of the most high-profile open source database systems, MonetDB; see §3. The interplay between fundamental research and societal needs bears serendipitous and transformative fruits, such as the Python language.

Five spin-off companies have been founded since 2005, making a total of 21 since CWI's founding in 1946: Personal Space Technologies (visualization and 3D interaction, 2005), Safiro Software Solutions (programming services, 2007), MonetDB (high-tech database technology, 2008), Vector-Wise (analytical database technology, 2008), and Spinque (databases and information retrieval, 2010).

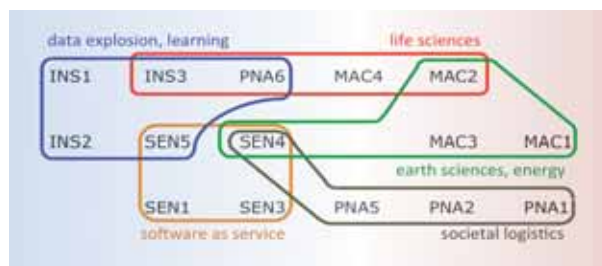


Figure 6. Research groups and societal themes.

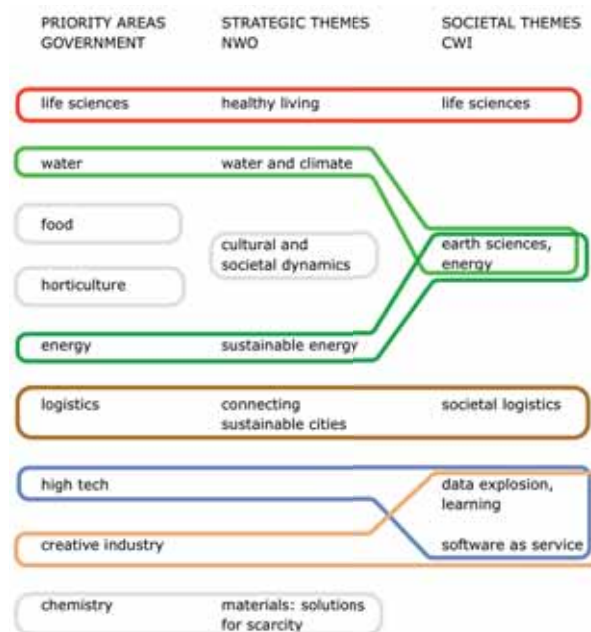


Figure 7. Thematic positioning.

As mentioned above and in §1, CWI maintains an extensive track record of innovation based upon research excellence. Recent highlights, fitting into CWI's societal themes, include cracking the MD5 hash function, with vast implications for data-security (PNA5), contributions to more efficient health care, through scheduling of medical students (PNA1) and hospital patients (SEN4), using domain-specific languages for digital forensics (SEN1), contributing to sustainability through smart grids for energy distribution (SEN4, MAC1) and dike integrity (MAC2), and facilitation of large-scale natural science experiments, e.g. through scalable data management for astronomy (INS1).

Contacts with industry are further maintained through the annual Study Group *Mathematics with Industry*, which is sponsored by CWI and in 2010 took place at CWI. While a sizeable number of CWI PhDs remain in academia, a comparable number move to industry.

CWI also transfers knowledge to students, teachers and specific societal groups. A large majority of its senior researchers regularly teach master-level classes, often involving their latest CWI research. Each summer, CWI organizes a two-day course for high-school teachers to keep them up to date with recent developments in mathematics, a tradition that was started in 1946. Several CWI researchers are involved in specialized lectures for professionals, such as courses on statistics for judges and lawyers and on performance management for IT architects. Finally, with more than 30,000 downloads a year, CWI open source software constitutes an important form of knowledge transfer.

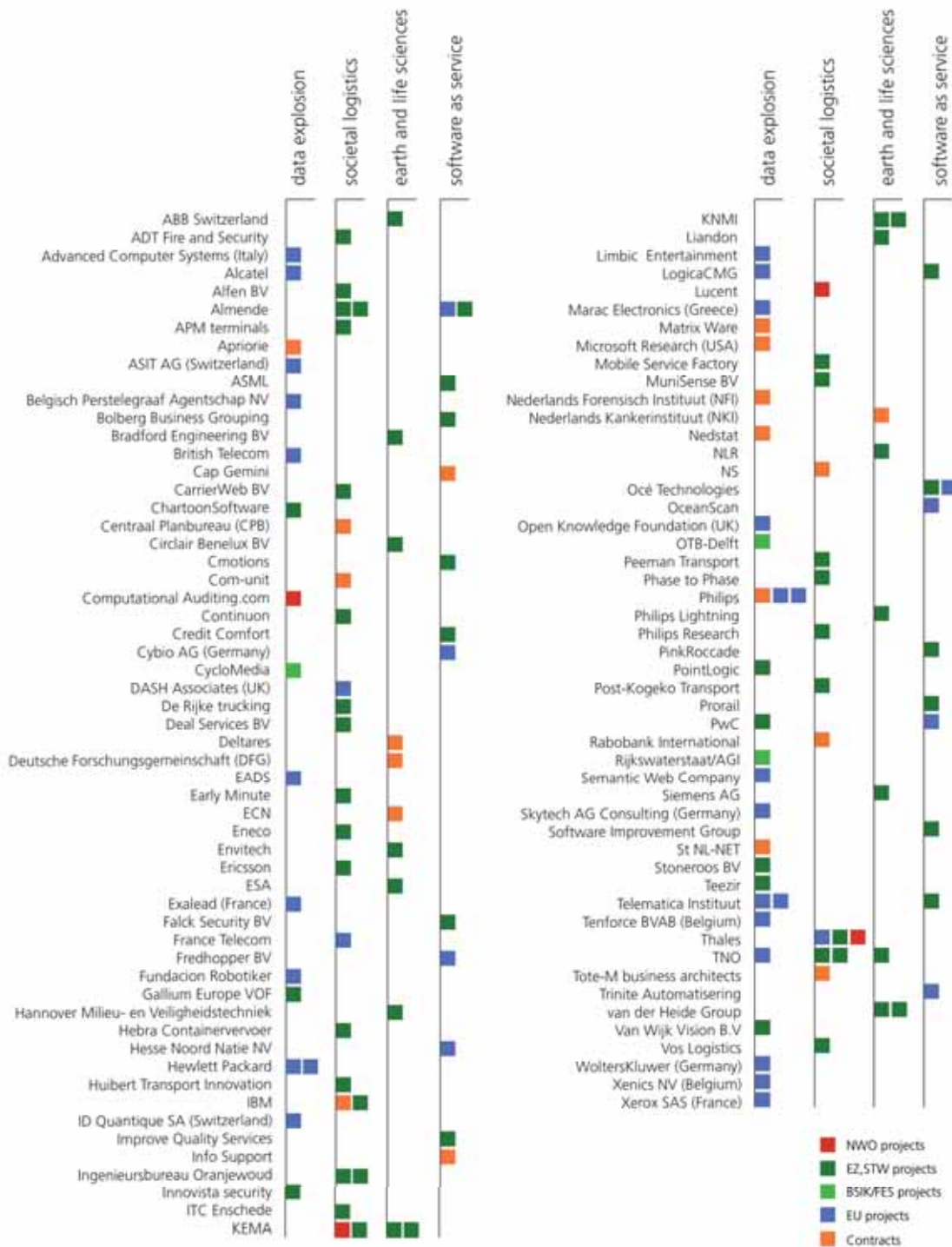


Figure 8. Project partners within industry.

9 Viability

The prevalence of glass in CWI's new wing reveals an institute abuzz: at whiteboards in the offices and matte glass boards in the atrium, there pervades a creative atmosphere of people working with heart and soul on science. To nurture such an atmosphere, CWI has invested notable effort in streamlining its internal structure and research focus in the period covered by the self-evaluation.

We illustrate this by addressing a question asked by NWO in the context of the present evaluation and several issues raised by the evaluation committee in 2005.

9a Institutional evolution

NWO's Governing Board asks whether CWI's internal organization, after recent adjustments, is adequate for its mission.

We made evolutionary steps to modernize the organization towards larger groups with activities centered around autonomous senior researchers. Figure 9 depicts CWI's internal dynamics over the evaluation period. We will explain these dynamics in roughly chronological order.

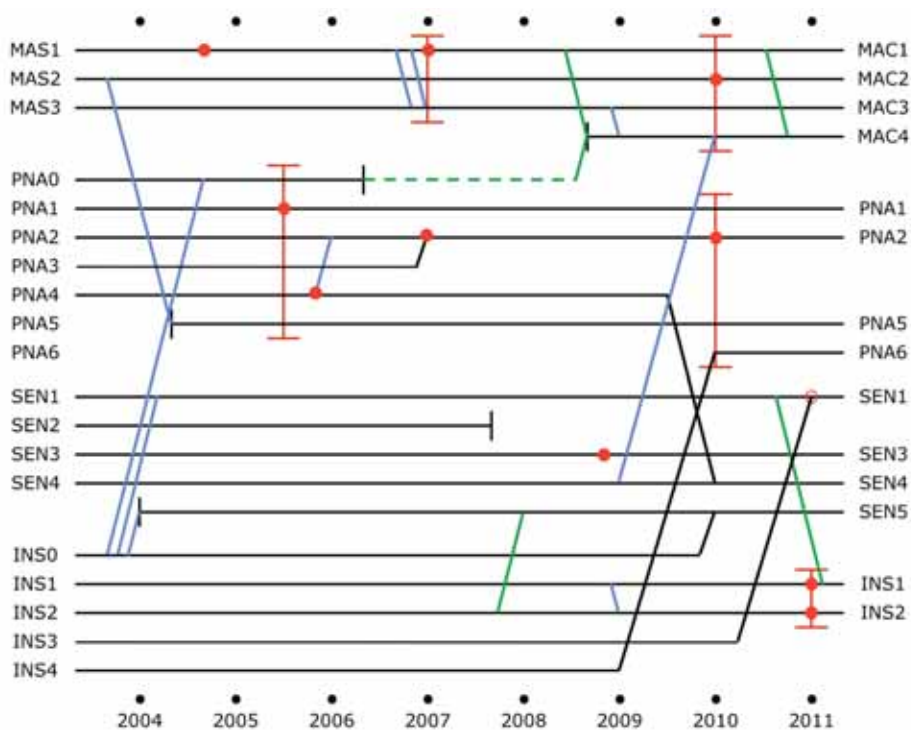


Figure 9. Institutional evolution; black lines: start, termination and merger of research groups; blue line: migration of researcher; green line: relocation of position; red dot: replacement of group leader; red line: replacement of cluster leader.

The two main milestones of 2004 were the creation of PNA5 (Cryptology) and SEN5 (Distributed and Interactive Systems). PNA5 has quickly become one of the world's leading groups in its area. SEN5 acquired a strong applied profile, broadening its focus to include complex media interaction in social networking.

In 2006, PNA0 was terminated due to the retirement of an algebraist and a statistician. 2007 saw the merger of PNA3 into PNA2, prompted by converging research topics and the retirement or departure of several staff members. The new PNA2 (Probability and Stochastic Networks) has been enlarged with two tenured staff. In the same year, SEN2 was discontinued with the departure of its group leader and sole senior researcher. The remaining junior researchers and programmer were moved to SEN1 (Software Analysis and Transformation).

A major milestone for CWI, in 2008, was the creation of MAC4 (Life Sciences) (see §9b-4). In 2009, the information retrieval subgroup of INS1 moved to INS2, resulting in two groups of about the same size. INS2 (Interactive Information Access) has thus become a coherent group active in interactive access to complex information sources. INS1 (Database Architectures) continues its leading role in database research.

On 1 January 2010, CWI's internal structure was further streamlined. PNA4 (Signals and Images) merged into SEN4 (Multi-Agent and Adaptive Computation), when the single staff member who had remained after the departure of three colleagues in 2005 and 2006 found considerable common scientific ground with SEN4. SEN5 absorbed INS0 (Standardization and Knowledge Transfer), due to their joint focus on web-related research. INS4 (Algorithms and Complexity) moved to the PNA cluster, in the light of its close links with PNA5 (Cryptology) and PNA1 (Algorithms, Combinatorics and Optimization), which were reinforced by

PNA1's expansion into algorithmic game theory. Further, the cluster MAS (Modelling, Analysis and Simulation) was renamed MAC (Modelling, Analysis and Computing), in view of its role in emerging themes like computational energy systems and machine learning and its growing interest in discrete and stochastic systems. These developments also led to the renaming of MAC1 (Dynamical Systems and Numerical Analysis) into Computational and Stochastic Dynamics per 1 January 2011.

On the same date, INS3 (Visualization and 3D User Interfaces), containing just one senior researcher, was absorbed into SEN1. This provides a strengthening of SEN1, which saw the attrition of four senior staff members during the evaluation period, due to retirement and moves to university positions. The group has been revitalized by the appointment of

a senior researcher and a tenure tracker, and the inclusion of INS3, which allows SEN1 to extend its research into visual software analysis.

In 2009 a working group examined the organization of research at CWI with respect to management structure, tasks and responsibilities, communication, HRM, and financial model. The group prepared a plan outlining changes. At the end of the year the plan as a whole was withdrawn, in favor of implementation of several of its elements in 2010:

- plans for improved internal communication (see §9b-9);
- formulation of a tenure policy (see §9b-3c);
- separation of cluster and group leadership (see §9b-3c);
- revision of the allocation of budgets to groups; the new model is a transparent management tool, putting an increased responsibility for obtaining project funding with the groups.

9b Issues raised in the evaluation of 2005

The committee that evaluated CWI in 2005 made ten *observations and recommendations*.

1. *Overall praise*. No comment.

2. *Many irons in the fire enhances impact, but hard to maintain leading position*. We already mentioned CWI's evolution towards fewer but larger research groups. The four strategic themes were chosen to reflect topics receiving institute-wide attention and to provide focus and direction to CWI research. Bonus funds received from NWO were invested in internal projects involving two or more groups and contributing to the strategic themes.

3. *Maintain maximum flexibility*

3a. *Groups less autonomous; more flexibility and management control*. We refer to the developments and plans outlined under 2 and 8. Since the implementation of the institute's research policy is managed at group level, a fine balance has to be maintained between group autonomy and overall management control.

3b. *External scientific council; strategic plan*. CWI established an external Scientific Advisory Committee consisting

of some fifteen representatives from science, politics and business from the Netherlands and abroad. It advises the institute in matters of strategy and long-term policy. Five of its members conducted CWI's mid-term review in 2008. A strategic plan was published in 2007 (see §1).

3c. Increase ratio of non-tenured to tenured staff; establish tenure tracks and career paths. In the evaluation period the number of tenured research staff decreased from 58.0 to 48.4; the number of non-tenured research staff including PhD students increased from 91.5 to 98.2. As a result, the ratio of non-tenured to tenured staff went up modestly from 1.58 to 2.03, peaking at 2.12 at the height of BSIK/FES in 2007. By a stricter tenure policy, the ratio will continue to increase. CWI has developed a tenure-track model in research and support. Using updated and transparent function-requirement descriptions, the tenure process is monitored with career development plans, yearly assessment interviews and explicit development goals. At the senior side, the terms of appointing group and cluster leaders have been revised to encourage managerial and strategic development, distribute the administrative burdens, and enhance mobility.

4. Decide on role in the life sciences. The group MAC4, started in 2008, reflects CWI's commitment to the rapidly developing fields of biomathematics and bioinformatics. MAC4 consists of a newly appointed group leader, two senior researchers from MAC3 and SEN4, two tenure-track appointments, and postdocs and PhD students funded by NISB, NCSB, NWO, and an internal bonus.

5. Housing. With the completion of a new wing and the renovation of the old building in 2009, CWI's urgent housing problems have been solved. The building activities and the internal moves were carried out with minimum impact on ongoing activities.

6. Redefine mission of library. CWI's high-quality library, which has a *de facto* national status, has oriented itself to meet the requirements of the digital age, a sweeping process that turns the library from the owner of a physical collection into an *information broker*.

7. Too large a fraction of budget spent on support. Over the past fifteen years, the budget spent on support and overhead has hardly increased, while expenditures for research doubled. CWI's further growth as envisioned in the strategic plan will not require the service organization to grow; in view of impending retirements, it will actually decrease in the years ahead. Meeting a higher demand for support with fewer people calls for more expertise and efficiency. Hence, a process of continual improvement, involving cooperative projects across support departments, has been put in place.

8. Increase corporate awareness; engage group leaders. Recently an internal Project Advisory Committee has been formed, charged with the task of reviewing research proposals and acting as a sounding board for project interviews such as those in effect with NWO and ERC. Cross-group familiarization is also promoted by having newly appointed senior staff give a plenary lecture. Turning the current group leader meetings into discussions on strategic, organizational and management issues is on the agenda for 2011.

9. Publicity needs considerable boosting. Reflecting an increased awareness of matters of communication, CWI formed an integrated Communication and Information department in 2005, which has formulated strategies for external and internal communication. Mobilizing research staff is an important part of their implementation. Since 2009 CWI has a new corporate identity.

10. Gender issue. 46% of support staff, 25% of PhD students, 16% of postdocs, and 10% of senior researchers at CWI are female. This is an unfortunate but fairly typical pattern. Since 2005, the number of female research staff increased from 23 to 30. CWI has signed the national charter *Talent to the top*, which asks for clear goals and means towards increasing the percentage of women at CWI.

10 Next generation

Training of PhD students. PhD training at CWI is a salaried, four-year, research-intensive program under direction of the senior researchers and involves one-on-one instruction following a mentor-apprentice model. The goal of PhD training is to prepare the candidate to conduct independent research, culminating in dissertation and defense. Depending on the project and the abilities and objectives of the student, the research program may be geared toward a career in academia or in industry, with about half of CWI trainees pursuing each trajectory. PhD candidates at CWI are immediately immersed in a dynamic research environment with an international scope. The individual groups organize regular work discussions, host visitors and encourage active participation in conferences and workshops abroad.

Besides research training, supplementary academic training is organized jointly with universities, through the research schools in which nearly all PhD students participate. CWI also offers technical courses on academic writing and scientific presentations, as well as Dutch and English language courses. CWI's P&O department asks the supervisory staff to draw up detailed personalized training and education plans, and update these at least once per year. Starting in 2011, CWI will collect statistics about the future career of its PhDs.

Employment of postdocs. Postdoc staff are also welcome to follow the technical courses offered to PhD students. For postdocs, supervision by senior staff is aimed at developing independent research skills and co-supervision of Master and PhD students.

11 SWOT analysis

11a Strengths

Quality of staff. CWI's research staff has a strong international reputation, is successful in obtaining prestigious external funding and experienced in knowledge transfer to society. Most senior scientists hold a full professorship at a university.

Strong position in research landscape. CWI is a talent pool for new ideas, new academic faculty and new companies, and has reinforced its role as a hub for new research communities, e.g., in the life sciences. It prominently participates in scientific organizations, discussions and policy setting on a national and international level. Its staff contributes to many Dutch BSc and MSc programs. CWI's administrative support for various national research projects and activities is in high demand.

Decentralized and dynamic research organization. CWI's research groups are accountable for their scientific program and budget control. Senior staff shows an active involvement in planning and organization at the institute level.

Small organization. CWI's size and independence allow for a flexible research policy and efficient administrative processes.

Facilities and support. CWI provides a high-quality infrastructure to its staff. It recently expanded its premises with a new wing. It introduced a transparent financial allocation model and a tenure-track system as part of a revised human resource policy. The library maintains a central national role.

Location. Amsterdam is an attractive city for young talent. The Science Park is easily reachable by bike, car and public transport.

11b Weaknesses

New research trends. It has become harder for CWI to set new trends in research in computer science, due to the technology push of large IT corporations.

Temporary versus permanent staff. The ratio of non-tenured to tenured staff is low. Each senior staff member should have at least two postdocs or PhD students. This however is not just a problem for CWI but holds nationwide, being caused by the low research funding in the Netherlands; see Threats.

Entrepreneurship in research staff needs further development. The five spin-off companies founded since 2005 and other activities mentioned in §8b show that there is no shortage of successful initiatives beyond research-as-usual. However, only a relatively small percentage of CWI's senior researchers is involved in such initiatives.

Social cohesion among employees is low. However, the amount of collaboration within and in between groups has greatly increased over the evaluation period, due to the measures described in §2d and §9b-2. In addition, the design of the new wing with its bright open spaces provides a great stimulus for social and scientific interaction.

Public relations, marketing and visibility are not optimal, in spite of years of effort.

11c Opportunities

Universality. The ubiquitous use and rapid development of tools from mathematics and computer science in today's society are a rich source of opportunities for CWI.

Emerging themes. New questions and national initiatives in, e.g., computational science, data-intensive research, sustainable energy, green IT and social networks provide opportunities for new research, new cooperation and new funding. The Dutch government has identified a number of priority areas for which CWI is well-positioned.

Strategic alliances. Many possibilities exist to establish or reinforce programmatic cooperation with institutes with similar or complementary research programs.

Open source. CWI can become even more visible in open source software development.

Spin-offs. Spin-off activities have been revived and should increase to one spin-off per year, across the entire institute.

Science Park Amsterdam, with its concentration of forces, provides good conditions for cooperation with two universities and two physics institutes of NWO in science, technology and innovation, in particular in e-science and systems biology.

11d Threats

Invisibility. As a counterpart to being universal, results from mathematics and computer science tend to be invisible in many of their applications. This is an obstacle to public appreciation of our work and calls for effective external communication. In particular, the overall public image of computer science and IT in the Netherlands is unfavorable.

Funding. Research funding in the Netherlands is low and decreasing. The financial crisis makes it hard to attract funding from industry and may endanger public funding. Moreover, the reallocation of research funding in the Netherlands as of 2008 may adversely affect groups oriented toward applied computer science.

Independence. Continual discussions at the ministerial level about the independence of KNAW and NWO institutes versus their incorporation in the universities threaten CWI's

contribution to science, technology and culture. CWI's small size and flexibility are great assets.

11e Analysis

Pertinent strategic issues emerge at the intersection of internal strengths and weaknesses and external opportunities and threats.

The flexibility of its research policy, its decentralized research organization, and its success in acquisitions allow CWI to capitalize on priority areas of the government and strategic themes of NWO. At the same time, CWI's participation in national policy discussions allows it to influence the scientific agenda.

The quality of CWI's staff and their strong leadership positions in the national landscape, in the form of professorships and memberships of advisory boards, provide the institute with several platforms for reinforcing its position as a compact and independent institute.

CWI is vulnerable to the threat of decreasing visibility of its research in light of the strong presence of large IT companies. A strategic focus on themes of high societal relevance in strong cooperation with European partner institutes will accentuate the unique role of CWI.

Decreased research funding in the Netherlands threatens the already low ratio of temporary to permanent staff. At the same time, economic concerns make industry leery of instigating contract research. CWI's new funding model ensures the institute can endure the current funding lull, and the strength of the staff proved itself by securing a record amount of prestigious funding in 2010 despite the strained research budgets. However, the institute should increase its acquisition efforts in the international arena.

