CWI self-evaluation 1999–2004

18th February 2005

Centrum voor Wiskunde en Informatica is the Dutch national research institute for mathematics and computer science. It is sponsored by the Netherlands Organisation for Scientific Research (NWO). CWI is a founding member of the European Research Consortium for Informatics and Mathematics (ERCIM) and a member of the World Wide Web Consortium (W3C), for which it runs the W3C Office in the Benelux.

Centrum voor Wiskunde en Informatica

General Director	Jan Karel Lenstra
Visiting address	Kruislaan 413, 1098 SJ Amsterdam, The Netherlands
Postal address	P.O. Box 94079, 1090 GB Amsterdam, The Netherlands
Telephone	+31 20 592 9333
Telefax	+31 20 592 4199
Website	www.cwi.nl

Colophon

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Preface

This document contains a self-evaluation of CWI's research results for the years 1999 through 2004. It is part of the standard review protocol for all institutes supported by the Netherlands Organization for Scientific Research (NWO). The format and contents of this report are defined by NWO, VSNU, and KNAW in [2]. While we have followed the requested format as much as was practical, a number of pragmatic choices were made in information organization and presentation to give our reviewers an accessible and digestible overview of CWI's activities.

In spite of the modest size of CWI, we are engaged in many activities on national, European and other international levels. The challenge in providing a self-evaluation of this work is to find a level of abstraction that is comprehensive in scope without overwhelming the reader with dozens of pages of tables, charts and bulleted lists. We have selected a level that – we feel! – provides a set of focused descriptions of the research programs and organizational structure of CWI and its researchers.

Chapter 1 contains an overview of CWI. General information is presented on the history, legal structure, and coarse-level output of the Institute during the past six years. We also provide a summary of and reactions to the 1999 review of CWI, covering the period 1993–1998. Chapter 2 describes the broad strategy of CWI in its current research environment. While part of this information reflects the positioning of the Institute during the review period, the focus is in describing how we intend to address the challenges in terms of research areas and administration that face the Institute in the coming years. Chapters 3, 4, 5 and 6 contain detailed descriptions of the research clusters and themes at CWI. Chapter 7 highlights the support staff activities.

Two companion volumes contain a selection of CWI publications over the review period. A companion CD-ROM contains the yearly *Overview Research Activities* publications. It is a good source of additional information on the staffing, output, and funding for all CWI's themes.

The NWO evaluation protocol [2] uses several administrative definitions that do not directly correspond with the names of CWI's organizational units. The NWO terms "department", "research program" and "research program in exploratory phase" are "cluster", "theme" and "pilot theme" in CWI terminology.

We are confident that this document, together with presentations by individual groups, will provide a useful insight into our activities during the review period.

Jan Karel Lenstra
Director CWI

Amsterdam, February 2005

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Summary

Identity and position. *Centrum voor Wiskunde en Informatica* (CWI) is the national research institute for mathematics and computer science of the Netherlands Organisation for Scientific Research (NWO). Founded in 1946, the Institute performs frontier academic research in the public interest on fundamental topics in mathematics and computer science, transfers new knowledge to a wide range of parties, acts as a breeding ground and meeting place for young researchers and academic staff, and provides facilities for various organizations such as W3C.

A single institute with a strong position in mathematics and computer science is in an excellent position to foster a strong interaction between fundamental and applied science. This is reflected in many of the topics addressed during the period under review. Research fields at CWI include
– analysis (nonlinear partial differential equations, nonlinear dynamics, computational fluid dynamics and electromagnetics, control and system theory, image and signal processing),
– stochastics (probability, stochastic geometry, queueing, communication networks, learning theory),
– algorithmics (optimization, constraint programming, complexity, cryptology, quantum computing, adaptive algorithms),
– software technology (software evolution and renovation, software verification and validation, security, coordination languages), and
– information systems (database architectures, information access, multimedia interfaces, human/computer interaction, visualization).

The research activities at CWI are organized in seventeen themes, which are grouped into four clusters: PNA (Probability, Networks and Algorithms), SEN (Software Engineering), MAS (Modelling, Analysis and Simulation), and INS (Information Systems). This structure facilitates effective management as well as interaction among researchers.

The research landscape in which CWI has to accomplish its mission has changed drastically over the last five years. As a result of the emphasis on near-to-market research in EU framework programs, the internet bubble, and the push for early economic exploitation of scientific results, the long-term research infrastructure in Europe has suffered severe damage. In spite of these developments, the Institute has been able to keep to its mission and maintain its prominent and unique position.

The evolution of CWI's field of research is making its potential impact on science and society bigger than ever before. Algorithmics has pervaded many branches of mathematics, and advanced information processing is turning areas like physics, biology, sociology, cognitive science, economics, and linguistics into computational sciences. As the new century develops, more and more empirical sciences will absorb insights from mathematics and computer science, creating rich sources of inspiration and opportunities. CWI sees it as a challenge to play a vital role in the development of the national and international research landscape from this perspective.

Costs and benefits. During the review period, the number of staff on CWI payroll averaged 172 FTE. 70% of these were research FTE. The total hosted staff averaged 200 FTE. CWI's staff published an average of 300 academic publications per year, as well as an average of eight monographs, 10 PhD dissertations and 100 other professional publications and products. The average of 2.4 academic publications per payroll research staff member compares well with the output of similar institutes. Since 1999, CWI gave rise to four spin-off companies.

The annual operating budget was approximately M€14. Personnel expenses constitute nearly 75% of costs. The primary source of funding was NWO, which provided approximately 65% of the budget. Approximately 20% of the budget was covered by grants obtained from competitive funding sources, 5% by direct contracts, and 5% by a variety of sources, including proceeds obtained from the sale of licenses or equity in spin-offs. A final 5% was extracted from reserves.

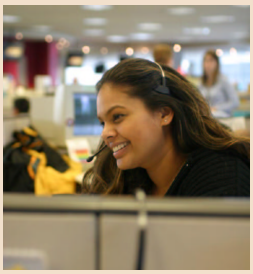
Analysis of present position. CWI has a unique position and an excellent reputation. Its mission has become more urgent since the previous review in 1999 in view of the more pronounced role of mathematics and computer science as foundational disciplines as well as the global decline in long-term research capacity. There is no lack of new research topics, but they have to be chosen carefully, since the scale and pace of developments, especially in ICT, make it hard to achieve sufficient critical mass. Strategic alliances with short-term oriented research institutes can help to alleviate this problem and to bridge the gap between theory and practice. Apart from this, CWI's housing facilities are a point of urgent concern, and its public relations need attention.

Strategy. Over the period 2005–2010, CWI intends to
– reinforce its prominent position in long-term fundamental research, and initiate new research in, for instance, multiscale analysis, hybrid systems, stochastic and dynamic networks, algebraic methods in optimization, algorithmic game theory, probabilistic algorithms, new computing paradigms, software systems tomography, self-organizing database systems, and knowledge elicitation,
– expand its position in long-term applied research in, for instance, the life sciences and health care related ICT research,
– strengthen its involvement in ICT research for the humanities and the social sciences,
– forge strategic alliances with industry and non-profit organizations with complementary areas of expertise, both at the national and international level,