12 Strategy

CWI's strategy for the period 2007–2012 was presented in *A fundamental difference*. In 2012 a new strategy will be outlined. CWI will stay true to its mission of performing fundamental research, firmly rooted in the disciplines and with an open eye towards questions occurring in society and industry. CWI will not hesitate to embark on high-risk long-term research, provided it is motivated by relevant questions. CWI's core business is mathematics directed at models and algorithms and computer science focusing on software and data technology. Consequently, and in the light of current developments of scientific methodology and infrastructure, CWI will reinforce its emphasis on computational science and strengthen its efforts in data-driven research.

New promising research topics will emerge within existing groups of a broad orientation, as CWI's recent past has amply and successfully shown. Societal themes will naturally evolve. We indicated some ongoing evolution in §8a, towards environment and energy (including their ICT aspects), learning, and measurable efficiency in software technology. Another direction is the use of mathematics and computer science in the humanities and social sciences, almost virgin territory and a rich source of inspiration.

Universality and invisibility are two sides of one coin. The one provides opportunities, and CWI will choose those which promise invention and innovation. The other carries the danger of a lack of public appreciation. The study of abstraction is both fun and useful. Learning to communicate this better in an ever changing landscape is forever on our agenda.

PNA1—Algorithms, Combinatorics and Optimization

Objectives and research area. PNA1 focuses on developing new efficient algorithmic methods for problems in combinatorics, optimization and algorithmic game theory, motivated by real-world applications, e.g., from societal logistics, networks like the internet and computational biology. The techniques PNA1 develops make use of tools from mathematics (discrete mathematics, algebra, Fourier analysis, geometry, probability, logic, game theory), operations research (linear, integer and semidefinite programming), and computer science (complexity, approximation algorithms).

Composition. PNA1 consists currently of four senior researchers (Apt, Gerards, Laurent, Schrijver), one tenure-tracker (Schäfer), five PhD students and five postdocs. Aardal was appointed full professor at TUD in 2008. The activity in combinatorial molecular biology was relocated to the new life sciences group in 2009. Müller (Veni recipient) joined PNA1 in 2009.

Quality and scientific relevance. We highlight some of our achievements over 2005–2010.

New algebraic techniques were developed to solve combinatorial and optimization problems, leading to stronger bounds, e.g., for coding and geometric packing problems, graph coloring, crossing numbers of graphs. The keys are exploiting symmetry using C^* -algebras and invariant theory combined with semidefinite programming and tools from real algebraic geometry. We mention only the new strong bounds for the famous kissing number problem.

New grounds in matroid research were broken by building a structure theory for minor-closed classes. For matroids over the 2-element field, we can now test any minor-closed property in polynomial time and prove that it is characterized by a finite list of excluded minors. This far-reaching generalization of the Robertson-Seymour Graph Minor Theory is a breakthrough towards a further extension to any finite field. We recently bridged the conceptually major gap between prime and non-prime fields by giving the structure around large projective geometries.

A new topic was explored, aiming to characterize the graph partition functions that describe the energy of particle systems in statistical mechanics. Key results include recognizing such graph parameters by reflection positivity. This research is part of the new international research stream on graph limits, with connections to extremal combinatorics and statistical physics.

Research in algorithmic game theory was started, by shifting previous activities in constraint programming to this new area and recruiting a tenure-track researcher in 2009. Topics studied include cooperative and strategic games, mechanism design, and auctions. Key contributions establish the intractability of finding Nash equilibria in repeated games and characterize the impact of centralized control in network routing games.

The research on algorithmic techniques in combinatorial and molecular biology was intensified from 2005. Topics studied include haplotyping, genome rearrangements, metabolic networks, and phylogenetic networks. Highlights include publications at top computational biology conferences like RECOMB and a successful NWO Computational Life Sciences grant. These research activities moved in 2009 to the new life sciences group, now MAC4.

Key publications:

K. Aardal, L.A. Wolsey. Lattice based extended formulations for integer linear equality systems. *Mathematical Programming* 121, 337–352, 2010. (repository id: 16725)

K.R. Apt, M. Wallace. *Constraint Logic Programming using ECLiPSe*. Cambridge University Press, 2007. (repository id: 15280)

J. Geelen, B. Gerards, G. Whittle. Excluding a planar graph from $GF(q)$ -representable matroids. *Journal of Combinatorial Theory Series B* 97, 971–998, 2007. (repository id: 11674)

C. Borgs, J. Chayes, N.S. Immerlica, A. Kalai, V. Mirrokni, C.H. Papadimitriou. The myth of the folk theorem. *Annual ACM Symposium on Theory of Computing (STOC)* 40, 365–372, 2008. (repository id: 13251)

J.B. Lasserre, M. Laurent, P. Rostalski. Semidefinite characterization and computation of zero-dimensional real radical ideals. *Foundations of Computational Mathematics* 8, 607–647, 2008. (repository id: 12809)

V. Bonifaci, T. Harks, G. Schäfer. Stackelberg routing in arbitrary networks. *Mathematics of Operations Research* 35, 330–346, 2010. (repository id: 16677)

M.H. Freedman, L. Lovász, A. Schrijver. Reflection positivity, rank connectivity, and homomorphisms of graphs. *Journal of the American Mathematical Society* 20, 37–51, 2007. (repository id: 11818)

C. Bachoc, F. Vallentin. New upper bounds for kissing numbers from semidefinite programming. *Journal of the American Mathematical Society* 21, 909–924, 2008. (repository id: 12655)

Output. In the evaluation period, a total of 109 journal articles, 73 conference papers, fifteen book chapters and two books were published.

The number of PhD students educated within PNA1 has increased, with ten PhD defenses since 2005 (among which six by full-time CWI PhD students) and five new PhD students hired since September 2009.

Earning capacity. Funding for PhD students and postdocs has been acquired through external sources: NWO grants (Spinoza award, Veni, Vidi, four Free Competition grants, Focus project, and Computational Life Science grant), BRICKS funding, EU funding (Marie Curie RTN ADONET project), and two ERCIM fellowships. Internally, the group has recently been granted NWO Bonus funding: for a PhD student in algorithmic game theory, a postdoc position in social networks (jointly with SEN1), a PhD student and postdoc positions in classical vs. quantum computing (jointly with PNA6). Additional funding includes a DFG grant, postdoc funding for Waki from the Japan Society for the Promotion of Science, PhD student funding for de Oliveira Filho from CAPES, Brasil, and several NWO visitor grants.

Academic reputation. The group is well positioned on the national and international levels. All senior researchers have a part-time professorship: Apt and Schrijver at UvA, Gerards at TUE/UM and honorary adjunct professorship at Waterloo Univ., Laurent at UvT, Schäfer at VUA.

Memberships of boards and societies: Academia Europaea (two), Royal Netherlands Academy of Arts and Sciences, two German Academies, Mathematical Optimization Society Council and Executive Committee, European Association for Theoretical Computer Science Council, Oberwolfach Scientific Committee, chair of Scientific Committee of the 5th European Congress of Mathematics in 2008, EU GAMES Steering Committee, NWO ACW Committee, NWO grants committees, and other national organizations (LNMB, Stieltjes, DIAMANT), a.o.

Editorships: *Combinatorica* (editor-in-chief), *ACM Trans. Comput. Logic* (area editor), *SIAM J. Discr. Math.*, *SIAM J. Optim.*, *Math. Prog. A/B*, *Math. Oper. Res.*, *J. Comb. Theory B*, *INFORMS J. Comput.*, *Oper. Res. Letters*, *J. Logic Comp.*, *Theory and Practice of Logic Prog.*, *Electr. Proc. Theoretic Comput. Science*, a.o.

Organization of scientific events: About fifteen international workshops (including three Oberwolfach Workshops), fifteen seminar or symposium days, and longer programs like the IPAM semester program on optimization at UCLA in 2010, and a trimester on extreme geometric structures at the Hausdorff Center for Mathematics in Bonn in 2008; several doctoral schools (a.o. semidefinite programming, polynomial optimization, graphs, games, network algorithms, constraint programming), including two Oberwolfach Seminars and an EIDMA mini-course at CWI (by Parrilo).

Awards and prizes: 2005: Schrijver: NWO Spinoza Prize (highest Dutch scientific distinction); 2006: Gijswijt: Tucker Prize finalist at ISMP; Schrijver: INFORMS Von Neumann Theory Award; Stougie: Harold Kuhn Award; 2007: Immorlica and Markakis (jointly with SEN4): Microsoft Research Beyond Search Award; 2008: Van Leeuwen: Philips Mathematical Prize for PhD research; Maroti, Schrijver and Steenbeek: Edelman Award of INFORMS; 2009: Wojtczak: ICALP 2009 Best Student Paper Award.

Invited lectures: Group members have given numerous invited lectures at international conferences, workshops, institutes, which cannot be detailed here. We only mention the invited lecture of Gerards at the 2006 International Congress of Mathematicians.

Combining forces. PNA1 is actively involved in (inter)national training activities, including participation in ADONET (EU RTN on discrete optimization), teaching at national graduate networks (LNMB/EIDMA, Mastermath), organizing and delivering invited courses at international institutes and doctoral schools (Oberwolfach Seminars, Academic "Kollegs", MPI Saarbrücken, Univ. Manila, Barcelona, etc.), and hosting PhD students internships.

Some strong researchers from Dutch universities are affiliated with PNA1 via courtesy appointments, and PNA1 regularly hosts foreign guests (a.o. A. Ben-Tal, J. Geelen, G. Karolyi, A. Karzanov, D. Samet, G. Whittle, each visiting CWI for more than one month). Regular seminars and workshops are organized fostering communication and collaboration within CWI and with other national institutes. The group has become a center of expertise in several forefront research areas including algebraic techniques in optimization and semidefinite programming (many joint initiatives with TUE, TUD, UvT), graphs and matroids (new series of biennial workshops since 2008), algorithmic game theory (workshop at CWI in 2010 with more than 70 participants).

Within CWI the group collaborates with SEN3 and SEN4 on distributed mechanism design (joint NWO project), with SEN3 on verification of object-oriented programs (joint book), with SEN4 on sponsored search auctions (Microsoft

Award), with PNA6 on fault-tolerance in quantum computation, Grothendieck type approximations, and using semi-definite programming for classical and quantum algorithms (ongoing joint CWI Bonus project). A new collaboration with SEN1 on social networks started recently (joint supervision of a PhD student and a postdoc). There are also links with PNA2 (probabilistic combinatorics, optimization on ambulance planning) and MAC4 (combinatorial algorithms in biology).

Outside CWI the group collaborates with researchers from institutes all over the world: Microsoft Research, Univ. Washington, MIT, UC Berkeley, Princeton Univ., Victoria Univ. Wellington, Univ. Waterloo, ETH Zurich, TU Berlin, Eötvös Loránd Univ. Budapest, Univ. Athens, CNRS-Toulouse, INRIA Sophia Antipolis and Lyon, Univ. Bordeaux, and more.

Societal relevance. The group has been engaged in contract research, which required developing novel tools and had a significant societal impact. The work for the Dutch Railways (NS) of Schrijver and Steenbeek culminated in the implementation by NS of the new timetable in 2007, which is still the backbone of the current timetable; some other component (with Maroti) optimizes railway rolling stock planning. Their project *The New Dutch Timetable – The OR Revolution* won the Franz Edelman Award of INFORMS in 2008. The research on scheduling internships for medical students led to the creation of the spin-off company Safiro Software Solutions by Steenbeek in 2006. The project DisWis, set up in 2006 by De Praktijk (a project agency for science education and communication) in collaboration with Schrijver and subsidized by his Spinoza grant, has developed courses in discrete mathematics for high schools, in order to increase the number of students in mathematics. DisWis received in 2008 the SIGMA Prize for the best project promoting connections of mathematics to education. PNA1 also contributes to knowledge dissemination to a broad public, e.g., via lectures at public institutions, organizing mathematics contests for high school students, editorial work for Pythagoras (Dutch magazine for high school students), co-organizing the National Mathematical Olympiads, and the forthcoming International Mathematical Olympiad in 2011 in Amsterdam.

Viability. There is an increased international focus on applying classical mathematics to combinatorics, optimization and algorithms. The areas of semidefinite optimization, algorithmic game theory, matroid minor structure theory, and graph limits belong presently to the most vital research areas internationally, with several excellent mathematicians and computer scientists working on it worldwide and with a high potential for important further results and applications.

Algorithmic game theory has become increasingly popular in Europe. This momentum will be used to set up new European projects leading to additional funding. This area has also a high potential to lead to contract research on challenging problems.

The group is well equipped to play a prominent role, but two senior researchers of PNA1 will retire in the coming four years.

Strategy. Our strategy is to constantly renew our research directions, leading and following international developments, based on our expertise and experience in several branches of mathematics and computer science. New challenging aspects include exploring robustness and smoothed complexity in algorithmic game theory; developing the matroid minor structure theory and resolving the main

conjectures for matroids over finite fields: well-quasi-ordering, polynomial-time minor testing and finiteness of the set of excluded minors (Rota's conjecture); developing efficient algorithms for real solving polynomial equations combining semidefinite programming and symbolic algebra; exploring links between classical and quantum computing (use of semidefinite programming, algebraic tools, graph

and knot invariants and other combinatorial objects in quantum setting). Our ambition is to continue the high quality research of the group and to keep up with the strong level of fundamental research as well as the engagement in contract research about challenging problems that cannot be solved by consultancy firms.

PNA2—Probability and Stochastic Networks

Objectives and research area. PNA2 is concerned with research of systems arising in the sciences, engineering and business. These systems are dynamic or spatial and are intrinsically stochastic. Examples are found in communication and information systems, biology, (geo)physics, finance and economics, production systems, maintenance, logistics and transportation. PNA2 develops and studies stochastic and statistical models that yield fundamental qualitative understanding and enable prediction and optimization. Analysis of these models relies on techniques from fundamental probability theory, operations research, queueing theory, mathematical physics, spatial stochastics and stochastic geometry.

Composition. The group is a merger of two groups, one focusing on theoretical probability and the other focusing on advanced communication networks. Since 2005, several senior staff members retired or moved to other jobs. Two new tenured staff members were appointed in 2007 and 2008. The current six senior researchers of the group (one appointed for one day per week only) are all internationally established experts. A substantial number of junior researchers were trained at CWI: a total of seventeen PhD candidates and eleven postdocs since 2005. As of December 2010, the group counts seven PhD students and four postdocs, and another eight PhD students are being advised outside CWI. The seconded staff is significant: a total of seven senior researchers from other Dutch universities have a courtesy appointment.

Quality and scientific relevance. We highlight some of our achievements over 2005–2010.

A considerable amount of effort has been spent on the analysis of bandwidth sharing networks resulting in three PhD theses, a Vidi grant and the Erlang Prize. A recent achievement was presented at a keynote talk of Zwart at Performance 2010: Combining probabilistic and continuous optimization techniques, Reed and Zwart obtained a diffusion approximation of a general bandwidth sharing network, for which the invariant distribution is computable in polynomial time in size of the network. They built on earlier work done at CWI in 2006 by Ayesta and Mandjes and in 2008 by Ayesta, Núñez Queija and Verloop. Van der Mei obtained heavy traffic limits of polling models by systematizing a connection with limit theorems for critical branching processes.

Queues with non-standard scheduling policies such as shortest remaining processing time and layered scheduling policies have received significant interest, resulting a.o. in a PhD thesis on the analysis and optimization of layered queueing networks directed by Van der Mei. In addition, the occurrence of rare events in such queues has been investigated, resulting a.o. in a keynote talk of Zwart to be given at a major scheduling conference (MAPSP) in 2011, and a best paper award.

A new research initiative within PNA2 is on revenue management and pricing, a research area on the interface of statistics, control, and operations research. PhD student Den

Boer and Zwart developed a new algorithm to simultaneously estimate demand and optimize profit for a baseline model. Through a seminar series, Van der Mei made contacts with industry (airline, hotel, travel and entertainment).

PNA2 continued and intensified its effort on the macroscopic analysis of spatial stochastic models, in particular in percolation, leading to several publications in major journals and a PhD project funded by NWO. For example, Van den Berg extended, simplified and unified several existing results in percolation by deriving a new zero-one law, of which the proof has a combinatoric/geometric flavor. Sidoravicius and Sznitman used renormalization techniques to obtain fundamental percolation results for the vacant set of random interacements.

Key publications:

J. van den Berg. Approximate zero-one laws and sharpness of the percolation transition in a class of models including 2D Ising percolation. *Annals of Probability* 36, 1880–1903, 2008. (repository id: 13857)

C. Gromoll, Ph. Robert, B. Zwart. Fluid approximation of a processor sharing queue with reneging. *Mathematics of Operations Research* 33, 375–402, 2008. (repository id: 13862)

R.D. van der Mei. Towards a unifying theory on branching-type polling systems in heavy traffic. *Queueing Systems* 57, 29–46, 2008. (repository id: 13883)

M.N.M. van Lieshout. Applications of stochastic geometry in image analysis. In: *New perspectives in stochastic geometry*, Oxford University Press, 2010. (repository id: 14752)

V. Sidoravicius, A.-S. Sznitman. Percolation for the vacant set of random interacements. *Communications on Pure and Applied Mathematics* 62, 831–858, 2009. (repository id: 15164)

Output. The productivity of the group has been significant. In the period 2005–2010, over 200 articles (journal and conference papers, book chapters) have been completed and published. A total of ten PhDs were awarded; one of these was awarded the Gijs de Leve Prize in 2009.

Earning capacity. The group secured funding from both basic research agencies (NWO, NSF, ESF) but also other governmental and industry sources. Examples are Totem, Bricks, IBM, Dutch Railways, SenterNovem, Agentschap.nl, ICTregie, TI Mobile, France Telecom, EU FP7.

Academic reputation. All senior group members fulfil leadership duties in their specialization. Currently, the total number of associate editorships of journals is twelve. Van der Mei is general chair of ITC22 organized at CWI in 2010, Núñez Queija is Technical Program Chair of Performance 2010, Zwart is area editor of stochastic models for Operations Research. In addition Zwart is co-EiC of Surveys in OR/MS, and Sidoravicius is editor of *Ensaio Matemáticos* (Mathematical Memoirs) of the Brazilian Mathematical Society. During the evaluation period, PNA2 members have

given over 100 invited seminars and lectures at international workshops and conferences. Apart from the above-mentioned conferences with refereed proceedings, all members have been active in the organization of around 20 national and international conferences.

Borst won the Van Dantzig Prize in 2005, awarded every five years to a Dutch researcher in statistics or operations research not older than 40. Zwart was the first person working at a non-US institution to receive the Erlang Prize in 2008, which is awarded every two years by the Applied Probability Society of INFORMS to a person working in Applied Probability not older than 35. In the same year, he received a Vidi grant from NWO and an IBM faculty award. Sidoravicius was elected by the Clay Mathematical Institute to organize a Clay summer school in 2010. In 2010 two prestigious best paper awards were won by Simatos ("Load balancing via random local search in closed and open systems" at the ACM-Sigmetrics conference) and Zwart ("Tail robust scheduling via limited processor sharing" at the IFIP WG 7.3 Performance Conference). Three group members were appointed full professor and one was appointed associate professor at Dutch universities.

Combining forces. All six senior members are affiliated with Dutch universities. The group has five full professors: Núñez Queija (UvA), Sidoravicius (UL), and Van den Berg, Van der Mei and Zwart (VUA). Van Lieshout is associate professor at TUE. Conversely, a large number of strong researchers from Dutch universities are affiliated with PNA2 through a courtesy appointment. PNA2 has also been privileged to host highly distinguished visitors. For example, the first Fields medal winner in probability (2006) Wendelin Werner visited in June 2010. In conjunction with the spatial stochastic seminar and national queueing colloquium that have been organized consistently during the past five years, the group has acted as a national centre in theoretical and applied probability. In particular, PNA2 plays key roles in the new national research cluster on stochastics (STAR) and LNMB. Van der Mei is involved as co-founder and chairman of the ICT Innovation Platform "Vital ICT Infrastructures" (co-founded by CWI, TNO ICT and UT) aimed at bringing industry and academia together, sharing knowledge and experience in the area of quality of service in communication systems. In addition, he is co-founder of the center of excellence E-Quality. Finally, PNA2 collaborates with other groups in CWI, in particular PNA1 and SEN3.

Societal relevance. Applied research at PNA2 over the past five years has broadened from communication networks to new areas of societal relevance such as revenue management and logistics. Van der Mei is leading the societal logistics theme within CWI and initiated research on revenue management. This has led to the founding of a national knowledge network on pricing and revenue management (PREMA) and consequently to interaction with

PNA5—Cryptography

Objectives and research area. Cryptology studies the extent to which problems pertaining to security in the presence of malicious adversaries can be solved by means of data processing, and, where it applies, how this can be done efficiently.

For example, encryption schemes and digital signatures are used to construct private and authentic communication channels ("uni-lateral security", security against malicious outsiders). These are instrumental to secure internet transactions and payments, mobile telephony and much more.

companies like KLM, RAI, Starwood Hotels and Transavia. On the basic research side, CWI provided funds for one PhD student (Den Boer), who, with Zwart, made significant contributions to the field, which were presented at the INFORMS pricing and revenue management conference. Van der Mei has been initiator of a new research line on planning ambulance services and established relevant contacts with, for example, GGD Amsterdam and RAV Utrecht. Van Lieshout is involved in the learning and estimation group, uniting research at CWI related to data analysis and mining, and works with researchers from earth sciences. PNA2 played a key role in the organization of the 2010 conference on Mathematics for Industry hosted by CWI.

Viability. The two research branches in spatial stochastics (percolation, mathematical physics, stochastic geometry) and stochastic operations research remain important cornerstones of PNA2. In particular, research in stochastic networks has been growing dramatically due to challenges raised by societal developments, such as the increase in the use of information and communication technology and user mobility, and the need for cost-efficient operation in areas such as healthcare and transportation. The fundamental research in this area has recently been awarded a Vidi grant. Research in percolation and related problems is currently booming as witnessed by the two Fields medals in this area awarded in the past five years. The techniques in this area of probability also become increasingly important in the analysis of algorithms, which makes this research strategically important for PNA and CWI in the long run.

Within PNA2, collaboration between the three branches of stochastics has been slowly developing but can be improved. Several research areas are converging. In revenue management, statistical and operations research techniques need to be integrated. The analysis of wireless networks requires techniques from percolation, stochastic geometry and stochastic networks, as well as the analysis of algorithms using techniques from mathematical physics. Phenomena like the spread of an infection also became important in the engineering and social sciences; think of P2P networks and marketing.

Strategy. Looking forward, the biggest challenge is to expand existing collaboration within the areas of expertise of PNA2, and of PNA2 with other groups at CWI. Current funding levels are fine, but should they be increased, this will require more emphasis on projects funded by industry or STW, and theoretical research may have to be secured by collaboration. Either way, good theoretical research is in the long run only viable if new practical questions are raised. PNA2 can secure its strong theoretical position, apart from continuing the current research directions), by means of collaborations within the group, within the institute, and with researchers from other academic disciplines and industry labs.

Another example is secure computation, which in principle enables an arbitrary computation to be distributed among the processors in a network so that computations remain secret and are performed correctly, even if a certain quorum of the network is under full control by an adversary ("multi-lateral security", security among mutually distrusting parties or parties with conflicting interests). Besides being a versatile theoretical primitive, potential real-life applications are myriad and include secure cooperation in the absence of trust, auctions, privacy-protecting data-mining and -

benchmarking. Notable examples that fit neither category include secure positioning and searching encrypted data.

The research in PNA5 is driven partly by questions such as: How reliable are the cryptographic methods in use today, really? Can they be made more secure or more efficient? Which are possible (minimal) assumptions under which security can be provided? Post-quantum cryptography: what to do if and when life-size quantum computers come into existence and, hence, today's standards for secure communication are rendered insecure? Can large-scale secure computations be made practical?

In search for answers to these questions, the research is organized around the following (partially overlapping) themes. First, communication security beyond the horizon: post-quantum security (crypto from geometry of numbers, information-theoretic methods), leakage-resilience and tamper-resistant cryptography. Second, theory: secure computation, composability, public-key cryptography. Third, alternative models: quantum cryptography and information theory, bounded storage model, noisy channels. Fourth, cryptanalysis and applications to information security: number-theoretic (number field sieve, elliptic curve discrete logarithms), hash-functions, security of public key infrastructures.

In addition, there is special focus on interplays with algebra, number theory, geometry, combinatorics, probability theory, complexity theory, formal methods, quantum physics and information theory, as advances in modern cryptology increasingly rely on deeper understanding of these interplays.

The PNA5 group was established by Cramer on 1 June 2004. The group conducts fundamental and application-oriented research in cryptology and information security with a broad basis in mathematics, computer science, and physics.

PNA5 is one of the leading research groups in cryptology in the world. We have frequent and often long-standing research collaborations and joint publications with other leading groups (in cryptology, computational number theory, or coding theory) such as those at Aarhus Univ. (DK), ETH Zurich (CH), EPFL Lausanne (CH), Weizmann Institute of Science (IL), Technion (IL), New York Univ., MIT (USA), NTU (Singapore), McGill Univ. (CA), Univ. Montreal (CA), IBM T.J. Watson (USA), and Microsoft (USA). Within the Netherlands we are part of the NWO mathematics cluster DIAMANT and we are strongly connected with the Mathematical Institute, UL. We also collaborate with TUE, RUN, TNO and Philips Research.

We are external partner of the Danish Center for Research in the Foundations of Electronic Markets (CFEM). Our national RISC seminar, established in 2004, regularly attracts top class speakers from the international research community, including Turing-Award Winners Adi Shamir and Ron Rivest. Attendance ranges from 15–25 people from all over the Netherlands to 80–150 from the Netherlands and abroad, depending on the theme and the speakers. We have organized three international workshops at Lorentz Center, UL and three international workshops at the KNAW, including 4th IACR TCC in 2007. We teach several cryptology related courses in the national Master-math Program and at the Mathematical Institute, UL. We also frequently teach invited short-courses all over the world.

Composition. Presently, the group consists of three senior researchers: Cramer, Te Riele and Fehr, and one external advisor: A.K. Lenstra. There are presently also three postdocs, four PhD students, and three guests. It is expected that

in 2011 three or four more postdocs and two more PhD students will be hired.

Quality and scientific relevance. A selection of highlights:

(2009) Since twenty years, the “Number Field Sieve Project” helps setting the industrial standards for key-length of the RSA-cryptosystems. Most recently, RSA-768 has been factorized.

(2008) Efficient chosen-prefix collision attacks for the MD5 hash-function have been invented. This has led to a successful attack strategy on SSL and caused the subsequent worldwide withdrawal of the MD5-hash function.

(2008) An efficient, practical crypto-system has been invented that is secure against chosen cipher-text attack under the factoring assumption. This resolved an open question that received wide attention for several decades.

(2008) Leakage-resilient cryptography has been invented. It provides a promising theoretical framework for the design of crypto-systems secure against side-channel attacks. This has spawned a wave of results in the cryptographic community and is currently one of the hot topics.

(2006) An asymptotic version of the Fundamental Theorem on Information-Theoretically Secure Multi-Party Computation has been proved, using a novel, deep link with algebraic geometry.

(2005) The “quantum-bounded storage” paradigm has been invented. This opened, for the first time, the door to application of quantum cryptography to problems beyond key-exchange, such as oblivious transfer and identification.

Key publications:

T. Kleinjung, K. Aoki, J. Franke, A.K. Lenstra, E. Thomé, J.W. Bos, P. Gaudry, A. Kruppa, P.L. Montgomery, D.A. Osvik, H. te Riele, A. Timofeev, P. Zimmermann. Factorization of a 768-bit RSA modulus. 29th Annual IACR CRYPTO, 55–69, 2010. (repository id: 16870)

M. Stevens, A. Sotirov, J. Appelbaum, A.K. Lenstra, D. Molnar, D.A. Osvik, B. de Weger. Short chosen-prefix collisions for MD5 and the creation of a rogue CA certificate. 29th Annual IACR CRYPTO, 55–69, 2009. (repository id: 14802)

D. Hofheinz, E. Kiltz. Practical chosen ciphertext secure encryption from factoring. 28th Annual IACR EUROCRYPT, 313–332, 2009 (repository id: 15191)

A. Bassa, P. Beelen. On the construction of Galois towers. Contemporary Mathematics, 487, 9–20, 2009. (repository id: 15207)

S. Dziembowski, K. Pietrzak. Leakage-resilient cryptography. 49th FOCS, 293–302, 2008 (repository id: 13770)

I. Damgård, S. Fehr, L. Salvail, C. Schaffner. Cryptography in the bounded quantum-storage model. SIAM Journal on Computing 37, 1865–1890, 2008. Also appeared in 46th FOCS, 449–458, 2005. (repository id: 12650)

H. Chen, R. Cramer. Algebraic geometric secret sharing schemes and secure multi-party computations over small fields. 26th Annual IACR CRYPTO, 521–536, 2006. (repository id: 15493)

Output. Over 80 publications; a total of four PhD degrees have been granted.

Earning capacity. In the period 2005–2010, PNA5 obtained one NWO Vici grant (Cramer 2007: two PhD students, six

postdoc years), one ERC Starting Grant (Pietrzak 2010: two PhD students, four postdoc years), two NWO Veni grants (Fehr 2006, Hofheinz 2007). Two postdocs (4.5 years, 1.5 years) were funded by the STW Sentinels PASC project (Cramer 2005–2010), one postdoc (three years) by the STW Sentinels Revocable Privacy project (Cramer 2010–2014), two postdocs by NWO DIAMANT (three years, one year), one postdoc (.75 year) by ERCIM, one postdoc by the USA NSF (one year). Three PhD students were funded by NWO Vrije Competitie (Te Riele (two), Fehr). Kiltz (2010) obtained a Sofya Kovalevskaya Grant (von Humboldt Foundation). We also frequently welcome visiting professors and visiting PhD students who bring their own grants.

Academic reputation. All group members have leadership roles in their field of specialization. They frequently serve on program committees on the top conferences on cryptology, such as CRYPTO, EUROCRYPT, TCC, PKC, and they frequently serve as scientific organizers of specialized research workshops at such international centers as Dagstuhl (DE), IPAM (USA), Lorentz (NL), KNAW (NL), CRM (ES). Cramer, Pietrzak, Kiltz, Fehr, Hofheinz all received major prestigious grants (NWO, ERC, von Humboldt). Cramer is full professor at UL. In the period 2005–2010 he is a frequent Visiting Professor at NTU (Singapore) and UPC Barcelona, has been a Visiting Professor at ENS (Rue d’Ulm, 2006), CRM Barcelona (2006), Complutense (Madrid, 2007). He is an alumnus of De Jonge Akademie (KNAW, 2005–2010), editor of Journal of Cryptology and of Journal of Mathematical Cryptology, and advisory board member of Springer Verlag series on Cryptology and Information Security. He was jury chair for the 2009 KNAW Christiaan Huygens Award. He also served as Program Chair of 24th Annual IACR EUROCRYPT (Aarhus, DK), of 5th Annual IACR PKC (Barcelona, Spain), and of the 2011 Workshop on Information Theoretic Security (Los Angeles, USA), and serves on the steering committees of IACR PKC and of ICITS. He served on the Board of Directors of the International Association for Cryptologic Research (IACR) and serves on the Advisory Board of the Center for Advanced Security Research Darmstadt. Te Riele was secretary of ERCOM, board member of KWG, and local organizer of ECM 2008. Fehr serves on the program committee of FOCS 2011 and as the Program Chair of ICITS 2011. He gave a public lecture at the Royal Dutch Society for Physics “Diligentia” (2010) and was visiting professor at UCLA (Fall 2010).

PNA6—Algorithms and Complexity

Objectives and research area. Algorithms and complexity form the theoretical basis for all information processing tasks. Whenever information needs to be processed one needs to develop procedures or algorithms that make efficient use of the available resources, e.g., running time, memory, communication, information, data, qubits, randomness. Within this broad field PNA6 focuses on four areas: quantum computing, learning theory, complexity and information theory, and computational biology.

The work program in *quantum computing* includes the design and analysis of new algorithms and communication protocols, and the development of new tools to establish complexity bounds of such algorithms. Another focus in our research is fault tolerance. We are active in making connections between quantum computing and non-quantum areas such as coding theory, approximation theory, and functional analysis. We also develop new quantum cryptographic protocols.

Awards:

(2010) Best Paper Award, 29th Annual IACR EUROCRYPT, Nice, France: Hofheinz, Kiltz et al.

(2009) Best Paper Award, 29th Annual IACR CRYPTO, Santa Barbara, CA, USA: Stevens et al.

(2009) Best Paper Award, 28th Annual IACR EUROCRYPT, Cologne, Germany: Hofheinz, Kiltz.

Combining forces. One professorship (Cramer). NL-links: UL, UvA, UU, TUE, RUN. Main international links: ETH, Aarhus, Bochum, Karlsruhe, UPC Barcelona, NTU Singapore, UCLA, MIT, NYU, Georgia Tech, UC San Diego, Weizmann Institute of Science, Technion.

Societal relevance. Much of our research is fundamental, inspired by practically relevant questions, and its impact beyond science will likely be felt in the future. A sample of results with more immediate consequences is as follows: Stevens’ hash-function caused the world-wide withdrawal of MD5 from the internet. The Number Field Sieve Project (Te Riele) is very important for internet security (RSA key-length). The Cramer-Shoup encryption scheme is an ISO standard.

Several of our main research results have been reported in prominent media, such as New York Times and NRC Handelsblad.

Viability. Recently, two of our postdocs landed tenure-track full professorships (Bochum, Karlsruhe), one of our postdocs got a position at Stanford, another one in the Israeli high-tech industry. One PhD alumnus got a position in the Dutch defense industry.

Strategy. Building on its deep connections with mathematics, computer science and physics, the group established itself internationally. Next, continuity has to be secured. New opportunities lie in experimental quantum cryptography (Fehr; mainly the bounded storage model, collaboration with PNA6) and collaboration with physicists, the development of leakage resilient cryptography (ERC Pietrzak; may have a huge practical potential as well), the re-focusing of our computational number theory activities from integer factorization to elliptic curve cryptography, in cryptanalysis of hash-functions, secure optimization (with links to PNA1), and the connections between information-theoretic cryptography and algebraic geometry.

In *learning theory* we work on minimum description length (MDL) learning, on-line prediction, and model selection. We focus on developing strategies that still perform well in situations where all model under consideration are wrong. This is typically the case in the very large but often polluted data sets that are rapidly becoming available, such as in machine learning applications but also, for example, forensic statistics (DNA sequences).

In *complexity and information theory* we study both Kolmogorov complexity and properties of computational classes. In particular we develop and analyze very efficient, sub-linear time, testing algorithms. We also develop tools to establish lower bounds for computation devices.

In *computational biology* we address the origin of early proteins and the genetic code. We study the robustness and fault tolerance that seem to be present in the genetic code and its small variants. We also model the evolutionary origin

of pan editing present in for example *Trypanosoma brucei*, the parasite that causes sleeping sickness in humans.

PNA6 is a leading group in quantum computation world-wide, as witnessed by the frequent interactions (visits to and from, joint publications) with other top groups in the field (Waterloo, Caltech, Berkeley, MIT). There is also close collaboration with physics-oriented groups (Brussels, Geneva, Bristol, Cambridge, ETH). Within the Netherlands we are founding member of the "Quantum information at Amsterdam" initiative that fosters cooperation between physics and computer science groups in Amsterdam. In information theory, machine learning and statistics, we collaborate with some of the world's leading groups, e.g. Cambridge (statistics) and Santa Cruz (learning) and we are an active member of the PASCAL II network (see *Combining forces*). On a national level there are close ties with UL and EURANDOM. In complexity theory we work together with world leading groups in e.g. Chicago, Prague, Moscow and Rutgers. The computational biology component collaborates with groups in Brussels, Stillwater, and locally the Amsterdam academic medical center (AMC). Within CWI, we collaborate with PNA1 (optimization, quantum fault tolerance), PNA5 (quantum crypto) and MAC4 (computational biology).

Composition. The group currently consists of four senior researchers: Buhrman, Grünwald, De Wolf, Gill, and six PhD students and four postdocs. CWI fellow Vitányi retired in 2009.

Quality and scientific relevance. *Fault-tolerance threshold.* In collaboration with PNA1, we have obtained stronger upper bounds on the level of noise that a quantum computer can tolerate during its operations. The precise value of this "fault-tolerance threshold" is one of the main open questions in the theory of quantum computing, with a strong link to practice: its answer will to a large extent determine if building a large-scale quantum computer ever becomes feasible.

Quantum proofs for classical theorems. It has recently turned out that one can fruitfully apply techniques developed in quantum computing in other areas of computer science and mathematics. This is an application of quantum computing that is relevant today, irrespective of whether a large-scale quantum computer will ever be built. We initiated and have been developing this line of research, producing applications of quantum techniques to diverse areas including error-correcting codes, polynomial approximation theory, and a solution to the Varopoulos problem in functional analysis. An internally funded project between PNA1 and PNA6 is to start this year.

MDL book. Grünwald wrote the first comprehensive book on the minimum description length principle for learning and statistical inference, containing an overview of existing work and various new results that tie existing approaches together.

Improving on Bayesian methods when models are wrong. Statistics is often applied with models that are wrong, yet useful. We showed that for such models, Bayesian inference can lead to arbitrarily bad predictions, even in the limit of an infinite amount of data. We also analyzed the slow convergence of Bayesian methods in adaptive estimation and model selection, and developed the *switch distribution*, an extension to Bayesian model selection that converges at a faster (optimal) rate while retaining the Bayesian consistency properties. This solves a special case of the *AIC-BIC dilemma*, a central issue in statistics since the 1980s.

In *computational complexity theory*, we proved for the first time that under reasonable assumptions (coNP is not in NP/poly) NP-complete sets contain exponentially many instances that are computationally hard to solve. This is the first result that has an exponential density conclusion from a relatively weak assumption on the computational complexity of coNP.

In *computational biology* we extended work on the origin of the genetic code and showed that the genetic code is close to optimal in a variety of possible codes spaces. We also established the absolute best code in one of these spaces. This work was jointly done with MAC4.

Key publications:

H. Buhrman, R. Cleve, M. Laurent, N. Linden, A. Schrijver, F.P. Unger. New limits on fault-tolerant quantum computation. Proceedings of the 47th Annual IEEE Symposium on Foundations of Computer Science (FOCS), 411–419, 2006. (repository id: 12635)

H. Buhrman, J.M. Hitchcock. NP-hard sets are exponentially dense unless $\text{coNP} \subseteq \text{NP/poly}$. Proceedings IEEE Conference on Computational Complexity (CCC) 23, 1–7, 2008. (repository id: 13767)

H. Buhrman, R. Cleve, S. Massar, R. de Wolf. Nonlocality and communication complexity. Rev. Mod. Phys. 82, 665–698, 2010. (repository id: 17616)

A. Drucker, R. de Wolf. Quantum proofs for classical theorems. Theory of Computing, 2010. (repository id: 16883).

T. van Erven, P.D. Grünwald, S. de Rooij. Catching up faster in Bayesian model selection and model averaging. Advances in Neural Information Processing Systems 20 (NIPS 2007), 1024–1031, 2008. (repository id: 12092)

P.D. Grünwald, J. Langford. Suboptimal behavior of Bayes and MDL in classification under misspecification. Machine Learning, 66, 119–149, 2007. (repository id: 11847)

P.D. Grünwald. The Minimum Description Length Principle, MIT Press, 2007. (repository id: 11997)

Output. In the period 2005–2010, a total of 75 journal papers, 90 conference papers, seven PhD theses, two books and fifteen book chapters were published.

Earning capacity. From 2005 to 2010, the group obtained two Vidi grants (Grünwald: one PhD student, two postdocs, De Wolf: one PhD student, two postdocs), three Veni grants (De Wolf, Schaffner, Toner; Toner then moved to Australia so grant remained unused) and one Vici grant (Grünwald: three PhD students, three postdocs), four PhD positions and seven postdocs were funded by Buhrman's Vici grant (2004–2011). Further postdocs were funded by NWO Free Competition, EU projects RESQ, QAP and QCS, and two Bricks grants. Also various NWO visitor grants were obtained.

Academic reputation. All group members fulfill leadership roles in their specialization. From 2005 to 2010, group members have given over 70 invited seminars and lectures at international workshops and conferences, including lectures for the general public (e.g. Paradiso-Lezing 2005 by Buhrman). They regularly act as program committee members of top international computer science conferences (STOC, FOCS, CCC, STACS, ICALP, QIP, COLT, UAI), including one program-chairmanship (UAI 2010). Buhrman is editor of TOCS, Computational Complexity, and ACM Transactions on Computation Theory, De Wolf is editor of Theory of Computing. We act regularly as members of NWO boards (Veni, Vidi). All group members have received prestigious NWO

grants. Buhrman was chair of the computer science board of the Lorentz center (2005–2010) and is on the advisory boards of the Canadian CIFAR program and the institute for quantum computing in Waterloo.

In 2008, Grünwald was appointed full professor at UL. Vitányi was knighted in the Order of the Netherlands Lion (2007). Grünwald was co-awarded the Van Dantzig Prize 2010, awarded every five years to a Dutch researcher in statistics or operations research not older than 40.

Combining forces. Three group members hold full professorships, at UvA (Buhrman) and UL (Gill, Grünwald). Several group members are involved in EU networks (Grünwald, steering committee member PASCAL and PASCAL II EU Networks of Excellence; Buhrman and De Wolf, work package leaders for EU funded projects RESQ, QAP, and QCS).

Societal relevance. Most of our research is theoretical, with only long-term implications for society—which could be high impact, such as fast computation by quantum computers or explicit demonstration of the impossibility thereof. Still, the work on improving Bayesian statistical inference has obvious immediate value for applications; within our group, we used it to develop prototypes of new lossless data compression algorithms. Also, through the connection learning-with-wrong-models and forensic statistics, Gill and Grünwald became involved in the ultimately successful

attempt by a number of scientists to reopen the case against Lucia de Berk, a Dutch nurse who had been convicted of murder based partly on flawed statistical evidence. This led to frequent media appearances (Dutch TV, radio stations, major daily newspapers). Grünwald was also a member of the DNA Advisory Committee of the Dutch Ministry of Justice for the Dutch Forensic Experts Register.

Viability. PNA6 is active in modern research themes with a bright future. After obtaining their PhD, PNA6 students typically find good jobs or postdoc positions (IBM TJ Watson, Google, Caltech, Berkeley, Cambridge, Rutgers). There is ample funding for the coming years, with several open PhD and postdoc positions.

Strategy. Promising directions for future research include: extending connections to forensic statistics, where model assumptions about how data are collected are violated. The link between quantum computing, semidefinite programming and functional analysis (PNA1) will be pursued as well as the work on new cryptographic protocols in the bounded storage model, such as secure quantum positioning (PNA5). Work on computational biology will be continued with MAC4 and the groups in Brussels, Stillwater, and the AMC. Other good opportunities are, in quantum computing, to cooperate with experimental groups and, in learning, to apply the computationally efficient switch distribution to practical problems in regression and time series.

SEN1—Software Analysis and Transformation

Objectives and research area. SEN1 studies software systems: their design, their construction, and their inevitable evolution. We focus on complexity of understanding as the primary quality attribute of software systems. Software complexity is an important subject, which is not only due to the ubiquity of software systems and failing ICT projects in society: there is a general lack of deep understanding of what causes software systems to be complex and how they can be made simpler.

With *software analysis* we propose and evaluate methods for observing software both quantitatively and qualitatively. We automatically extract models of software systems, which can then be simulated, measured, checked and visualized. On the one hand such analyses may provide insight into specific software systems, which is valuable in itself. On the other hand, by collecting information about sets of software systems, we may also use software analysis to come to general insights. We work on a variety of increasingly rich models of software systems that would allow increasingly meaningful analyses to be performed.

With *software transformation* we propose and evaluate automated methods of construction and maintenance of software systems. Using large-scale automated software renovation we improve software quality by transforming existing systems to better systems. Using the construction of domain-specific languages we improve quality of newly designed systems by carefully constructing automated but reconfigurable transformations from high-level domain concepts to high-quality source code.

Software transformation and analysis go hand in hand. Automated software analysis is used for checking preconditions of automated software transformations. Also, software transformation plays an important role in many software analyses that consist of pipelines of incremental transformation steps of a software system, via software models, to a final analysis result. Software analysis is also the key to

observing and evaluating the effects of software transformation.

From a birds-eye perspective the research methods of the group can be classified as empirical, but theoretical methods are applied to introduce and verify new models, algorithms and methods. Examples are the construction of *general parsing and disambiguation algorithms*, decision methods for *ambiguity of context-free grammars* and our contributions to *epistemic modal logic*.

Composition. At the end of 2010, SEN1 consists of three seniors (Klint, Van Eijck, Vinju), one tenure tracker (Van der Storm), two postdocs, seven PhD students, two programmers, one guest. We expect Michael Godfrey (Univ. Waterloo, Canada) to visit us for a period of one year. In 2009, the group SEN2 was discontinued, and the remaining researchers and a scientific programmer were moved to SEN1. In 2011, SEN1 will join forces with INS3 to create a multi-disciplinary team that will perform research in the domain of software visual analytics.

Quality and scientific relevance. Highlights: three former team members became full professor at universities (Van Deursen at TUD, Van den Brand at TUE, Fokink at VUA); creation of joint research team with INRIA; design and implementation of the meta-programming language Rascal.

Key publications:

J. van Eijck, C. Unger. Computational Semantics with Functional Programming. Cambridge University Press, 2009. (repository id: 17807)

J. van Eijck, R. Verbrugge. Discourses on Social Software. Amsterdam University Press, 2009. (repository id: 14967)

P. Klint, R. Lämmel, C. Verhoef. Toward an engineering discipline for grammarware. ACM Transactions on Software Engineering and Methodology 14, 331–380, 2005. (repository id: 14284)

M.G.J. van den Brand, M. Bruntink, G.R. Economopoulos, H.A. de Jong, P. Klint, A.T. Kooiker, T. van der Storm, J.J. Vinju. Using the meta-environment for maintenance and renovation. Proceedings of 11th European Conference on Software Maintenance and Reengineering, Software Evolution in Complex Software Intensive Systems (CSMR), 2007. (repository id: 11713)

P. Klint, T. van der Storm, J.J. Vinju. Rascal: a domain specific language for source code analysis and manipulation. Proceedings of IEEE International Working Conference on Source Code Analysis and Manipulation (SCAM), 2009. (repository id: 15097)

Output. About 170 publications, eleven PhD theses.

Earning capacity. In the period 2005–2010 SEN1 obtained over 6M€ in funding from NWO Vrije Competitie, NWO Jacquard, NWO Grammar Laboratory, NWO Kisen, NWO Escher, NWO Kennisbenutting, NWO Top SenterNovem, INRIA and EC. This includes the total funding both for projects that were started before 2005 but ended in the period 2005–2010 and projects that were started in that period and will end later.

Academic reputation. Klint is an internationally well-known research lead, who pioneered algebraic specification of programming languages, software composition using coordination languages, among many other subjects. He has supervised more than 31 PhD projects and countless master projects. He is editor of *Science of Computer Programming* and the Springer Book series on *Services Science*. Klint is known for his focus on industrially relevant research topics, and is a founding father of the Software Improvement Group, a CWI spin-off. He is a wanted keynote speaker at forums such as Holland Open and NIOC and various conferences. He is well known for the inception of the ASF+SDF Meta-Environment, a high quality tool for programming language specification, for the design of the Rascal meta-programming language, and for starting and directing the successful Master Software Engineering at UvA. In 2010, NWO awarded Klint a prestigious NWO-TOP subsidy on “Domain-specific languages: a big future for small programs”.

Vinju is a visible member of the international community on software analysis and transformation, having been PC chair of LDTA 2008 and 2009 and SCAM 2010. He is now steering committee member of SCAM, the international working Conference on Software Analysis and Transformation. Vinju won an IBM Bravo award after his visit to IBM Thomas J. Watson Research in Hawthorne, NY, for his contributions to the Eclipse IDE Meta Tooling platform. He is known for being co-responsible for the design and implementation of the ASF+SDF Meta-Environment 2.0, and the inception of Rascal, a domain-specific language for source code analysis and transformation. Vinju has been heavily involved with the Master Software Engineering at UvA.

Van Eijck is well known for his work on logic in natural language analysis and on the analysis of communication with epistemic model checking. He is the author of the epistemic model checker DEMO. Van Eijck is a frequent lecturer at the European Summer Schools in Logic, Language and Information (ESSLLI). He has written influential textbooks and handbook papers, on functional programming, dynamic logic, discourse representation, and the use of logic for analyzing social software. His most recent textbook, on computational semantics with functional programming, appeared in October 2010 with Cambridge University Press. He is professor of Computational Linguistics

at UU and fellow at NIAS (Netherlands Institute for Advanced Studies, Wassenaar). He teaches Software Testing at the Master Program Software Engineering at UvA.

Van der Storm (tenure track) and Mark Hills are both high-potential multi-disciplinary postdocs that we are proud to have on our team. They are major contributors to the initial conception of the Rascal language and its implementation.

Combining forces. Three professorships: Van Eijck (UU) and Klint (UvA and Royal Holloway Univ. of London). Klint was chair of Informatica Onderzoek Platform Nederland (Dutch national organization of computer science researchers) and is member of the TWINS council of the Royal Netherlands Academy of Arts and Sciences. SEN1 also hosts the ATEAMS research group, a joint CWI/INRIA team. We cooperate with the Netherlands Forensics Institute, IBM Thomas J. Watson Research, Univ. Koblenz, Univ. Waterloo, Univ. Bergen, PriceWaterhouseCoopers, Dutch Tax Authority, and Software Improvement Group.

Societal relevance. In 2000 the Software Improvement Group (SIG, www.sig.nl) was created as a spin-off company from SEN1. Today, SIG has over 40 employees and hundreds of customers in government and industry. SIG is also active in Switzerland, Belgium, Germany and Scandinavia. SIG received the Innovator Award 2007 and was listed in 2009 in the FD Gazellen Top 100 and in the 2009 Deloitte Technology Fast 500 EMEA. SEN1 research results are being transferred to SIG and there is also a close cooperation in joint Master’s projects.

Many members of SEN1 are involved in teaching courses at the Master Software Engineering at UvA. Since many software professionals are enrolled in this Master’s program, the courses provide a direct person-to-person means for transferring SEN1 research results to industry.

Viability. In the last five years SEN1 has seen the departure of three senior researchers to university positions and the retirement of another senior researcher (Heering). In response to these developments the group has been revitalized by attracting funding for young researchers and by planning the gradual transition of the group leadership from Klint to Vinju at the end of 2011. The recently started work on a new language for meta-programming (Rascal, www.rascalimpl.org) will form a focal point for research in the coming years.

Strategy. Very similar to the role of ASF+SDF in the past, the Rascal language acts as a guide for SEN1. It provides a common conceptual and technological framework for experimentation with software analyses and transformations. As such it has a common vocabulary and a reusable “laboratory setup” for doing experimental research. It helps new group members to position both their theoretical and empirical research. It acts as a long-term visionary perspective as well. As a name, Rascal provides a brand label for our group’s research results.

Our strategy is to work on the intersection between the academic fields of software analysis and software transformation. Our group has a unique heritage in both domains. For the future this combination will prove to be fruitful. Software visual analytics is a related, but new, domain that we will explore. We continue using both empirical and theoretical research methods, using theory for innovative ideas and empirical research for their validation. We—and the software engineering research community at large—are becoming increasingly skeptical about academic results that are not sufficiently validated in practice. We also keep investing in programming language theory and epistemic

logic, since without theory there can be no experimentation.

To make experimental evaluation possible we invest in joint research and industrial projects that investigate what are “applications” from our point of view. Our collaborative studies in forensic and computational auditing software exemplify this. Such collaborations provide the raw data to use in experimental research and they also lead us to the

SEN3—Foundations of Software Engineering

Objectives and research area. Research of SEN3 focuses on modeling and analysis of concurrent and distributed software systems. Specifically, in the context of service-oriented computing, we seek to provide well-founded technology for the easy and reliable composition of third-party applications, accommodating for such extra-functional properties as quality of service and compliance. Integral to our approach is the development of solid mathematical foundations, using proof theory and coalgebra, to define the formal semantics and reasoning mechanisms.

Composition. The group consists of three tenured senior researchers (Arbab, De Boer, Rutten), each of whom coordinates his own subgroup. Since 2005, a substantial number of junior researchers have been trained: twenty PhD students, seven postdocs and three ERCIM fellows. The seconded staff amounts to four.

Quality and scientific relevance is described in terms of SEN3’s three closely related sub-groups: component-based models and software architectures (Arbab), formal methods (De Boer), coalgebraic models of computation (Rutten).

The coordination language Reo presents a new paradigm for composition and orchestration of distributed software components and services based on the notion of mobile channels. The basic operational semantics of Reo and its timed version were developed by C. Baier, F. Arbab, M. Sirjani, J. Rutten, and F. de Boer, as presented in *Modeling component connectors in Reo by constraint automata* (Science of Computer Programming 61, 75–113, 2006; repository id: 14373) and *Models and temporal logical specifications for timed component connectors*. (International Journal on Software and Systems Modeling 6, 59–82, 2007; repository id: 11972). Work on the semantics, implementation and tools for Reo has resulted in a number of PhD theses to be defended in 2010 and early 2011. Tool support for Reo consists of a set of Eclipse plug-ins that together comprise the Eclipse Coordination Tools visual programming environment. In the EU STREP project COMPAS these tools have been successfully applied to the specification and verification of compliance requirements of business processes provided by the industrial partners PriceWaterHouseCoopers, Thales, and TeleCordia.

The work on formal methods for object-oriented languages has resulted in a comprehensive proof-theory of a variety of object-oriented features and mechanisms like aliasing, method calls, object creation, multi-threading, inheritance and subtyping. The basic Hoare logics of aliasing, method calls and object creation in a sequential setting have been described in the third extended edition of the key publication *Verification of Sequential and Concurrent Programs* (Springer, 2009; repository id: 14569). In the foreword of this book Amir Pnueli writes: “This is especially true for the treatment of object-oriented programs which is entirely novel and is strikingly elegant”. On the other hand, the key publication *An assertion-based proof system for multi-threaded Java* (Theor. Comput. Sci. 331, 251–290, 2005;

real bottlenecks in industrial software engineering that generate new research questions.

Our cooperation with INRIA in the joint ATEAMS project gives us ample opportunities to work with related teams within INRIA, and to attract new talent and to disseminate our results via the INRIA network.

repository id: 14587) describes a sound and complete proof theory for multithreaded Java. The work on formal methods for object-oriented programming and modeling languages has been successfully applied to UML in the FP5 IP EU project Omega, to distributed object-oriented services in the FP6 EU STREP project Credo and are currently further developed and applied to software product lines in the FP7 IP FET project HATS.

In recent years, coalgebra has come to play an ever more important role in the theory of computing and computer science. It is the natural environment for specifying and reasoning about infinite behaviour. Prototypical examples of such coalgebras are streams, which are infinite sequences, and many kinds of automata, including deterministic automata and transition systems. Rutten’s paper *Universal coalgebra* (Fundamental Study in TCS, 2000; repository id: 48) is one of the most cited papers written at CWI (<http://repository.cwi.nl/scopus/list.php>). A recent highlight is *Non-deterministic Kleene coalgebras* (Logical Method in Computer Science, 6, 2010; repository id: 16641), which is also one of the central chapters in Silva’s PhD thesis. Kleene’s theorem establishes the link between regular expressions and finite automata. Brzozowski described the construction of an automaton from an expression on the basis of a calculus of derivatives. In earlier work, Rutten used this result for the formulation of a coalgebraic calculus, in which equality of expressions is proved by coinduction. In the above key publication, similar coinductive calculi and Kleene theorems have been developed for many other types of automata and expressions, including Mealy automata, Kleene algebras with tests, labeled transition systems, and many more.

Output. About 160 publications. Two coauthored books. Supervision of thirteen PhD theses.

Earning capacity. In the past six years, SEN3 has been involved in twelve projects with national funding, and several international projects: Credo (Modeling and analysis of evolutionary structures for distributed services), FP7, 2006–2009; Trust4All, ITEA, 2005–2007; COMPAS (Compliance-driven Models, Languages, and Architectures for Services), FP7, 2008–2011; HATS (Highly Adaptive and Trustworthy Software unifying Formal Models), FP7, 2010–2012.

Academic reputation. *Professorships:* UL (Arbab, De Boer) and RUN (Rutten). *Program committees:* In this period the senior researchers of SEN3 have been involved in over 100 PCs including DISCOTEC, ICALP, CONCUR and FOSSACS.

Editorial boards: Logical Methods in Computer Science, Scientific Annals of Computer Science (Rutten), Computer Science and Engineering section of Scientia Iranica, International Journal of Next-Generation Computing (Arbab). *Editorships:* Special issues of Fundamenta Informaticae, Journal of Universal Computer Science, ENTCS, LNCS proceedings (Arbab), TCS and SCP special issues, LNCS proceed-

ings of the International Symposia on Formal Methods for Components and Objects (De Boer).

Invited talks: ICTAC 2005, FACS 2005, ETAPS Software Composition 2007, SAMOS 2008, CONCUR workshop ICE 2009, ASCI winter school on embedded systems, CSDM 2010 (Arabab), NVTI Theory Day 2009, The 9th International Key Symposium 2010, CONCUR 2010 (De Boer), FACS 2009, Univ. Braunschweig, Amsterdam Theoretical Computer Science Colloquium (Rutten).

Awards: Veni grant (Niqui). Best paper award of the 11th Pacific RIM International Conference on Multi-Agents (Aștefănoaei and De Boer), Nederlands Architectuur Forum-Architectuurprijs for the ARCHIMATE project, ITEA Bronze Achievement Award for the TRUST4ALL project.

Combining forces. Within CWI, SEN3 has active collaborations with SEN1 (Klint, Vinju), PNA1 (Apt), PNA2 (Van der Mei), MAC4 (Merks). On the national scene, SEN3 collaborates with UL, UU, VUA, UvA, RUN and TUE. SEN3 has also been engaged in joint work with numerous universities and international organizations, both in the context of funded EU projects, and other close academic collaborations. These include the universities of Dresden, Braunschweig, Oslo, Kiel, Uppsala, Cornell Univ., Univ. Illinois, Univ. Iasi, Imperial College, the Uppsala Programming for Multicore Architectures Research Center, the International Institute of Software Technology of the United Nations Univ. Macau, Rikshospitalet–Radiumhospitalet HF, the Dutch companies Almende and Fredhopper, the international companies Thales Services SAS, PriceWaterhouseCoopers, Telcordia Poland.

SEN4—Multi-agent and Adaptive Computation

Objectives and research area. SEN4 focuses on adaptive decision making in multi-actor and uncertain environments. This comprises (1) computational intelligence (CI) techniques, like evolutionary algorithms, graphical models, and hybrid heuristics, and (2) decentralized paradigms, like multi-agent systems, sensor networks, and non-cooperative (economic) games. On the one hand, the group performs fundamental research on the underlying techniques: the development of advanced CI techniques (like estimation of distribution algorithms, EDA) and the design of adaptive agent strategies and simulation systems in strategic economic games (like negotiation, repeated auctions, or market based planning). On the other hand, the group develops generic and enriched models as well as adaptive solutions for target problems in key application areas that include smart electricity networks, health care and transportation logistics, electronic markets, and smart ambient environments. In these areas, decentralized and adaptive decision making becomes crucial and meets the requirements in actual practice.

Adaptive decision making in multi-actor and uncertain environments becomes more important both in science and in society. This is especially true for the combination of non-cooperative agent systems with computational intelligence techniques. SEN4 addresses this issue via a combination of fundamental and applicable research.

Composition. The former group PNA4 (Signals and images) merged into SEN4 in 2010. PNA4 had decreased in size from three tenured researchers in 2005 to one tenured researcher in 2009: one tenured researcher left due to serious illness, another moved to PNA2. The techniques used by the former PNA4 had become close to those of SEN4. Furthermore, in

Societal relevance. In the context of EU projects, SEN3 has been successfully engaged in knowledge transfer to industry (Almende, Thales, PriceWaterhouseCoopers, Fredhopper). As an example, results of ARCHIMATE, for which SEN3 developed formal modeling and analysis techniques, have been published in a book and have been further exploited by our former partners, making it a standard in the industry. All of the PhD students and postdocs that we have educated have found permanent academic and industrial positions.

Viability. The high level and the varied portfolio of SEN3's external funding, its improved software development activities, and its increased number of successful PhD students, all indicate the health of this group as a viable active research unit. The viability of SEN3 has also been confirmed by the committee of SEN3's in-depth evaluation in 2006. Scaling modeling and analysis tools and techniques to accommodate large applications remains a challenge.

Strategy. We intend to intensify collaboration with SEN1 on integrating formal analysis techniques and program transformation tools, expand our ongoing joint work with PNA2, and join forces with MAC4, UL and VUA in applications in systems biology and life sciences. We strive to improve our tools and techniques and to apply them to relevant problems in collaboration with a broader range of industrial partners. Programming and applications of multi-core systems, quality of service, compliance, and dynamic reconfiguration in service oriented computing, and coordination and concurrency in systems biology are promising application areas to implement this strategy.

2010, one tenured SEN4 member moved to MAC4 and tenure tracker Bosman was given tenure. The group currently (end of 2010) consists of three tenured researchers, two postdocs, six PhD students (including four vacancies to be filled early 2011), and two scientific programmers.

Quality and scientific relevance. We investigated multi-issue negotiations between a supplier agent and customers about priced bundles of items together with interdependent valuations, and we achieved massive speed-up over earlier literature. We introduced a search approach for negotiating mutually beneficial bundles and developed a scalable method for online learning of aggregated bundle preferences, while respecting privacy. We showed that it is possible to exploit the decomposable structure of complex utility functions in order to reach more efficient negotiation agreements.

We investigated sequential auctions where agents bid for single items while trying to obtain bundles of items with interdependent valuations. Agents run the risk of acquiring only a partial bundle. We examined how option mechanisms can reduce the risk exposure. Previous literature only considered zero-priced options. We analyzed the use of priced options, in order to provide a sufficient incentive for both buyers and sellers to use this mechanism.

We designed the first-ever algorithmic framework for dynamic online optimization with evolutionary algorithms (EAs) that is capable, by using online learning and prediction, of explicitly performing anticipation, i.e. taking into account the future consequences of current decisions. We extended it to tackle multiple objectives, via offline optimization of policies to be used online. We constructed EAs for complex optimization problems based on (multi-agent)

simulations and demonstrated their feasibility, including a real-world problem (resource management in a hospital). Correspondingly, the first foresighted multi-agent reinforcement learning algorithms were developed that let an agent explicitly account for reactive behaviour of other agents.

We studied the issue of diversity loss as a result of exponentially shrinking variance in continuous, Gaussian-based, EDAs (a principled type of evolutionary algorithms). We proposed various remedies, leading to the design of a novel, easy-to-apply, parameter-free, EDA, called AMaLGaM. It is currently ranked among the best optimization algorithms for black-box numerical optimization.

We analyzed the concept of the gradient in multi-objective optimization and showed that the gradient is actually a Pareto-front of directions. We provided, based on analytical derivations, algorithms to compute this set.

We extended and improved Magnusson's TPatterns methodology for finding temporal patterns in sensor datastreams. The original T-pattern algorithm has quadratic time complexity in the number of sensors and in the number of discrete time steps considered for pattern search. We showed how this complexity can be reduced and proposed a modified algorithm that is quadratic only in the number of sensors.

Key publications:

P.A.N. Bosman, J. Grahl. Matching inductive search bias and problem structure in continuous estimation-of-distribution algorithms. *European Journal of Operational Research* 185, 1246–1264, 2008. (repository id: 13414)

E.H. Gerding, J.A. La Poutré. Bilateral bargaining with multiple opportunities: knowing your opponent's bargaining position. *IEEE Transactions on System, Man, and Cybernetics, Part C36*, 45–55, 2006. (repository id: 14438)

V. Robu, D.J.A. Somefun, J.A. La Poutré. Modeling complex multi-issue negotiations using utility graphs. *Proceedings of 4th International Conference on Autonomous Agents and Multiagent Systems (AAMAS)*, 280–287, 2005. (repository id: 14810)

I.B. Vermeulen, S.M. Bohté, S.G. Elkhuisen, J.S. Lameris, P.J.M. Bakker, J.A. La Poutré. Adaptive resource allocation for efficient patient scheduling artificial intelligence in medicine 46, 67–80, 2009. (repository id: 15107)

A.A. Salah, E.J. Pauwels, R. Tavenard, T. Gevers. T-Patterns revisited: mining for temporal patterns in sensor data sensors 10, 7496–7513, 2010. (repository id: 16756)

P.A.N. Bosman. The anticipated mean shift and cluster registration in mixture-based EDAs for multi-objective optimization. *Proceedings of ACM Annual Genetic and Evolutionary Computation Conference*, 351–358, 2010. (repository id: 16758)

T.B. Klos, D.J.A. Somefun, J.A. La Poutré. Automated interactive sales processes. *IEEE Intelligent Systems* 99, 2010. (repository id: 16759)

Output. About 180 publications and two PhD theses (from the former SEN4). The research and publications for a third PhD project have been completed.

Earning capacity. The group has acquired projects funded by NWO (health care planning, learning agents in games, negotiation), EU-FP7 (sensor networks), EU-FP6 (machine learning for video understanding, NoE), Agentschap.nl

(formerly SenterNovem) (electricity distribution networks, transportation logistics, and sensor networks; co-funded by companies), and private funding (health care and electricity networks). Also, the group acquired internal funding (revenue management and electricity distribution networks).

Academic reputation. Members of SEN4 received various best papers awards and nominations at conferences and workshops, including a best paper award for Bosman at the GECCO conference (ACM). La Poutré gave four invited plenary lectures, Pauwels gave two invited plenary presentations and received the ERCIM Working Group Award as chairperson of the ERCIM Working Group on Image and Video Understanding. PhD student Robu was awarded the funded participation in the prestigious summer school 'Complex Systems' (one month) at the Santa Fe Institute, USA. An MSc student graduating in the group received a national best thesis award on information systems (Bakkenist Prize, Koninklijke Hollandse Maatschappij der Wetenschappen). Several non-tenured researchers moved to academic institutes like Southampton, TUD, TUE, La Rochelle, or to frontrunning companies.

Conference organization and editorships. La Poutré was member of editorial boards of ACM Transactions on Internet Technology, Computational Management Science, and Netnomics. He also was special-issue editor for Computational Economics, IEEE Computational Intelligence Magazine, IEEE Transactions on Computational Intelligence and AI in Games, and two Springer LNAI proceedings. The group in addition organized and chaired two times the well-established workshops on Agent-Mediated Electronic Commerce (AMEC) and two other workshops/conferences. Pauwels was guest editor of the EURASIP Journal on Advances in Signal Processing and program chair of the International Workshop on Content-Based Multimedia Indexing. He has been organizer of the DELOS-MUSCLE Summer School on Multimedia Digital Libraries. Bosman was member of the editorial board of International Journal of Applied Metaheuristic Computing (IJAMC). He was also two times track chair and late-breaking papers chair for the GECCO conference. He co-organized the Evolutionary Algorithms for Dynamic Optimization Problems EvoDOP workshop at GECCO and the Optimization by Building and Using Probabilistic Models OBUPM workshops at GECCO.

Combining forces. La Poutré has become full professor of computer science at UU as of April 2010. Before, he had been full professor at TUE. Pauwels has been visiting research professor at Ecole Nationale Supérieure de l'Electronique et de ses Applications (ENSEA). Bosman is parttime lecturer at TUD. Further cooperation occurred with groups from e.g. Southampton, INRIA, Birmingham, Duke, Fraunhofer Sankt-Augustin, Cardiff, Warwick Business School, Johannes Gutenberg-Univ. Mainz, Sandia National Laboratories, and several Dutch universities. Within CWI, the group had joint projects and activities with SEN3, INS3, PNA1, PNA2, MAC1, and MAC2.

Role in other networks and science policy. La Poutré is member of the Scientific Directory of Schloss Dagstuhl, coordinates CWI's participation in EIT ICT Labs, and has been member of several national research strategy committees for smart energy systems as well as member of several NWO selection committees. He has been chair of the IEEE Technical Committee on Computational Finance and Economics and of the board of the Belgium-Netherlands Association for Artificial Intelligence. Pauwels was Scientific Coordinator EU-FP6 Network of Excellence MUSCLE, and coordinates CWI's participation in LIFEWATCH. Bosman has been manager of the large national project BRICKS.

Societal relevance. Many projects of SEN4 are carried out together with companies and societal institutions, like major hospitals (AMC, CZE), major transportation companies (Vos Logistics, APM Terminals), and major energy companies and institutions (KEMA, ECN, Joulz). Although the group performs fundamental research with an eye on applications, knowledge is used by several companies, projects are followed up by more applied projects (SUPPORT), and interest exists for the further implementation of (health care) software prototypes (ORTEC). In addition, more than ten publications for wide audiences have occurred, including two in the prominent Dutch newspaper NRC Handelsblad. Finally, several presentations for wide audiences have been given (on transportation logistics, health care planning, and electronic markets) and a workshop “Europhlukes Photo-IDs” has been organized at the Conference of the European Cetecean Society (ECS), transferring the results and knowledge of the group to biologists.

Viability. The research and problem areas of SEN4 are closely related to potential application domains. As adaptive and decentralized logistics is one of the major problem areas, health care logistics has been an important focus. On the other hand, new, high-potential problem domains have arisen in recent years. To this end, the group started and extended activities in smart energy systems. In 2010, we acquired funding for four PhD student positions in energy. This area strongly matches the expertise of the group and

SEN5—Distributed and Interactive Systems

Objectives and research area. Combining analytic and experimental approaches, SEN5 studies problems related to the interactive consumption of complex, interrelated content in a distributed setting. These problems include the development of active interfaces for rich social networking systems, the integration of sensor-based data from the ‘internet of things’, the modeling of high-level semantic properties of content, and the development of rendering architectures that allow application-driven, time-constrained synchronization of user interaction across wide area networks.

SEN5 is internally structured into three related sub-groups: *interactive systems*, which studies user interface models and architectures for consuming, manipulating and sharing media content; *distributed systems*, which studies lower-level network protocols for support soft real-time media delivery; and *web technologies*, which studies domain-specific languages and architectures for deploying our research in a broad network environment.

Our work on interactive systems is highly experimental in nature and is conducted with partners in the social sciences and partners in various application disciplines. The work on distributed systems focuses on a mixture of analytical and experimental techniques, often in the context of larger application systems developed jointly with international partners. The work on web technologies primarily focuses on interaction within the context of W3C.

The research conducted within this group falls under the CWI theme software as service. We also have connections to the data explosion theme.

The current application areas for our work include social media environments, educational, financial and medical domains, and coordinated immersive environments for the arts. The group has active research cooperation with VUA, UvA, and with a wide range of Dutch and European companies. We participate in a wide range of European and inter-

national projects. In order to ensure societal impact, we invest a great deal of effort in the development and distribution of open source prototypes and in standardization activities via the W3C.

Strategy. The group performs fundamental research in the area mentioned above, inspired by potential applications and societal relevance. Society is rapidly moving towards an abundance of distributed, autonomous computational resources and sensors. As a consequence, the relevance of a new paradigm of computing is increasing, in which decision making is decentralized, adaptive and highly dynamic, in order to adequately deal with changes in the environment as, e.g., detected by sensors. The group, with its focus on multi-agent and adaptive computing, is well positioned to contribute to both the fundamental problems raised by this transition, and the significant applications that will emerge from it. To this end, next to fundamental research on the techniques themselves, also more applicable projects are carried out. For the latter, SEN4 cooperates with researchers and companies with expertise in application domains like health care, electrical engineering, and economics. One of the important new focus areas of the group is the application domain of sustainable energy systems.

During the past decade, the group has been a prime contributor to leading international research on multimedia specification languages. This work was an important part of our activities during the evaluation period, although in recent years our focus has begun to shift to better understanding complex media interaction (and its impact on the networking layer) within social networking applications.

Composition. The group currently consists of two senior researchers: Bulterman and Herman (seconded to W3C), two researchers: Kuijk and Pemberton (seconded to W3C), and one tenure-track researcher: César. César has been granted tenure, effective October 2011. In addition, the group has three PhD students and two research programmers. Of these, one (Jansen) is currently working on his PhD and effectively operates as a senior researcher. SEN5 has grown steadily since its start in 2005. We expect to continue this growth with the addition of new postdocs and PhD students in the coming years, as funding permits.

Quality and scientific relevance. During the evaluation period, SEN5 achieved several important results across our three interest areas.

Interactive systems. Much of the work performed in the period focused on new interaction models and interfaces for interactive television applications. Together with our partners at Philips Research, we developed a model for integrating multi-user interaction in a networked social television environment. This system allowed concurrent non-destructive graphical annotations to be layered in a social sharing network based on group use (instead of single-person PC use). This work led to two best papers and a gold medal for the implementation prototype.

Distributed systems. A new protocol for quality-of-service support in soft real-time systems was developed. This extension to Diffserv (named Estimate-and-serve, or Estserv), provides an adaptation of deadline based scheduling mechanism to multihop networks. Estserv provides improved bandwidth utilization while limiting end-to-end delays over under-provisioned network links.

Web technologies. In 2009, the newest version of W3C's SMIL language was released. Much of the new technology, including SMIL State and SMIL Text, was developed at CWI. Bulterman's SMIL 3.0 book was the first comprehensive guide to the language and remains the most wide-used and cited SMIL book to date. CWI's open source Ambulant player became the first publicly available SMIL 3.0 software. This platform was integrated into Daisy's reference engine for books for the blind.

Key publications:

P.S. César García, D.C.A. Bulterman, D. Geerts, A.J. Jansen, H. Knoche, W. Seager. Enhancing social sharing of videos: fragment, annotate, enrich, and share. Proceedings of the ACM Multimedia Conference, 11–20, 2008. (repository id: 13693) This paper was selected as the ACM SIG Multimedia Best Paper of 2008.

P.S. César García, D.C.A. Bulterman, A.J. Jansen. Usages of the secondary screen in an interactive television environment: control, enrich, share, and transfer television content. Proceedings of European Interactive TV Conference (EU-ROITV), 168–177, 2008. (repository id: 13686) This paper received the Best Paper award at the conference.

A.J. Jansen, D.C.A. Bulterman. Enabling adaptive time-based web applications with SMIL state. Proceedings of ACM Document Engineering (DocEng), 18–27, 2008. (repository id: 13687) This paper received the Best Paper award at the conference.

D. Zucker, D.C.A. Bulterman. Open standard and open sourced SMIL for interactivity. Interactions 14, 41–46, 2007. (repository id: 12018)

R. Kernchen, P.S. César García, S. Meissner, M. Boussard, K. Moessner, C. Hesselman, I. Vaishnavi. Intelligent multimedia presentation in ubiquitous multidevice scenarios. IEEE MultiMedia, 17, 52–63, 2010. (repository id: 17609)

Output. In the period 2005–2010, a total of twenty journal papers, 77 conference papers, one PhD thesis, two books and eleven book chapters were published. We served as editors for five conference proceedings and six international standards. We produced open-source software that has been downloaded by over 89,000 users in the period.

Earning capacity. During the evaluation period, SEN5 has been quite successful in attracting external research funding. In the period, we have participated in three European IP projects, two ITEA projects and two national contract research projects. The group has generated approximately 2.3 M€ of subsidy income.

Academic reputation; combining forces. The roots of current SEN5 work lie in the area of temporal modeling and support for complex multimedia systems. Within this space, we have enjoyed a strong international reputation for the development of domain-specific temporal languages for multimedia (SMIL), for the development of analytic models for temporal synchronization in hybrid networks, for the development of innovative user interfaces to support end-user interactivity in networked systems, and for the de-

ployment of reference software to support W3C multimedia standards (Ambulant).

With the past five years, we have collaborated with a wide range of academic and industrial research centers through our European and national projects. In addition, we have established strong working relationships with several leading international universities and research groups in bilateral work. These include institutions in the USA (Georgia Tech, MIT, Univ. Illinois at Champaign-Urbana, Univ. North Carolina) and Brazil (PUC-Rio and Univ. Sao Paulo).

Our published work has been well received within our research community. We have been given three best paper awards in the periods and have delivered three keynotes at major international conferences. Our user-interface software won a Gold Medal at the 2007 ITEA-2 symposium in Paris. In the evaluation period, we organized three major symposia and conferences in the areas of networking, document engineering and interactive television, and organized three workshops on interactive/social television at major academic conferences. On a personal level, Pemberton was given the ACM CHI Lifetime Achievement award in 2009. In the same year, Bulterman accepted a professorship at VUA.

Members of the group are active in academic societies, mostly within ACM. We are active as associate editors for major academic journals within our field. We also have participated as invited experts and expert reviewers within EU activities.

Societal relevance. In addition to a strong international presence in the academic arena, we have also been active with various broader technical committees. Two members of the group are seconded to W3C as senior coordinators of activity domains. The group has provided chairpersons and co-chairs for four W3C working groups. We have worked closely with the DAISY organization, supporting models and interfaces for accessible media (with a particular focus on support for blind and dyslectic users). Our Ambulant software forms the basis for a large number of DAISY readers supporting books for the blind. The same open-source Ambulant software serves the needs of tens of thousands of users world wide in a broad range of non-commercial media applications.

Viability. SEN5 studies relevant research problems that address a range of topics across the systems/user boundary of distributed and interactive systems. We have established long-term partnerships with leading institutions in the EU, in Asia and in North/South America. While current economic pressures will make future research funding much more competitive, we are confident that we can continue to exploit our added value in systems and web technology expertise.

Strategy. Our future research strategy is to continue to invest in partnerships with leading academic, industrial and societal organizations. These organizations serve as a reservoir for new research problems and a forum for joint experimentation and evaluation. We expect to continue three research sub-groups: high-level user interfaces, lower-level systems/networks, and web technologies. A postdoc will be attracted in the systems/network area. The other two sub-groups will continue with strengthening the depth and breadth of their work. By focusing on interactions with partners, we can maintain a high degree of flexibility in the range of problems we address, and we can offer our PhD students much broader research training than could otherwise be supported locally.

MAC1—Dynamical Systems and Numerical Analysis

Objectives and research area. MAC1 conducts application-inspired mathematics research with a high level of innovation and a transdisciplinary character: modeling and computation of dynamical systems, in the form of time-dependent partial differential equations, especially those in earth and energy science. Research of MAC1 is evolving toward the interface of numerical and stochastic analysis and statistics: (1) stochastic modeling methodology to generate probabilistic subgrid scale models from data obtained from fine scale simulations or a database e.g. of instrument readings, (2) conservative numerical discretizations whose statistical accuracy ensures the correct response to slow external forcing or slowly varying parameters. These topics grew naturally from MAC1 research in 2005–2010, which focused on dynamics of time-dependent partial differential equations, coherent structures and pattern formation, numerical integration of evolution problems and geometric numerical integration.

MAC1 collaborates with application scientists. Currently the focus lies on atmosphere/ocean science and (very recently) energy science. New applications are cloud convection parameterization and integrity of electrical power networks with wind and solar production and storage. Topics of recent years include atmospheric dynamics, internal ocean waves, vegetation pattern formation, coastal dynamics, phytoplankton dynamics and Maxwell equations. Mathematical cell biology research initiated in MAC1 moved to MAC3 and eventually gave rise to MAC4 on life sciences.

National research collaborations include UL, UU, UT, and TUD, as well as the meteorological institute KNMI and the oceanographic institute NIOZ. International collaborations include Courant Institute, Potsdam, Edinburgh, Boston and Michigan State Universities, TU Darmstadt, INRIA Sophia Antipolis and the British Antarctic Survey.

Composition. MAC1 leaders were Doelman (2005–2006) and Frank (2007–). Senior staff included Blom, Crommelin, Sommeijer, Temme, and Verwer. Staff changes during the evaluation period were due to retirements: Temme (2005) and Verwer (2011); moves: Blom (MAC3, 2006) and Doelman (UL, 2009); and one death: Sommeijer (2009). Crommelin joined MAC1 in 2006 on tenure track, funded by NDNS+, and received tenure in 2009. Currently only Frank and Crommelin remain.

MAC1 staff served as promotor or co-promotor on a total of fifteen PhD degrees in the period 2005–2010. Six PhD students spent at least half of their time in MAC1. Current PhD students number seven.

Quality and scientific relevance. *Research highlights:* We constructed a new stochastic parameterization method for unresolved (e.g. subgrid scale) processes in numerical models. The approach is data driven and does not require scale separation of resolved and unresolved dynamics. This is a challenging problem in e.g. turbulence modeling and climate science.

We investigated statistical bias arising from (lack of) conservation properties of numerical discretizations for Hamiltonian partial differential equations, in particular 2D ideal fluids. Equilibrium statistical theories we developed for a number of discretizations and these were contrasted with continuum theories. An approach for correcting the dynamics for statistical errors was proposed.

We developed a renormalization group approach by which the dynamics of localized structures that interact in a semi-

strong fashion can be rigorously reduced to an explicitly determined finite dimensional system.

We designed a second-order component splitting technique that applies to any spatial finite-difference or finite-element discretization of the Maxwell equations and maintains its second temporal order for any decomposition of the space domain into implicitly and explicitly treated subdomains. This eliminates severe time step size restrictions caused by excessive, geometrically induced local grid refinement.

Numerical models developed by MAC1 researchers revealed the important result that reduced mixing generates sustained fluctuations in oceanic deep chlorophyll maxima (dcm). This result is counterintuitive to the general belief that dcm's are stable features only tracking seasonal changes in light and nutrient conditions. Sustained fluctuations enhance variability in primary oceanic food production and in carbon export into the ocean interior (Nature, 2006).

Additional highlights: Knighthood Temme 2005. *Appointments* of Verwer CWI Fellow 2007, Planqué assistant professor VUA 2007, Crommelin tenure 2009, Doelman Director of Lorentz Center 2009, Zagaris assistant professor UT 2009, Frank full professor UvA 2010. *Launches* of national mathematics cluster NDNS+ (Nonlinear Dynamics of Natural Systems), co-initiated by Doelman, 2005, and NISB (Netherlands Institute for Systems Biology) co-initiated by Blom 2007. *Nature* publication of Pham Thi (439, pp. 322–325, 2006). *Veni* grant for Zagaris 2006. *National mathematics policy* documents chaired by Doelman: Mathematics Research Strategy and Master Plan for Mathematics 2008. *Stieltjes Prize* best thesis 2009 for Van Heijster. *Digital Library of Mathematical Functions*, successor to the famous Handbook of Mathematical Functions, edited by Temme, among others, 2010.

Key publications:

D.T. Crommelin, E. Vanden-Eijnden. Subgrid-scale parameterization with conditional Markov chains. *Journal of the Atmospheric Sciences* 65, 2661–2675, 2008. (repository id: 12673)

A. Doelman, T.J. Kaper, K. Promislow. Nonlinear asymptotic stability of the semi-strong pulse dynamics in a regularized Gierer-Meinhardt model. *SIAM J. Math. An.* 38, 1760–1787, 2007. (repository id: 17983)

S. Dubinkina, J. Frank. Statistical relevance of vorticity conservation with the Hamiltonian particle-mesh method. *J. Comput. Phys.* 229, 2634–2648, 2010. (repository id: 17084)

S. Dubinkina, J. Frank, B. Leimkuhler. Simplified modelling of energetic interactions with a thermal bath, with application to a fluid vortex system. *SIAM Multiscale Model. Simul.*, 2010. (repository id: 17083)

J. Huisman, N.N. Pham Thi, D. Karl, B.P. Sommeijer. Reduced mixing generates oscillations and chaos in the oceanic deep chlorophyll maximum. *Nature* 439, 322–325, 2006 (repository id: 14467)

A.J. Majda, C. Franzke, A. Fischer, D.T. Crommelin. Distinct metastable atmospheric regimes despite nearly Gaussian statistics: A paradigm model. *Proceedings of the National Academy of Sciences of the United States of America*, 8309–8314, 2006. (repository id: 15084)

J.G. Verwer. Component splitting for semi-discrete Maxwell equations. *BIT Numer. Math.*, DOI 10.1007/s10543-010-0296-y, 2010. (repository id: 17193)

Output. MAC1 researchers published 71 journal articles, amassing 314 citations to date (source: Scopus). MAC1 staff served as promotor or co-promotor for fifteen PhD degrees.

Earning capacity. MAC1 has been very successful at securing public funding at the national level. BRICKS (for which Verwer was project leader) provided substantial financing for CWI and partners at the institute level, including project funding in MAC1 (Blom, Sommeijer, Verwer). NDNS+ was initiated by Doelman and others and provided funding at CWI for two tenure-tracks, one PhD student, one postdoc, and a number of workshops.

NWO competitions: Veni (1), Dynamics of Patterns (1), Computational Life Sciences (3), Climate Variability (3), Free Competition (3). UvA and CWI directly funded two PhD students, the latter in the Computational Energy Systems project.

Academic reputation. *Invitations for major lectures:* Crommelin: IPAM (Los Angeles); Doelman: AIM (Palo Alto), BIRS (Banff), Institut Henri Poincaré (Paris), MSRI (Berkeley), Oberwolfach; Frank: NUMDIFF 2006 (Halle, DE), Oberwolfach, IPAM, Newton Institute (Cambridge); Verwer: NUMDIFF 2009, Oberwolfach.

Conference organization: Lorentz Center workshops (3): Geometric and multiscale methods in geophysical fluid dynamics 2006, Numerical modeling of complex dynamical systems 2008, Mathematical challenges in climate science 2009; Seminar NUMDIFF Numerical Solution of Differential and Differential-Algebraic Equations, Halle, DE 2006 and 2009; Dutch-Flemish Woudschoten Conference on Numerical Analysis 2009; 72nd European Study Group Mathematics with Industry, 2010; Program committees: Dynamic Days Europe 2008, Delft (Crommelin), SIAM Conference on Applications of Dynamical Systems 2007 (Doeleman), SciCADE 2011, Toronto (Verwer).

Editorships: Doelman: *Physica D* (Editor-in-chief), *J. Comput. Sci.*; Frank: *SIAM J. Sci. Comput.*; Sommeijer: *J. Comput. and Appl. Math.*; Temme: *Z. Angew. Math. Phys.*, *Math. Comp.*, *Digital Library of Mathematical Functions*; Verwer: *ACM Trans. Math. Software*, *Adv. Numer. Math.*, *Appl. Numer. Math.*, plus three special issues.

Combining forces. *Professorships:* Doelman: UvA and UL; Frank: UvA; Verwer: UvA (the fifteen PhD students promoted by MAC1 staff generated an estimated 1.5 M€ in promotion revenues for the universities). *Teaching:* Frank: UvA 2005–; Doelman: UvA 2005–2009, UL 2010–, Verwer: summer schools Univ. Magdeburg 2005 and Univ. Valladolid 2007.

Memberships and organizational activities: Frank: Board member of NDNS+, Lorentz Center Computational Science program, and NWO Complexity Program; Doelman: Director of the Lorentz Center, Chair ACW-OOW Strategy Committee for Mathematics, Vice-chair SIAM Activity Group on Dy-

namical Systems, memberships: KNAW Council of Mathematics, VSNU Mathematics Council, board member NDNS+, NWO programs Dynamics of patterns, Climate variability, Complexity; numerous hiring committees for full professorships; Verwer: Chair Dutch-Flemish Research Community on Scientific Computing (2006–), Project leader BRICKS (2004–2009), KNAW committee Biomathematics (2006–2008), Member Advisory Board Center for Mathematics, Univ. Coimbra, Portugal, Chair external evaluation group for Erasmus Mundus masters program, numerous hiring committees.

MAC1 hosted about twenty international visitors.

Societal relevance. The degree, causes and consequences of climate change are issues of great public concern. Mathematics provides methods to treat complexity and reduce and quantify uncertainty. MAC1 research improves convection parameterizations for climate models, a widely acknowledged source of uncertainty. Structure-preserving discretizations ensure that reliable statistics can be obtained from simulations. New research in energy science is also highly relevant for society. Meeting the growing demand both locally and globally using clean sources is a hard challenge for the future. MAC1 research provides tools to deal with stochastic and multiscale supply and demand.

Viability. MAC1 has undergone significant change during the review period. Moves of Blom and Doelman, the death of Sommeijer and retirements of Temme and Verwer have left a significantly smaller group. However, we are optimistic and see it as a sign of strength and viability that MAC1 has rejuvenated and refocused itself despite the loss of five senior staff members over 2005–2010. The current staff is well aligned scientifically, with a more precisely defined focus. The new team is dynamic, young and ambitious, with a vision oriented towards the future. Internationally we are strongly positioned. The research focus has shifted towards computational and stochastic methods in earth/climate and energy sciences, and away from nonlinear PDE analysis, life sciences, and the more traditional numerical analysis for evolutionary differential equations. As of 1 January 2011, MAC1 is named *Computational and Stochastic Dynamics*.

Strategy. MAC1 will expand its research in stochastic modeling and computational science. Applications in geosciences and energy are expected to grow in priority for the coming years, and MAC1's alignment with these areas will provide good funding opportunities. Both Frank and Crommelin are eligible for ERC Starting Grants and NWO Vidi and Vici grants; success along any of these routes will strengthen the group substantially. MAC1 will also be alert for opportunities in the form of collaborative programs at either the national or EU level. If NDNS+ is funded anew, we will press for a tenure track hire to strengthen the group. We will maintain the energy and dynamics in the group by encouraging long-term visitors.

MAC2—Scientific Computing and Control Theory

Objectives and research area. *Scientific computing* relates to the robust and efficient numerical solution of mathematical equations on state-of-the-art hardware. Advanced discretization and solution methods are developed to handle a next generation of applied problems. The emphasis has been on problems in electrical engineering, ship hydrodynamics, and is currently on computational energy systems, with a focus on nonlinear partial differential equations (PDEs), optimization of designs with PDE constraints, as well as on economic decision-making and financial engi-

neering. This latter topic is at the intersection of numerics and stochastics. Here, the treatment of integral equations by spectral methods is of particular interest.

Computerized tomography has become an active research topic with the recent arrival of Batenburg. The mathematics of the related inverse problems is an area of active interest. Also working relations with the computer science groups within CWI have been established.

Control and system theory is primarily motivated by control problems from engineering and biology (mechanical and manufacturing systems, communication and biochemical reaction networks). Research focuses on fundamental control and realization problems for hybrid systems, discrete-event systems, rational positive systems, and nonlinear stochastic systems. In addition, research has been done on computational topology for dynamical and hybrid systems. Common research with the scientific computing group is on a mathematical formulation of the optimal control of dike height to balance the expected cost of flooding and dike increases.

The group maintains excellent connections to the three TU's in the Netherlands, as well as to UL, Univ. Antwerp and VUA. At the national level there are tight connections with several national research institutes: Netherlands Bureau for Economic Policy Analysis (CPB), Deltares, Energy Research Centre of the Netherlands (ECN), FOM Institute for Plasma Physics, Nuclear Research Group (NRG), as well as with the Stieltjes Institute, the J.M. Burgerscentrum Research School for Fluid Mechanics, and the Dutch Institute of Systems and Control. At an international level, there are contacts and active cooperations with top groups at ETH Zurich, Oxford Univ., INRIA, Fraunhofer SCAI, Univ. Michigan and Univ. California at Berkeley, among others. MAC2 group members are active in ECCOMAS (European Community on Computational Methods in Applied Sciences). In the EU project led by Van Schuppen, twelve European research groups participate.

Composition. Several personnel changes occurred in the evaluation period. Hemker retired in 2006. Oosterlee started in 2007 and was appointed leader per 1 January 2010, when Koren, group leader until then, became cluster leader. Collins left the group after his NWO Vidi grant period was finished in 2010. Also in 2010 scientific programmer Nool moved to MAC3 and Batenburg joined on a tenure track position. At present, MAC2 has four senior researchers, all part-time full professors at universities: Batenburg (Univ. Antwerp), B. Koren (UL), C.W. Oosterlee (TUD), and Van Schuppen (TUD). By the end of 2010, we have ten PhD students. In the evaluation period eleven PhD students graduated with MAC2 supervisors, and nine postdocs worked in MAC2.

Quality and scientific relevance. Major research achievements:

3D imaging at atomic resolution: Obtaining 3D images of nano-materials at atomic resolution has been a longstanding goal in electron microscopy. Discrete tomography algorithms have been developed at CWI that allow for computing such images from a small set of two-dimensional projections, recorded with an electron microscope. By combining state-of-the-art microscopy with advanced statistical models and discrete tomography, a team of researchers from CWI, Univ. Antwerp and ETH Zurich has succeeded in creating the first atomic resolution 3D reconstruction of a complex nanocrystal. This work has been accepted for publication in *Nature* (Batenburg).

Computability: One of the major difficulties in the mathematical analysis of dynamic systems is the handling of uncertainty or noise. In a wide range of application domains, one would ideally like to be sure that the system behaves as expected given a detailed model with absolute bounds on the degree of uncertainty. The first efficient general-purpose and rigorous numerical method was developed for the solution of nonlinear systems with nondeterministic noise in continuous time. This method should allow for

more reliable and trustworthy analysis of safety-critical systems than possible with traditional techniques (Collins, Zivanovic).

Manifold mapping for optimization: A highly efficient numerical method was developed for shape-optimization problems. The method makes elegant use of the defect-correction principle. It gave promising results for the shape-optimization of coils and magnets from electrical-mechanical devices (Hemker, Echeverria).

Multigrid and turbulence: A likewise efficient multigrid solution algorithm was developed to compute turbulent water flow with free-surface waves. The method, the fastest in the world, is of great importance to ship and off-shore building industries. The work received the ECCOMAS Award for the best PhD thesis in CFD in 2007 (Koren, Wackers).

Computational finance: A novel numerical method for pricing a variety of financial derivatives, called the COS method and based on Fourier cosine expansions, has been developed. This method is currently one of the fastest computational methods for pricing European options, under general Lévy processes for the asset price dynamics. The method is being used within the financial calibration framework of several national and international financial institutions, and by financial and insurance SMEs in the Netherlands (Oosterlee, Fang).

Control: Coordination control of distributed systems as developed by CWI in the C4C EU Project will be demonstrated for several small underwater vehicles at a review meeting in the harbor of Porto, Portugal, scheduled for July 2011. Structural identifiability conditions of polynomial and of rational systems based on realization theory will be useful for system identification of biochemical reaction networks used in systems biology (Van Schuppen).

Key publications:

F. Fang, C.W. Oosterlee. A novel pricing method for European options based on Fourier-cosine series expansions. *SIAM Journal on Scientific Computing* 31, 826–848, 2008. (repository id: 13283)

J. Němcová, J.H. van Schuppen. Realization theory for rational systems; the existence of rational realizations. *SIAM Journal on Control and Optimization* 48, 2840–2856, 2009. (repository id: 14880)

J.J. Kreeft, B. Koren. A new formulation of Kapilla's five-equation model for compressible two-fluid flow, and its numerical treatment. *J. Comput. Physics* 229, 6220–6242, 2010. (repository id: 17386)

L. Sella, P. Collins. Computation of symbolic dynamics for one-dimensional maps. *J. Comput. Appl. Math.* 234, 418–436, 2010. (repository id: 17806)

A. Stolk, K.J. Batenburg. An algebraic framework for discrete tomography: revealing the structure of dependencies. *SIAM J. Discrete Math.* 24, 1056–1079, 2010. (repository id: 17490)

Output. 84 refereed journal articles; two books; eight book chapters; 94 conference proceedings, five PhD theses fully prepared at CWI.

Earning capacity. Research funding was obtained from European programs, national programs and directly from national institutes and companies. Some PhD students were partially funded by (foreign or national) universities and by CWI's NWO bonus. An interesting project by Koren, Ooster-

lee and Van Schuppen on optimal dike-height control was funded by Deltares.

Public – nationally funded projects: Deltares (two postdocs); two NWO-Vidi's; NWO-bonus CWI (one PhD student); IOP-EMVT, Senter Novem (one PhD student, one postdoc); BRICKS (one PhD student), DCSE-TUD (one PhD student); FOM (two PhD students); NWO-NCF (one scientific programmer); STW (one PhD student); NWO Free Competition (one PhD student); NWO Computational Life Sciences (one PhD student); NBIC Biorange (one postdoc).

Private – nationally funded projects: ECN (one PhD student); Rabobank (three PhD students); NRG (one PhD student); CPB (one PhD student, partly NWO-bonus CWI); ORTEC Finance (one PhD student).

Public – internationally funded projects: Erasmus Mundus (one PhD student); Marie Curie Incoming Fellowships (one postdoc); CSC cooperation with China (one PhD student); EU-FP7: C4C (one PhD student, two postdocs), DISC (two postdocs), EU-FP6: EC-MOAN (one postdoc).

Academic reputation. Prizes, awards: Batenburg: NWO-Vidi 2010. Hemker: Royal Decoration 2006. Koren: MSc student Naber awarded Best Graduate 2006 Prize, Faculty Aerospace Engineering, TUD; PhD student Jeroen Wackers awarded ECCOMAS 2008 Award for Best PhD thesis in CFD. Van Schuppen: appointed CWI Fellow as of 1 January 2011.

Edited publications: Oosterlee, Koren, Vuik, J. *Comput. Phys.*, special issue dedicated to retirement Piet Wesseling, 2007. Brandts, Koren, Verwer, *Appl. Numer. Math.*, special issue in honor of Piet Hemker, 2008. Koren, Vuik, *Adv. Comput. Methods in Science and Engin.*, *Lect. Notes Comput. Science Engin.*, Springer, 2009.

Editorial board members: Oosterlee: Assoc. editor of four journals (among which *SIAM J. Sci. Comput.*). Hemker: Assoc. editor of one journal. Koren: Assoc. editor of two journals (among which *J. Comput. Phys.*). Van Schuppen: Editor-in-chief of one journal, Assoc. Editor of Springer Book Series.

MAC2 members gave about ten major lectures at symposia and conferences in the review period. They were committee members of several national and international workshops and conferences, e.g., ECCOMAS CFD 2006 and 2010, European Multigrid Conference 2007 and 2010, Workshop Applications of Discrete Geometry and Mathematical Morphology, Istanbul 2010, Workshop Control Theory for Systems Biology, Groningen 2007.

Combining forces. Full professorships: Batenburg at Univ. Antwerp, Belgium, 2010. Koren at TUD, 2002 and UL, 2008. Oosterlee at TUD, 2007. Van Schuppen at VUA, 2000, and TUD, 2010. All four have been on numerous PhD committees within the Netherlands and abroad.

Other duties: Batenburg: vice-chair Technical Committee Intern. Association for Pattern Recognition, since 2009; co-supervision of two PhD students at UL and two PhD students at Univ. Antwerp. Hemker: vice-chairman Working Group 2.5 on Numerical Software; chair NWO evaluation committee Applied Mathematics; member Evaluation Panel

for Higher Education and Training Awards Council, Ireland. Koren: member Executive Committee DCSE-TUD until 2008; coordinator BRICKS-project Scientific Computing until 2008; member Mathematics and Computational Science Boards Lorentz Center; board member of project leaders J.M. Burgerscentrum; member Steering Committee FOM program Active Control of MHD Modes in Burning Plasmas; member Evaluation Committee NWO Free Competition Mathematics 2010. Oosterlee: scientific consultant Fraunhofer Institute SCAI, 2007–2010; member Evaluation Committee Mathematical Sciences FWO Flanders, Belgium, since 2010; member Evaluation Committee NWO Free Competition Mathematics, 2010. Van Schuppen: chair INRIA Panel of Experts Bio.A Program 2005; member visiting committee INRIA/IRISA, 2005, and Department of Business Mathematics and Informatics, North-West Univ., Potchefstroom, 2005.

Memberships and organizational activities: Batenburg, Koren and Oosterlee organized workshops at the Lorentz Center at UL. Koren and Oosterlee have been organizers of the Woudschoten Conference on Numerical Mathematics, in 2007, 2009 and 2010. Hemker: Member of Koninklijke Hollandse Maatschappij der Wetenschappen. Koren: Vice-chairman of the CFD Committee of ECCOMAS since 2008. Oosterlee: Committee member of the Summer School for Mathematics Teachers in the Netherlands and Belgium, since 2007. Van Schuppen: Participant in EU Consultations on Control, for the European Commission, since 2008.

Societal relevance. Seniors participate in various public outreach events. Several PhD students are present at companies each week, and most of the MSc students have their projects in companies. Several research projects are directly funded by industry or research institutes. Examples include the control of dike heights along the sea and rivers, option pricing methods, and new hybrid financial derivative models.

Viability. MAC2 members are involved in modern research themes and publish in renowned scientific journals. Many contacts with other research groups exist, on a national and an international level. There are also direct links with industry and governmental agencies. During the evaluation period, two new MAC2 members were appointed (Batenburg and Oosterlee). Van Schuppen will retire in October 2012. Our ambition is succession by a top talent on a tenure-track position.

Strategy. MAC2 will continue to develop efficient numerical techniques for challenging problems from science and engineering. One focus will be on applications in which stochastics and numerics play an important role. Another focus will be on numerical techniques for inverse problems and optimal design. From the application side, computational energy systems will play a central role. Computing in MAC2 will take place more and more on graphics processing units. In control and system theory, the focus in the coming years is on control of distributed systems with applications in engineering, and on system theory and system identification for systems biology and biotechnology. The potential benefits of scientific computing and control are still enormous. Simulation, design and control are desired for ever more realistic problems.

MAC3—Multiscale Modeling and Nonlinear Dynamics

Objectives and research area. Ebert and Hundsdorfer are staff of MAC3 since 2002. Ebert has a background in applied nonlinear analysis and theoretical physics, Hundsdorfer in numerical mathematics. Through joining expertise, hiring very good PhD students and postdocs, and close collaboration with plasma science at TUE, they have acquired an internationally leading role in modeling highly transient discharges; such spark-precursors occur in many fields of plasma technology as well as in lightning and in related phenomena in the geosciences. These discharges evolve on many different scales from molecular to macroscopic in a rather hierarchical manner and are approached through (combined) simulations on particle and density level as well as through analytical steps of model reduction. Ebert also contributes to planning and evaluating plasma experiments at TUE, that correspond to theory at CWI.

Hundsdorfer also investigates fundamental questions of numerical mathematics. Main topics of interest are multi-rate methods, and monotonicity and boundedness properties of time stepping schemes for differential equations.

In 2006, Blom moved from MAC1 to MAC3 to join the multi-scale modeling efforts, Bruggeman joined in 2007, first as a postdoc, later as NISB junior groupleader. They focused on life sciences and moved to the newly founded life sciences group MAC4 in 2009. Their work is covered under MAC4.

Rademacher joined MAC3 in 2007 on a tenure track position funded through the NWO mathematics cluster “Nonlinear Dynamics of Natural Systems”; he got tenure in 2009. His expertise lies in nonlinear analysis, dynamical systems and pattern formation.

Since 2010, scientific programmer Nool supports the growing computational needs of MAC3, in particular in parallelization and optimization.

Composition. MAC3 has eight past and present postdocs and currently six PhD students. Another postdoc and four PhD students are to be hired.

Quality and scientific relevance. As stated above, Ebert and Hundsdorfer have joined forces and succeeded in establishing world leading theory and simulations for transient discharges in lightning and plasma technology. Highlights are 3D simulations of interacting streamer discharges with comoving adaptive meshes, dynamic spatial coupling of Monte Carlo particle models with density models to understand particle accelerations in streamers, derivation and solution of moving boundary models for streamer ionization fronts, and simulations of halo and sprite discharges high above thunderclouds. In 2005–2010, the group has published 51 journal articles and 19 articles in refereed proceedings on related subjects. There is also broad media coverage, in particular, of lightning research, see <http://homepages.cwi.nl/~ebert/PublPubl.html>.

Key publications:

A. Luque, U.M. Ebert, W. Hundsdorfer. Interaction of streamers in air and other oxygen-nitrogen mixtures. *Physical Review Letters* 101, Art. nr. 075005, 2008. (repository id: 12681)

C. Li, U.M. Ebert, W. Hundsdorfer. 3D hybrid computations for streamer discharges and production of runaway electrons. *Journal of Physics D: Applied Physics* 42, Art. nr. 202003, 2009. (repository id: 14730)

U.M. Ebert, B.J. Meulenbroek, L. Schäfer. Convective stabilization of a Laplacian moving boundary problem with kinetic undercooling. *SIAM Journal on Applied Mathematics* 68, 292–310, 2007. (repository id: 11792)

A. Luque, U.M. Ebert. Emergence of sprite streamers from screening-ionization waves in the lower ionosphere. *Nature Geoscience* 2, 757–760, 2009. (repository id: 14729)

W. Hundsdorfer, S.J. Ruuth. IMEX extensions of linear multi-step methods with general monotonicity. *Journal of Computational Physics* 225, 2016–2042, 2007 (repository id: 12118)

W. Hundsdorfer, A. Mozartova, M.N. Spijker. Stepsize conditions for boundedness in numerical initial value problems. *SIAM Journal on Numerical Analysis* 47, 3797–3819, 2009. (repository id: 14979)

J.D.M. Rademacher, A. Scheel, B. Sandstede. Computing absolute and essential spectra using continuation. *Physica D, Nonlinear phenomena* 229, 166–183, 2007. (repository id: 11559)

J.D.M. Rademacher. Lyapunov-Schmidt reduction for unfolding heteroclinic networks of equilibria and periodic orbits with tangencies. *Journal of Differential Equations* 249, 305–348, 2010. (repository id: 16906)

Output. 125 publications. Seven PhD theses, including two that were prepared in MAC3 and completed in MAC4

Earning capacity. Multiscale plasma modeling has become the main activity of the group. During the evaluation period, the group holds a significant and growing number of major grants with at least one PhD position at CWI, eleven of them are in the field of multiscale plasma modeling. (Some PhD positions were converted into postdoc positions.) The plasma modeling grants are in BSIK-project BRICKS, in FOM/EW programs “Computational science” and “Dynamics of patterns”, in STW’s Open Technologie Programma, in IOP-program “Electromagnetische Vermogenstechnologie”, and in STW-program “Multiscale Simulation Tools”; three projects were granted within STW-program “Building on transient plasmas”, and one PhD position is in the FOM program “Active Control of Magneto-hydrodynamic modes in Burning Plasmas”. An NWO valorization grant will support a programmer to make developed codes better available. More applications are pending.

Funding for two PhD students in basic numerical research came from two projects in NWO’s Free Competition, and a new project (2011-2015) on a KAUST grant was just funded. Rademacher was supported by the math cluster NDNS (see above), and recently got a project together with Doelman (now UL) in NWO’s Complexity program. The strength of the group lies in combining basic research in applied and numerical mathematics and theoretical physics with applications.

Academic reputation. *Major lectures:* In 2005–2010, Ebert gave three plenary lectures and fourteen invited lectures at international conferences and workshops. Hundsdorfer gave one plenary lecture and twelve invited lectures, Rademacher gave fourteen, and PhD students and postdocs gave nine invited conference lectures. *Editorships:* Hundsdorfer is editor of *Applied Numerical Mathematics*. Ebert was guest editor of a cluster issue on “Streamers, Sprites and Lightning” in *J. Phys. D* in 2008 and acts as co-guest editor for a special issue on plasma modeling in *J. Comput. Phys.* edited by Koren (MAC2). *Conference organization:* Ebert was main

organizer of four international workshops in NL and co-organizer of two international conferences. Bruggeman and Blom organized an international workshop in 2007, and Hundsdoerfer and Blom co-organized another one in 2008.

Combining forces. *Professorships, memberships:* Ebert is part-time professor at TUE since 2002, Hundsdoerfer at RUN since 2009. Ebert is member of De Koninklijke Hollandsche Maatschappij der Wetenschappen since 2006, and steering group member of the research school "Center for Plasma Physics and Radiation Technology" (CPS), of the STW program "Building of Transient Plasmas", and of the FOM program "Active Control of Magneto-hydrodynamic Modes in Burning Plasmas".

Nine former PhD students and postdocs of the group are presently developing academic careers.

Most plasma projects are with partners at TUE. TUE has an internationally leading concentration of applied plasma physics and technology and related electrical engineering, historically due to the neighborhood of Philips. The FOM Institute for Plasma Physics will be broadened to an institute on fundamental energy research, and move to the campus of TUE within the next four years. MAC3 has developed into a strong partner of this growing plasma center, offering expertise in numerical and applied analysis and in multiscale plasma modeling that is not available in Eindhoven.

While most technological collaboration is with TUE and Dutch industry, the group has also become well embedded into an international network on atmospheric discharges, through project collaborations with Denmark, Spain, Israel and Alaska, through organization of three international workshops in 2005, 2007 and 2010 in the Netherlands and through participation in three European networks (EU-COST, GDRE, ESF). The frequent media coverage of the group is almost completely for lightning related phenomena.

Societal relevance. Electrical discharges and reactive plasmas have a large technological relevance in the fields of

MAC4—Life Sciences

Objectives and research area. In the life sciences, conventional wet lab experimentation is being increasingly accompanied by mathematical and computational techniques in order to deal with the overwhelming complexity of living systems. New technologies lead to massive amounts of data as well as to novel and challenging research questions. More and more biological processes can be analyzed, modeled and simulated with the help of mathematics and computational science.

MAC4, CWI's life sciences group, started formally on 1 January 2009, with researchers that had previously been affiliated to MAS1, MAS3 and PNA1 (Blom, Bruggeman, Stougie, and their postdoctoral and PhD students) and two newly hired researchers on tenure track (Merks and Klau). The foundation of the new group was celebrated with a workshop in June 2009 with Turing Award recipient Richard M. Karp as an invited speaker.

Current research topics and PIs of the group are algorithmic computational biology (Klau), biomodeling and biosystems analysis (Merks), combinatorial problems in biology (Stougie), neuroinformatics (Bohte), scientific computing for systems biology (Blom), systems biology of regulatory molecular networks (Bruggeman), and statistical modeling and comparative genomics (Schönhuth).

energy, environment and health, as well as in the atmospheric and planetary sciences. Examples are energy production (fusion reactors, plasma deposition in the production of solar panels, plasma aided combustion), energy transport (high voltage technology and switches), energy efficient technology (welding, energy saving lamps, water cleaning, biofuel processing, plasma assisted aviation), environment (air cleaning), health (plasma disinfection, plasma medicine), atmospheric and planetary science (lightning, lightning protection of modern light-weight and nano-technology, green house gases produced by lightning, transient luminous events and terrestrial gamma-ray flashes on earth and on other planets). All topics require the theory and computations developed by the group, except for fusion reactors that presently are mainly developed in MAC2. With our present projects, the range of applications is far from exhausted.

Viability. The theory of reactive nonequilibrium plasmas in technology and nature is presently being developed by only few groups worldwide, despite its large relevance in technology and nature. Developing this theory at an institute for applied math has major advantages of support in numerical mathematics, computational science, applied analysis and model reduction. Together with excellent experimental partners in physics and electrical engineering at TUE, we have reached an internationally leading position in this field. This is underscored by the growing number of grants.

Strategy. To maintain the leading role in reactive and pattern forming plasmas, and to further extend the range of applications as well as the range of fundamental methods. To continue the joined development of applied analysis and model reduction, of large multi-scale simulation tools, and of the evaluation and application to discharges in nature and technology. To develop a well-documented open source modeling platform for transient reactive plasmas and their interaction with outer fields or electric circuits. To maintain the current role in understanding lightning and related atmospheric phenomena.

The group combines expertise in a variety of mathematical, computational and application-oriented disciplines such as scientific computing, discrete and combinatorial algorithms, modeling, computational and theoretical biology, statistical learning and information theory. Its interdisciplinary composition as well as its orientation by application field rather than mathematical discipline makes it a special group at CWI. In the Netherlands, the group is unique in its effort to develop fundamental contributions to the life sciences by combining a large number of mathematical and computational disciplines.

MAC4 maintains strong links to cooperation partners from biology and biomedicine, including the Dutch Cancer Institute (NKI), the Free University Medical Center (VUMC) Amsterdam, the Academic Medical Centre (AMC) Amsterdam, and the KNAW institutes Netherlands Institute for Neuroscience (NIN) and Fungal Biodiversity Centre (CBS). CWI is also one of the three partners within the Netherlands Institute for Systems Biology (NISB), takes part in the Amsterdam Center for Multiscale Modeling (ACCM) and hosts the modeling core group of the Netherlands Consortium for Systems Biology (NCSB). Internationally, the group has cooperations with top institutions such as INRIA and EMBL/CRG Barcelona.

Composition. MAC4 currently has four senior researchers, two researchers on tenure track, three postdocs and seven PhD students. Within CWI, cooperation exists with MAC2 and PNA6. MAC4 is currently funded by an internal bonus from NWO and, to a large part, by external funding from NCSB and NISB. Further external grants come from NWO's Computational Life Sciences program, BRICKS, NWO's Free Competition, NWO's Vernieuwingsimpuls, and the Deutsche Forschungsgemeinschaft.

Quality and scientific relevance. Research highlights of MAC4 are the following.

Phylogenetic networks. These networks are a generalization of evolutionary trees to incorporate reticulate evolutionary events, i.e., events whereby, rather than diverging, two lineages merge. Recombination, horizontal gene transfer and hybridization are examples of such events. Associated optimization problems are challenging, and MAC4 researchers have made significant progress on tractably constructing such networks (from conflicting gene trees, for example) without over-hypothesizing the number of reticulation events required to explain the conflicting phylogenetic signals.

Stochastic survival processes in the cell. The understanding of stochastic survival strategies and processes is a timely problem in biology where the mathematics of stochastic processes, like statistical physics and probability theory, can play a leading role. An article in PNAS (see below) shows how two mechanisms for mRNA synthesis can lead to transcription bursts and offer quantitative measures for the analysis bursty transcription behavior.

Neural code. The neural code – the interpretation of the spikes that biological neurons communicate with – is one of the great open scientific questions. A recent article (see below) puts forward the notion that the spikes themselves can be interpreted as representing the fractional differentiation of the computed signal: individual spikes then carry information not just about the history of the signal, but—via the non-local nature of fraction differentiation—they would also carry information about the expected future of the signal. This neural coding interpretation ties together seemingly incongruent observations of real neural behavior, and promises a rich foundation for neural signal processing.

Cancer networks. Cancer is caused by a combination of multiple genetic and environmental factors and is more and more studied as a disease of malfunctioning biological networks. An award-winning ISMB paper (see below) describes how a combination of techniques from combinatorial optimization and statistics can be used to identify novel functional modules in terms of certain subnetworks. Better understanding the mechanisms of disease will make it possible to identify new drug targets.

NCSB. The Netherlands Consortium for Systems Biology implements systems biology as a powerful scientific approach in three major Dutch biological research areas: biomedical research, agricultural biotechnology, and microbial biotechnology. CWI hosts the core modeling group of NCSB, which develops innovative computational models of a range of biological systems studied by experimental partners within NCSB focusing on multicellular systems. Topics include plant development, gut microbiota, and blood vessel growth. Merks received an NWO Vidi grant in 2010 to further develop models of blood vessel growth, focusing in particular on cellular coordination via the extracellular matrix.

Key publications:

L.J.J. van Iersel, S.M. Kelk, R. Rupp, D.H. Huson. Phylogenetic networks do not need to be complex: using fewer reticulations to represent conflicting clusters. *Bioinformatics* 26, i124–i131, 2010. (repository id: 17982).

M. Dobrzynski, F.J. Bruggeman. Elongation dynamics shape bursty transcription and translation. *Proceedings of the National Academy of Sciences of the USA* 106, 2583–2588, 2009. (repository id: 13920)

S.M. Bohte, J.O. Rombouts. Fractionally predictive spiking neurons. *Advances in Neural Information Processing (NIPS)*, 2010. (repository id: 17237)

J. Blom, M. Mandjes. Traffic generated by a semi-Markov additive process. *Probability in the Engineering and Informational Sciences* 25, 2011. (repository id: 17545)

M. Dittrich, G.W. Klau, A. Rosenwald, T. Dandekar, et al. Identifying functional modules in protein-protein interaction networks: an integrated exact approach. *Bioinformatics* 24, 223–231, 2008. (repository id: 12699)

R.M.H. Merks, E.D. Perryn, A. Shirinifard, J.A. Glazier. Contact-inhibited chemotactic mobility in de novo and sprouting blood vessel growth. *PLoS Computational Biology* 4, e1000163, 2008. (repository id: 12648)

Output. Since the start of the life sciences group in 2009, its group members have published 47 journal and 17 proceedings articles. Two PhD theses were defended.

Earning capacity. The group has managed to secure a number of national and international grants: NWO Vidi (Merks), NWO Computational Life Sciences program (one postdoc), NWO Free Competition (one PhD student), Deutsche Forschungsgemeinschaft (one PhD student). Two PhD students are co-funded by the Dutch Cancer Institute (NKI) and VUA, respectively. Merks has a Marie Curie European reintegration grant. Furthermore, Stougie and Klau are members of an INRIA Associated Team.

Academic reputation. Two Lorentz workshops and a number of other workshops have been organized by group members. Several group members were program committee members of important conferences. Klau was scientific co-editor of an ERCIM News issue on computational biology and was jury member for the French ANR bioinformatics program. Bruggeman and Bohte have been involved in NWO committees. Bohte was part of the Belgium IWT Expert Panel Earth Sciences.

Combining forces. Researchers in the group are well linked with academic institutions and participate in national research schools. Stougie: full professor at VUA; Bruggeman: affiliated with VUA and UvA; Blom, Merks, Bohte: guest lectureships; Klau: habilitation at FU Berlin.

Societal relevance. MAC4 provides fundamental mathematical and computational contributions to biology, biomedicine and biotechnology in close cooperation with experimental and theoretical life scientists. Furthermore, the group develops and maintains a number of software tools that are freely available for the research community. Among these are CASS (construction of phylogenetic networks), the Cell Behavior Ontology (describing cell behavior), VirtualLeaf (support for modeling plant tissue growth), the Tissue Simulation Toolkit (tissue patterning and development), BioNet (a Bioconductor package for integrated, functional analysis of biological networks), and planet lisa (software tools for solving combinatorial problems in biology).

Viability. MAC4 is a fast growing interdisciplinary group. Two new PI's, Bohte and Schönhuth, joined in 2010, complementing the groups research portfolio with the more computer science-based research directions neuroinformatics and information theory. The challenge is to use the heterogeneity of backgrounds within the group for cross-fertilization and to keep the focus on fundamental mathematical and computational contributions while pursuing more cooperations with experimental groups.

INS1—Database Architectures

Objectives and research area. The database architecture group INS1 fulfills a recognized leading role in system-oriented database research both nationally and internationally. The work carried out is focused on bridging the gap between database architectures and demanding application areas, such as (structured) information retrieval and scientific databases. A use-inspired approach is considered pivotal to make progress in both fields.

The research line on structured (multimedia) information retrieval (De Vries, moved to INS2 per 1 January 2009) aims at developing database technology for both application developers and researchers working on content analysis techniques and search engines. The computational framework requires integration of large sparse arrays in a set-oriented database architecture. At the core of such a system, a sound and flexible probabilistic model is called for to steer the retrieval process, integrated with query optimizers and kernel functionality.

The advanced database architecture research lines investigate a broad range of novel scalable data management techniques in the context of high-performance columnar database systems. The requirements for scalable and high-performance data management from various research projects, among others in close cooperation with astronomers (SkyServer, LOFAR) and other scientists, led to pioneering and successful research in self-organizing distributed databases (Armada), exploitation of fast networks for database processing (Data Cyclotron), flexible query caching (Recycler), adaptive indexing (database cracking), and data stream management (DataCell). Research is conducted both in the context of large national projects like MultimediaN and BRICKS, and internationally through internships (IBM Almaden, IBM Watson, Microsoft Research, HP Labs), participation in European projects and international cooperation.

Within the Pathfinder project (Konstanz Univ., Technical Univ. Munich, Tuebingen Univ.), a full-fledged XML/XQuery DBMS has been built based on the MonetDB database kernel. It supports XQuery updates, semantically correct and efficient distributed XQuery processing (XRPC), text search (PF/Tijah), and run-time query optimization (ROX) to cope with data correlations. The system is widely used in research and education on XQuery worldwide.

The MonetDB/X100 project produced a number of highly cited papers on vectorized execution, compression and cooperative scans, and also led to a business intelligence database spin-off (Ingres VectorWise) which leads the state of the art in various ways, and continues to produce top-class scientific results and international cooperations (e.g. through the HadoopDB project from Yale Univ.).

All research is supported by activities geared at bridging the technology gap in house, using MonetDB as our experimentation platform. The system is used as a vehicle for instant

Strategy. The goal of MAC4 is to continue and extend its excellent fundamental mathematical and computational research for the life sciences, and thus make CWI an internationally renowned top go-to address in this area. To achieve this goal, the group will continue to organize interdisciplinary workshops and to acquire external, increasingly international, funding. The focus will be simultaneously on extending the group's international network as well as on increased internal collaboration with other mathematical core groups at CWI.

dissemination of our research results into an open-source product. MonetDB is widely distributed to provide others with a sound and modern database education and experimentation platform, but also to collect user experiences about the choices made. Significant efforts by all members of the group ensure a high quality product and a clear focus on an experimentation platform.

Composition. The group's permanent staff consists of senior researchers Kersten (group leader, CWI Fellow as of 1 January 2011), Boncz, Manegold (group leader as of 1 January 2011), Nes (0.6 fte manager ITF as of 1 January 2010), and scientific programmer Mullender. In the evaluation period, six PhD students completed their thesis in INS1. One of these, Idreos, continues as tenure tracker (NWO bonus) since then. Two others remained in INS1 as postdoc. One PhD student suspended his PhD track in 2008 as co-founder of VectorWise B.V. INS1 currently has one other postdoc and four PhD students. Per 1 January 2009, the "information access" part of INS1, consisting of senior researcher De Vries, two postdocs and one PhD student, moved to INS2.

Quality and scientific relevance. Our pioneering hardware-aware and column-store database research in the context of MonetDB has received several best paper awards, e.g., VLDB 2009 10-year best paper award and SIGMOD 2009 best paper award (runner-up). Our research on database cracking and recycling, and their integration in MonetDB, are widely recognized as successful pioneering work on adaptive indexing and fine-grained intermediate result caching. Open-source MonetDB/XQuery is one of the fastest and most scalable XML/XQuery DBMSs. MonetDB makes leading column-store database technology available in a completely functional open-source DBMS.

Key publications:

P.A. Boncz, M.L. Kersten, S. Manegold. Breaking the memory wall in MonetDB. *Communications of the ACM* 51, 77–85, 2008. (repository id: 13805)

P. Svensson, P.A. Boncz, M. Ivanova, M.L. Kersten, N.J. Nes, D. Rotem. Emerging database systems in support of scientific data. In: *Scientific Data Management: Challenges, Technology, and Deployment*, Chapman & Hall/CRC, 235–277, 2008. (repository id: 14982)

M. Ivanova, M.L. Kersten, N.J. Nes, R.A. Goncalves. An architecture for recycling intermediates in a column-store. *ACM Transactions on Database Systems* 35, 2010. (repository id: 16695)

R. Cornacchia, S. Héman, M. Zukowski, A.P. de Vries, P.A. Boncz. Flexible and efficient IR using array databases. *VLDB Journal* 17, 151–168, 2008. (repository id: 13817)

Y. Zhang, N. Tang, P.A. Boncz. Projective distribution of XQuery with updates. *IEEE Transactions on Knowledge and*

Data Engineering 22, 1059–1076, 2010. (repository id: 16682)

Output. Over 170 publications. Six PhDs.

Earning capacity. The group secured funding for research projects from both national and international sources, among others within the projects MultimediaN (Bsik), BRICKS (Bsik), GeinfoNed (Bsik), FOCUS (NWO), VITALIS (EU), XIRAF (NL), Emilie (EU), LOD2 (EU), PlanetData (EU), Teleios (EU), as well as several NWO projects (e.g. DataCell, Graph Querying). Funding was received for dissemination from MultimediaN, NWO, SenterNovem and international cooperation with an eScience program in the UK. The group's participation to bootstrap the spin-off companies generated an additional income of 200 k€, with an additional substantial revenue for 2011 from selling VectorWise to Ingres in December 2010. Overall, the funding is a healthy mix of science, science related and dissemination sources.

Academic reputation. Boncz, Manegold and Kersten won the VLDB 2009 10-year best paper award and gave the respective invited keynote speech. Ivanova, Kersten, Nes and Gonçalves won the SIGMOD 2009 best paper award (runner-up). Boncz won the ICT Regie Award 2006. Heman, Nes, Zukowski and Boncz won the Best Paper Award at DaMoN 2007. Zukowski, Nes and Boncz won Best Paper Award at DaMoN 2008. Kersten gave invited keynote speeches at ICDE 2008 and EDBT 2006. Boncz co-taught the VLDB summer school 2009. Boncz co-presented a tutorial on column oriented database systems at VLDB 2009.

Manegold co-presented a tutorial on performance evaluation in database research: principles and experiences at EDBT 2009 and ICDE 2008. Kersten served as co-chair of XLDB 2009, general program chair for EDBT 2009, industrial, applications and experience program co-chair for VLDB 2006, core database technology program chair for VLDB 2005, co-organizer of XLDB in 2009, and is associate editor for ACM TODS and member of the PVLDB steering board. Boncz and Manegold co-chaired DaMoN 2005 and 2006. Boncz co-chaired DaMoN 2009 and 2010 and was area chair in CIKM 2009. Manegold was demonstrations chair for EDBT 2009 and co-chaired the SIGMOD Repeatability & Workability Evaluation 2009 & 2010, the VLDB 2007 panel "Performance Evaluation and Experimental Assessment — Conscience or Course of Database Research?", and ExpDB 2007. De Vries served as general chair of SIGIR 2007 and is editorial board member of Information Retrieval. In any given year, several members of the group serve on the program committees of any of the major database venues (SIGMOD, VLDB, ICDE, EDBT). Regularly, members of the groups are invited to review submissions for any of the major database journals (TODS, TKDE, VLDB Journal).

Combining forces. Kersten is part-time full professor at UvA. De Vries has been appointed full professor at TUD. Manegold teaches a database course at UvA, and Boncz does so at VUA. All supervise Master and PhD students. The group maintains long-term productive research cooperations with, a.o., UvA (CS and astronomy), UU, UT, Univ. Tübingen, TU Ilmenau, ETH Zürich, EPF Lausanne, Queen Mary Univ. London, INRIA, Yale Univ. and HP Labs. Kersten

INS2—Interactive Information Access

Objectives and research area. The goal of the group is to study and develop models and techniques that enable effective interactive access to rich and complexly structured information sources. To achieve this goal the group deploys a mix of quantitative and qualitative research methods from

was scientific co-director of the 32 M€ MultimediaN projects, associate editor of ACM TODS, member of the steering committee for PVLDB, member of the EDBT steering group, member of the Board of Trustees of the VLDB Endowment, member of the Scientific Advisory Boards of HIIT (Helsinki, Finland), MPII (Saarbrücken, Germany) and Philips, and served on the evaluation board for several NWO and EU projects and programs. Kersten and Boncz serve on the review board of PVLDB.

Societal relevance. Distribution and use of the open-source MonetDB system has been steadily growing; exceeding 10,000 downloads per month from our site mid 2010 and google analytics showing a reach out to over 80% of the countries.

Three spin-off companies have been founded. MonetDB BV aims at disseminating our multi-modal columnar database technology. Vectorwise BV commercializes the X100 vectorized execution technology. Spinqe BV commercializes our database-supported information retrieval technology into a strategy-based search engine. A close cooperation with a Dutch SME leads to product innovation in the telecom market.

Reaching out towards the eScience challenges has been started, leading to inclusion of the MonetDB software in the LOFAR pipeline for transient analysis. The SDSS Skyserver demonstrator has been the first realization of this highly visible data intensive research science application realized outside the premises where it was originally developed. Work on dissemination has commenced through the SciLens project and international cooperative actions around XLDB and the UK funded eScience theme Data Intensive research with the eScience centre in Edinburgh and Johns Hopkins Univ.

Viability. The group's vision is to create a sound architecture for multi-modal database systems based on a columnar database kernel. The experiences and expertise gained from our leading research on high-performance and scalable data management of tree-structured XML data provides us with a head-start to generalize and extend our technology towards supporting RDF and other graph-structured data. Our in-depth knowledge of relational and columnar database technology form a solid foundation for research into efficient and scalable n-dimensional array-structured data for scientific applications and data-driven research.

Strategy. The group's strategy is inspired by the fourth paradigm, i.e., management and analysis of huge amounts of (mostly sensory) data is becoming a dominant task in scientific research in, among others, biology, astronomy, meteorology. Data-driven research requires the reconsideration of algorithms, theory and system architecture. It calls for sustained development of flexible and scalable database technology to efficiently manage and analyze the ever growing amount of digital data. In this context, ensuring seamless and low-investment integration into the existing scientific workflows is crucial to lower the acceptance threshold for introducing database technology into data-driven scientific research.

the fields of information retrieval, semantic web and human-computer interaction. Example methods include the use of user studies and benchmarks in interactive information retrieval, the mining of semantic relations in search

logs and the combination of content-based and metadata-based retrieval techniques.

The group is well positioned both nationally and internationally. The three senior members have positions at Dutch universities. De Vries is full professor of multimedia dataspace at TUD, Hardman is full professor in multimedia interaction at UvA (after her previous professorship at TUE), Van Ossenbruggen is university lecturer two days per week at VUA. In addition, all are SIKS research fellows. Van Ossenbruggen is closely involved with a number of key cultural heritage partners both nationally and internationally. De Vries, Hardman and Van Ossenbruggen have also participated in EU projects, in particular K-Space, VITALAS and Europeana, further extending their existing international networks. Van Ossenbruggen, Rutledge and Troncy have contributed extensively to W3C initiatives, including SMIL and the Semantic Web activities (Troncy co-chaired the Media Fragments Working Group).

Composition. The group has consisted of around seven members during the evaluation period, with a maximum of nine in 2006.

Quality and scientific relevance. Scientific highlights:

Gold exhibition award for Passepartout project at ITEA2 Symposium 2006, Paris.

The MultimediaN E-culture project, in which members of INS2 played key roles, won the first prize of the Semantic Web Challenge at the 5th International Semantic Web Conference held in Athens, GA, USA, 2006. The results from this were further developed into the highly influential Europeana ThoughtLab.

Hildebrand was awarded the best doctoral consortium paper at the 7th International Semantic Web Conference Karlsruhe, Germany, 2008.

Key publications:

M. Hildebrand, J. van Ossenbruggen, L. Hardman. A browser for heterogeneous semantic web repositories. *The Semantic Web—ISWC 2006*, 272–285, Springer-Verlag, 2006. (repository id: 11421)

G. Schreiber, A.K. Amin, L. Aroyo, M. van Assem, V. de Boer, L. Hardman, M. Hildebrand, J. van Ossenbruggen, B. Omelayenko, A. Tordai, J. Wielemaker, B. Wielinga. Semantic annotation and search of cultural-heritage collections. *The MultimediaN E-Culture demonstrator Web Semantics 6*, 243–249, 2008. (repository id: 13260)

R. Arndt, R. Troncy, S. Staab, L. Hardman, M. Vacura. COMM: Designing a well-founded multimedia ontology for the web. *The Semantic Web—ISWC/ASWC 2007*, Lecture notes in computer science 4825, 30–43, Springer, 2007. (repository id: 12354)

L. Hardman, Z. Obrenovic, F.-M. Nack, B. Kerhervé, K. Pierson. Canonical processes of semantically annotated media production. *Multimedia Systems 14*, 327–340, Springer, 2008. (repository id: 13655)

M. Hildebrand, J. van Ossenbruggen, L. Hardman, G. Jacobs. Supporting subject matter annotation using heterogeneous thesauri, a user study in web data reuse. *International Journal of Human-Computer Studies 67*, 888–903, Academic Press, 2009. (repository id: 13989)

S. Bocconi, F.M. Nack, L. Hardman. Automatic generation of matter-of-opinion video documentaries. *Journal of Web*

Semantics 6, 139–150, ScienceDirect, 2008. (repository id: 12383)

A.K. Amin, J. van Ossenbruggen, L. Hardman, A. van Nispen. Understanding cultural heritage experts' information seeking needs. *Proceedings of the 8th ACM/IEEE joint conference on digital libraries*, ACM, 2008. (repository id: 12381)

Output. Four PhDs. In addition Hardman and Van Ossenbruggen co-supervised PhD students at TUE and VUA, respectively.

Earning capacity. The main large projects during the evaluation period were the nationally funded MultimediaN E-Culture (Van Ossenbruggen), EU funded K-Space (Hardman) and EU funded VITALAS (De Vries) projects.

Academic reputation. Hardman attended three Dagstuhl seminars and gave a keynote at the Fourth IEEE International Conference on Semantic Computing. She was a panel member for computer science and informatics in the ERC Starting Grants, 2007 and 2009.

Conference organisation, editorships: Hardman: program co-chair of SAMT 2008, 3rd International Conference on Semantic and Digital Media Technologies; vice-president SMaRT (Semantic Multimedia Research and Technology) association; area editor for Multimedia/HCI for Elsevier Journal of Web Semantics; member of editorial board NRHM; co-edited a special issue of the Multimedia Systems Journal 2008. Van Ossenbruggen: co-organized First International Workshop on Cultural Heritage on the Semantic Web at ISWC 2007; senior PC member of ISWC 2010, International Semantic Web conference. De Vries organized TREC entity track.

Combining forces. Hardman full professor at UvA, De Vries at TUD. Previous postdocs from the group now have permanent positions at TUE, Dutch Open Univ. and Eurecom (Troncy). Hardman was daily supervisor of Nigten (PhD 2006, Univ. of the Arts, London). Hardman is one of the core players in the European "semantic multimedia" field, contributing to conference organization (SAMT 2008), building the field together with colleagues in the SMaRT association and organizing the SSMS 2010 summer school.

Societal relevance. The work of INS2 has maintained close connections with W3C, where SMIL is one of the outputs of the group, and with more recent contributions to the development of the semantic web. In particular, Van Ossenbruggen co-founded the W3C incubator group on Media Semantics, which was followed up by Troncy co-chairing the Fragments working group.

De Vries launched a spin-off company Spinque, along with two ex-CWI colleagues. In addition, contributions to the IR community have been made through the joint development of the open source text search system PFTijah.

Viability. Ground-breaking research has culminated in a number of PhD theses on constructing meaningful video sequences, semantic structures for improving user information access, and novel user interfaces across multiple information sources, providing a basis for further work in these areas.

A lack of funding in the mid-period led to a lack of new PhD students. A new project at the end of 2010, Fish4Knowledge (media and semantics), provides a base for continuing the research lines built up within K-Space and MultimediaN while we continue to attract further funds. In particular, new connections through Fish4Knowledge provide oppor-

tunities for further work in life sciences domain, e.g. through the LifeWatch initiative.

The information retrieval group of De Vries (a sub-group within INS1) was integrated with the semantic media interface group of Hardman (INS2) to form the current interactive information access group. The complementary skills and networks provide an excellent base for developing innovative research.

Hardman replaces Kersten as INS cluster leader as of January 2011, while De Vries takes over the leadership of INS2.

INS3—Visualization and 3D User Interfaces

Objectives and research area. The research goal of INS3 is to obtain a better understanding of the methodologies involved in building and evaluating interactive scientific visualization methods and systems. An important aspect is the application of these systems in real world scientific applications, particularly from the data intensive sciences. The research is organized in two tracks. The *visualization* track concerns the visual analysis of large and complex data collections, with the research focus on model driven visualization methods. The key question that drives the research is related to the definition and the extraction of data features in order to provide semantic meaningful visualizations of very large data sets. The *3D user interfaces* track concerns the application of virtual reality techniques for the design and evaluation of 3D desktop user interfaces. The research is focused on 3D interaction modeling and its experimental evaluation.

Composition. INS3 currently consists of one senior researcher, Van Liere, augmented with externally funded postdoc and PhD students. Van Liere is part-time full professor at TUE. The only other INS3 senior researcher, De Leeuw, left CWI in 2006. At present INS3 has two postdocs and one PhD student. During the evaluation period, four PhD students graduated under the supervision of Van Liere. Van Liere also was co-promotor for a PhD student at TUE.

Quality and scientific relevance. The following three highlights illustrate the multi-disciplinary approach to scientific visualization: Mulder: Development and application of the Personal Space Station, a new paradigm for near-field virtual reality desktop systems, leading to the spin-off company, PS-tech (www.ps-tech.com). Kruszynski: Visual analysis and interactive measurements of complex branching objects, that computational methods and tools have been utilized by international coral researchers. Broersen and Smit: Novel data analysis methods and applications in very high resolution mass spectrometry data.

Key publications:

M. Filatov, J. Kaandorp, M. Postma, M. Vermeij, R. Bak, R. van Liere, G. Streekstra, K. Kruszynski. A comparison between coral colonies of the genus *Madracis* and simulated forms. *Proc. of the Royal Society B (Biological Sciences)*, 2010. (repository id: 17343)

F.A. Smit, R. van Liere, B. Froehlich. A programmable display layer for virtual reality system architectures. *IEEE Transactions on Visualization and Computer Graphics (TVCG)*, 2010. (repository id: 17350)

M. Chen, D.S. Ebert, H. Hagen, R. Laramée, R. van Liere, K.L. Ma, W. Ribarsky, G. Scheuermann, D. Silver. Data, information, and knowledge in visualization. *IEEE Computer Graph-*

Strategy. Investigate innovative combinations of tools and techniques from information retrieval and semantic web communities, in conjunction with methods from human computer interaction, in order to explore the boundaries between human interaction and machine processing of data. This would continue to contribute to the data explosion theme, while at the same time developing experience in the life sciences domain. Both will contribute to competing for project funding to grow the group. The group will maintain a balance of externally funded PhD students and postdocs, with a long-term goal of graduating two to three PhD students per year (one per senior fte).

ics and Applications 29, 12–19, IEEE Computer Society Press, 2009. (repository id: 15053)

L. Klerk, A. Broersen, I. Fletcher, R. van Liere, R. Heeren. Extended data analysis strategies for high resolution imaging MS: new methods to deal with extremely large image hyperspectral datasets. *International Journal of Mass Spectrometry* 260, 222–236, 2007. (repository id: 11837)

K.J. Kruszynski, J.A. Kaandorp, R. van Liere. A computational method for quantifying morphological variation in scleractinian corals. *Coral Reefs* 24, 831–840, Springer, 2007. (repository id: 11838)

Output. Fifteen refereed journal articles; three books; 32 international conference and symposium proceedings; four PhD theses.

Earning capacity. During the evaluation period, INS3 has received funding from the following projects: NWO VIEW QUASID two PhD students; NWO VEARD one PhD student; BSIK-BRICKS one postdoc; BSIK-VL-e three PhD students; NWO-bonus of CWI one postdoc.

Academic reputation. The group has received two best paper awards: Liu: Best Paper Award, 3D user interfaces, 2010. Smit: Best Paper Award, Virtual reality software technology, 2009.

Van Liere is Associate Editor of Elsevier Journal of Computers and Graphics. He co-chaired the following conferences: Knowledge Assisted Visualization, IEEE Visualization, 2007 and 2008, EuroGraphics Virtual Environments, 2007 and 2008,

Van Liere holds a professorship at TUE since 2004, has served as first promotor for four PhD students, served in various PhD committees within the Netherlands and abroad; member of the Eurographics Association Executive Committee, Benelux region; member of the NWO VIEW program committee; member of the NWO Beoordelingscommissie Informatica (BCI) NWO-EW; coordinator BRICKS-project Scientific Computing.

Combining forces. There are strong connections with the computer graphics and visualization research groups at the TU's in the Netherlands. For example, joint NWO projects have been honored together with TUD and TUE. On the international level, there are active cooperations with Bauhaus Univ., Weimar, Swansea Univ. and Univ. North Carolina at Chapel Hill.

Societal relevance. Scientific visualization is by its nature inherently multi-disciplinary. As such, all INS3 projects have always had strong links with research institutes and departments in other disciplines. Examples include the multi-modal analysis of high-resolution image mass spectrometry data with AMOLF and quantitative measurement analysis of

coral structures with UvA. A useful metric to measure the success of these cooperations is the number of joint publications in multi-disciplinary journals. In 2007, the work on desktop virtual reality has resulted in a spin-off company PS-tech (www.ps-tech.com). One postdoc (Mulder) and one PhD student (Van Rhijn) have left INS3 to join PS-tech.

Viability. During the evaluation period, INS3 built up a leading national reputation in the area of large-scale data visualization and virtual reality. Van Liere has also been involved in advisory and steering committees for virtual reality research. It has become increasingly difficult, however, to secure funding for scientific visualization research in

national multi-disciplinary projects. In addition, the group has only one tenured senior researcher. Combined, these developments have hampered the growth potential of INS3. It has become clear that a new direction is necessary in order to obtain the required critical research mass.

Strategy. Starting on 1 January 2011, INS3 will join the software engineering group SEN1. The research will focus on problems from software visualization with emphasis on visual software analysis. We are confident that the expertise of INS3 in interactive visualization will contribute to new approaches in visual software analysis, which will also lead to new funding opportunities.

Appendix

This appendix contains the following tables, based on the templates given in KNAW's SEP 2009–2015:

- Research staff in fte (SEP table 5.2)
- Main categories of research output from researchers on CWI payroll (SEP table 5.3)
- Main categories of research output from researchers hosted by CWI (SEP table 5.3)
- Funding (SEP table 5.4)
- Standard PhD candidates (SEP table 5.5)
- Contract PhD candidates (SEP table 5.6)

Research staff in fte (SEP table 5.2)

Institute	2005	2006	2007	2008	2009	2010
Tenured staff	49.0	47.3	44.3	43.3	42.4	41.7
Tenured scientific programmers	9.0	9.2	6.9	6.7	6.7	6.7
Non-tenured staff	33.6	43.3	46.2	44.6	43.2	45.2
PhD candidates	58.0	63.8	62.2	57.4	53.6	53.1
Total research staff	149.6	163.5	159.6	152.0	145.9	146.6
Support staff	49.7	46.6	45.0	47.4	45.2	44.9
Visiting fellows	10.7	19.2	16.6	24.2	37.2	34.5
Total staff	210.0	229.3	221.2	223.6	228.2	226.1
PNA1	2005	2006	2007	2008	2009	2010
Tenured staff	4.0	3.4	3.4	3.4	3.4	3.4
Tenured scientific programmers	0.9	0.9	0.3	0.0	0.0	0.0
Non-tenured staff	2.5	4.6	6.4	4.2	3.1	4.6
PhD candidates	4.0	4.0	3.8	2.1	1.5	3.4
Total research staff	11.4	12.9	13.8	9.7	8.0	11.5
Visiting fellows		0.8	1.6	2.8	1.4	0.7
PNA2 (incl. PNA3)	2005	2006	2007	2008	2009	2010
Tenured staff	4.4	4.0	3.5	4.5	4.8	4.8
Non-tenured staff	0.3	2.8	2.3	1.0	0.3	2.3
PhD candidates	3.5	5.0	5.0	4.6	3.7	5.4
Total research staff	8.2	11.7	10.8	10.1	8.8	12.6
Visiting fellows	3.4	3.0	1.7	3.5	3.5	3.4
PNA5	2005	2006	2007	2008	2009	2010
Tenured staff	1.8	1.8	1.8	1.8	1.8	2.8
Non-tenured staff	1.6	3.0	4.3	5.3	4.9	3.5
PhD candidates	3.0	2.7	2.3	4.3	4.0	3.7
Total research staff	6.4	7.5	8.3	11.3	10.7	10.0
Visiting fellows	1.0	1.0	1.0	2.2	3.2	1.0
PNA6	2005	2006	2007	2008	2009	2010
Tenured staff	3.2	3.6	3.5	3.6	3.2	2.8
Non-tenured staff	3.5	3.7	4.4	5.3	5.8	5.4
PhD candidates	5.0	6.4	5.0	4.9	5.3	6.2
Total research staff	11.7	13.7	12.9	13.8	14.3	14.4
Visiting fellows			2.2	2.2	3.2	2.0
SEN1 (incl. SEN2)	2005	2006	2007	2008	2009	2010
Tenured staff	5.7	5.5	4.6	3.6	2.8	2.6
Tenured scientific programmers	1.0	1.0	1.0	1.0	1.0	1.0
Non-tenured staff	5.7	4.9	2.8	2.3	2.8	3.1
PhD candidates	9.1	7.7	7.8	4.5	2.5	1.9
Total research staff	21.5	19.1	16.3	11.3	9.1	8.6
Visiting fellows	1.6	5.0	2.8	4.6	6.0	7.0
SEN3	2005	2006	2007	2008	2009	2010
Tenured staff	2.8	2.8	2.8	2.8	2.8	2.8
Tenured scientific programmers	1.6	1.6	0.0	0.0	0.0	0.0
Non-tenured staff	3.5	4.6	6.0	6.5	4.3	3.3
PhD candidates	3.0	4.1	7.8	7.5	8.7	7.4
Total research staff	10.9	13.1	16.6	16.8	15.8	13.5
Visiting fellows	1.4	1.9	0.4	1.6	1.8	3.6
SEN4 (incl. PNA4)	2005	2006	2007	2008	2009	2010
Tenured staff	4.8	4.1	2.9	2.9	2.9	1.9
Tenured scientific programmers	2.2	2.2	2.0	2.0	2.0	2.0
Non-tenured staff	8.8	6.8	3.8	3.2	1.7	1.6
PhD candidates	2.1	3.8	4.0	3.0	3.3	3.5
Total research staff	17.8	16.8	12.7	11.0	9.8	8.9
Visiting fellows	0.4	1.1	0.1	0.3	0.2	0.2
SEN5 (incl. INS0)	2005	2006	2007	2008	2009	2010
Tenured staff	3.0	3.0	3.0	3.8	3.8	3.8
Tenured scientific programmers	1.8	2.0	2.0	2.0	2.0	2.0
Non-tenured staff	0.4	1.0	1.7	2.0	2.0	2.0
PhD candidates	0.0	0.8	1.3	2.0	2.0	2.0
Total research staff	5.2	6.8	8.0	9.8	9.8	9.8
Visiting fellows					2.0	

Research staff in fte (SEP table 5.2)

MAC1	2005	2006	2007	2008	2009	2010
Tenured staff	5.2	4.8	3.8	3.8	4.1	3.0
Non-tenured staff	1.7	3.3	1.8	1.0	0.7	0.0
PhD candidates	5.2	4.9	3.0	3.1	3.5	2.8
Total research staff	12.0	13.1	8.6	7.9	8.2	5.8
Visiting fellows	1.5	2.6	2.4	2.2	3.2	2.3
MAC2	2005	2006	2007	2008	2009	2010
Tenured staff	2.6	2.7	3.4	2.6	2.5	2.4
Tenured scientific programmers	0.6	0.6	0.6	0.7	0.7	0.0
Non-tenured staff	1.8	2.8	2.7	3.3	4.8	4.5
PhD candidates	4.4	5.5	2.9	2.8	3.1	2.2
Total research staff	9.4	11.6	9.6	9.4	11.1	9.1
Visiting fellows	0.2	1.4	3.0	3.5	5.5	7.6
MAC3	2005	2006	2007	2008	2009	2010
Tenured staff	1.8	1.8	2.8	2.8	1.9	2.8
Tenured scientific programmers	0.0	0.0	0.0	0.0	0.0	0.7
Non-tenured staff	0.7	2.0	4.6	4.0	2.7	1.0
PhD candidates	3.9	2.6	5.0	4.1	2.1	3.2
Total research staff	6.4	6.4	12.4	10.9	6.6	7.6
Visiting fellows				1.0		1.2
MAC4	2005	2006	2007	2008	2009	2010
Tenured staff				0.0	1.0	2.0
Non-tenured staff				0.7	5.6	7.1
PhD candidates				0.3	2.5	6.6
Total research staff				1.0	9.1	15.6
Visiting fellows					1.2	0.2
INS1	2005	2006	2007	2008	2009	2010
Tenured staff	4.8	4.8	4.8	4.8	3.8	3.1
Tenured scientific programmers	1.0	1.0	1.0	1.0	1.0	1.0
Non-tenured staff	1.0	2.0	2.9	3.7	2.0	4.0
PhD candidates	6.5	7.3	8.0	7.9	5.2	2.8
Total research staff	13.3	15.1	16.7	17.3	12.0	10.8
Visiting fellows		0.2	1.2	0.2	0.8	1.2
INS2	2005	2006	2007	2008	2009	2010
Tenured staff	3.0	3.0	3.0	2.0	2.6	2.6
Non-tenured staff	1.1	1.9	2.5	2.4	2.6	1.3
PhD candidates	3.7	4.2	2.0	2.0	3.6	1.0
Total research staff	7.8	9.0	7.5	6.4	8.8	4.9
Visiting fellows	1.2	2.2	0.2		4.0	4.0
INS3	2005	2006	2007	2008	2009	2010
Tenured staff	2.0	2.0	1.0	1.0	1.0	1.0
Non-tenured staff	1.0	0.0	0.0	0.0	0.1	1.7
PhD candidates	4.5	4.9	4.3	4.4	2.7	1.0
Total research staff	7.5	6.9	5.3	5.4	3.8	3.7
Visiting fellows				0.1	1.2	0.2

Main categories of research output from researchers on CWI payroll (SEP table 5.3)

Institute	2005	2006	2007	2008	2009	2010
Refereed articles	128	154	133	159	134	136
Non refereed articles	6	14	5	3	0	2
Books	3	4	5	5	5	3
Book chapters	27	26	19	28	34	20
PhD theses	8	9	11	10	20	13
Refereed conference papers	216	218	208	198	186	151
Professional publications	24	19	11	14	12	7
Publications aimed at general public	8	8	1	1	4	1
Other research output	241	316	239	245	249	229
edited volumes	14	15	12	9	8	13
editorships	82	83	87	94	100	84
major/inaugural lectures	79	156	92	90	102	92
software	26	29	13	7	11	18
media appearances	40	33	35	45	28	22
Total publications	661	768	632	663	644	562
PNA1	2005	2006	2007	2008	2009	2010
Refereed articles	10	22	24	21	26	14
Non refereed articles	1	2	0	1	0	0
Books	0	0	1	0	1	0
Book chapters	5	0	2	4	3	2
PhD theses	1	1	0	2	2	0
Refereed conference papers	8	8	15	21	13	9
Professional publications	0	2	4	3	0	1
Publications aimed at general public	5	5	0	0	0	1
Other research output	53	65	51	53	50	34
edited volumes	1	0	0	1	0	0
editorships	29	31	32	28	24	23
major/inaugural lectures	16	23	13	16	20	8
software	1	0	0	0	0	1
media appearances	6	11	6	8	6	2
Total publications	83	105	97	105	95	61
PNA2 (incl. PNA3)	2005	2006	2007	2008	2009	2010
Refereed articles	26	21	13	23	13	22
Non refereed articles	1	1	1	0	0	0
Books	0	0	0	0	0	0
Book chapters	0	1	0	1	1	2
PhD theses	1	1	1	1	4	0
Refereed conference papers	19	21	6	11	8	4
Professional publications	4	1	0	1	1	0
Publications aimed at general public	0	0	0	0	0	0
Other research output	24	28	27	25	42	36
edited volumes	0	3	1	1	1	2
editorships	9	10	6	14	20	17
major/inaugural lectures	9	12	16	9	19	14
software	0	0	0	0	0	0
media appearances	6	3	4	1	2	3
Total publications	75	74	48	62	69	64
PNA5	2005	2006	2007	2008	2009	2010
Refereed articles	2	7	1	5	5	6
Non refereed articles	1	4	0	0	0	0
Books	1	0	0	0	0	0
Book chapters	0	0	0	1	0	0
PhD theses	0	1	0	0	1	1
Refereed conference papers	14	22	21	18	14	14
Professional publications	1	0	0	0	0	0
Publications aimed at general public	0	0	0	0	1	0
Other research output	8	21	7	15	9	4
edited volumes	2	0	0	1	0	2
editorships	1	3	3	2	2	2
major/inaugural lectures	3	16	3	2	6	0
software	0	0	0	0	1	0
media appearances	2	2	1	10	0	0
Total publications	27	55	29	39	30	25
PNA6	2005	2006	2007	2008	2009	2010
Refereed articles	9	19	9	17	16	15
Non refereed articles	2	3	0	0	0	0
Books	0	0	1	1	0	0
Book chapters	2	3	3	3	2	0
PhD theses	0	1	1	2	0	1
Refereed conference papers	15	18	16	21	16	13
Professional publications	4	2	0	0	0	0
Publications aimed at general public	0	2	0	0	0	0
Other research output	20	27	25	28	25	11
edited volumes	1	0	0	1	0	0
editorships	8	9	10	13	13	5
major/inaugural lectures	4	17	8	6	8	5
software	1	0	0	0	0	0
media appearances	6	1	7	8	4	1
Total publications	52	75	55	72	59	40

Main categories of research output from researchers on CWI payroll (SEP table 5.3)

SEN1 (incl. SEN2)	2005	2006	2007	2008	2009	2010
Refereed articles	20	18	8	10	2	2
Non refereed articles	1	1	0	0	0	0
Books	1	0	0	0	1	1
Book chapters	5	3	2	1	13	3
PhD theses	2	1	4	3	1	1
Refereed conference papers	44	35	33	22	16	13
Professional publications	10	7	5	3	5	2
Publications aimed at general public	1	0	0	0	1	0
Other research output	30	26	19	8	16	22
edited volumes	2	1	0	0	1	0
editorships	8	5	5	2	2	2
major/inaugural lectures	2	6	5	1	7	11
software	7	8	4	2	1	2
media appearances	11	6	5	3	5	7
Total publications	114	91	71	47	55	44

SEN3	2005	2006	2007	2008	2009	2010
Refereed articles	18	20	15	5	10	7
Non refereed articles	0	0	1	0	0	0
Books	0	3	1	1	2	2
Book chapters	2	4	1	1	2	0
PhD theses	1	0	1	1	0	3
Refereed conference papers	31	21	32	29	33	30
Professional publications	0	0	0	0	0	0
Publications aimed at general public	0	0	0	0	0	0
Other research output	12	13	18	14	11	15
edited volumes	5	0	6	3	2	6
editorships	3	3	3	3	6	6
major/inaugural lectures	4	4	4	3	3	3
software	0	1	1	0	0	0
media appearances	0	5	4	5	0	0
Total publications	64	61	69	51	58	57

SEN4 (incl. PNA4)	2005	2006	2007	2008	2009	2010
Refereed articles	4	9	8	8	3	4
Non refereed articles	0	2	1	0	0	1
Books	0	0	0	0	1	0
Book chapters	6	4	4	8	3	2
PhD theses	0	0	0	0	1	1
Refereed conference papers	27	24	26	13	12	10
Professional publications	1	2	1	0	1	2
Publications aimed at general public	1	0	0	1	0	0
Other research output	17	28	7	11	10	7
edited volumes	0	4	0	0	0	1
editorships	2	3	4	5	7	4
major/inaugural lectures	6	15	1	5	3	0
software	9	6	0	1	0	0
media appearances	0	0	2	0	0	2
Total publications	56	69	47	41	31	27

SEN5 (incl. INS0)	2005	2006	2007	2008	2009	2010
Refereed articles	3	3	3	4	4	4
Non refereed articles	0	0	1	0	0	0
Books	1	0	1	1	0	0
Book chapters	2	1	1	2	1	6
PhD theses	0	0	0	0	0	0
Refereed conference papers	4	10	18	26	16	13
Professional publications	0	0	0	2	1	0
Publications aimed at general public	0	0	0	0	0	0
Other research output	25	30	26	27	27	46
edited volumes	1	1	1	0	2	0
editorships	5	4	6	6	6	4
major/inaugural lectures	14	19	15	15	10	26
software	3	5	3	3	7	13
media appearances	2	1	1	3	2	3
Total publications	35	44	50	62	49	69

Main categories of research output from researchers on CWI payroll (SEP table 5.3)

MAC1	2005	2006	2007	2008	2009	2010
Refereed articles	11	9	9	7	5	3
Non refereed articles	0	2	0	0	0	1
Books	0	0	0	0	0	0
Book chapters	1	1	0	0	0	0
PhD theses	3	2	0	0	1	1
Refereed conference papers	2	1	0	0	0	1
Professional publications	2	1	0	1	0	1
Publications aimed at general public	0	0	0	0	0	0
Other research output	12	24	11	10	11	11
edited volumes	1	4	0	0	0	1
editorships	7	4	4	5	5	3
major/inaugural lectures	4	15	5	4	6	7
software	0	0	0	0	0	0
media appearances	0	1	2	1	0	0
Total publications	31	40	20	18	17	18

MAC2	2005	2006	2007	2008	2009	2010
Refereed articles	12	8	20	20	10	20
Non refereed articles	0	0	0	1	0	0
Books	0	1	0	1	0	0
Book chapters	1	0	2	2	2	2
PhD theses	0	1	2	0	2	0
Refereed conference papers	13	19	10	16	28	13
Professional publications	0	1	0	0	2	0
Publications aimed at general public	0	0	0	0	0	0
Other research output	17	12	16	18	12	8
edited volumes	0	1	0	0	1	0
editorships	5	4	7	8	7	7
major/inaugural lectures	12	5	8	10	4	1
software	0	1	0	0	0	0
media appearances	0	1	1	0	0	0
Total publications	43	42	50	58	56	43

MAC3	2005	2006	2007	2008	2009	2010
Refereed articles	8	14	17	26	13	13
Non refereed articles	0	0	1	0	0	0
Books	0	0	1	1	0	0
Book chapters	0	2	4	2	0	0
PhD theses	1	1	0	1	2	0
Refereed conference papers	3	3	5	6	2	5
Professional publications	1	1	1	3	1	0
Publications aimed at general public	1	1	1	0	2	0
Other research output	9	20	11	18	19	7
edited volumes	0	0	0	0	0	0
editorships	1	1	2	2	2	2
major/inaugural lectures	3	17	9	11	8	3
software	0	0	0	0	0	0
media appearances	5	2	0	5	9	2
Total publications	23	42	41	57	39	25

MAC4	2005	2006	2007	2008	2009	2010
Refereed articles				4	23	17
Non refereed articles				0	0	0
Books				0	0	0
Book chapters				0	2	2
PhD theses				0	0	0
Refereed conference papers				1	3	8
Professional publications				0	1	1
Publications aimed at general public				0	0	0
Other research output				1	7	18
edited volumes				0	0	1
editorships				0	0	2
major/inaugural lectures				1	6	13
software				0	1	1
media appearances				0	0	1
Total publications				6	36	46

Main categories of research output from researchers on CWI payroll (SEP table 5.3)

INS1	2005	2006	2007	2008	2009	2010
Refereed articles	5	2	4	7	1	3
Non refereed articles	0	1	0	0	0	0
Books	0	0	0	0	0	0
Book chapters	2	3	1	4	3	1
PhD theses	0	0	1	0	3	2
Refereed conference papers	16	22	22	9	16	8
Professional publications	1	1	0	0	1	0
Publications aimed at general public	0	0	0	0	0	0
Other research output	6	7	9	9	5	4
edited volumes	2	2	3	0	2	1
editorships	0	0	1	2	1	1
major/inaugural lectures	1	4	2	6	2	0
software	1	0	1	0	0	0
media appearances	2	1	2	1	0	2
Total publications	30	36	37	29	29	18

INS2	2005	2006	2007	2008	2009	2010
Refereed articles	3	3	2	8	2	2
Non refereed articles	0	0	0	1	0	0
Books	0	0	0	1	0	0
Book chapters	3	5	0	0	3	2
PhD theses	0	1	0	0	0	3
Refereed conference papers	15	7	14	15	18	12
Professional publications	0	0	0	2	0	0
Publications aimed at general public	0	0	0	0	0	0
Other research output	10	17	11	7	5	6
edited volumes	0	0	0	0	0	1
editorships	4	6	4	4	5	5
major/inaugural lectures	0	4	2	3	0	0
software	4	7	5	0	0	0
media appearances	2	0	0	0	0	0
Total publications	31	33	27	34	28	25

INS3	2005	2006	2007	2008	2009	2010
Refereed articles	1	4	4	1	4	5
Non refereed articles	0	0	0	0	0	0
Books	0	0	0	1	1	0
Book chapters	0	0	0	0	0	0
PhD theses	0	0	1	0	3	0
Refereed conference papers	9	8	5	5	5	3
Professional publications	0	0	0	0	0	0
Publications aimed at general public	0	0	0	0	0	0
Other research output	4	3	3	5	4	3
edited volumes	0	0	2	2	0	0
editorships	0	0	0	1	1	1
major/inaugural lectures	2	1	1	1	2	1
software	2	2	0	1	1	1
media appearances	0	0	0	0	0	0
Total publications	14	15	13	12	17	11

Main categories of research output from researchers hosted by CWI (SEP table 5.3)

Institute	2005	2006	2007	2008	2009	2010
Refereed articles	4	0	12	12	28	17
Non refereed articles	0	0	0	0	0	1
Books	0	0	1	0	0	0
Book chapters	1	0	1	2	3	2
PhD theses	6	5	8	9	11	6
Refereed conference papers	6	8	12	9	19	10
Professional publications	0	0	0	0	0	0
Publications aimed at general public	0	0	0	0	0	0
Other research output	1	5	7	9	18	28
edited volumes	0	2	0	0	1	0
editorships	0	0	7	7	14	22
major/inaugural lectures	0	1	0	2	3	4
software	0	0	0	0	0	0
media appearances	1	2	0	0	0	2
Total publications	18	18	41	41	79	64

Centrum Wiskunde & Informatica (CWI) is the national research institute for mathematics and computer science in the Netherlands. The institute's strategy is to concentrate research on four broad, societally relevant themes: earth and life sciences, the data explosion, societal logistics and software as service.

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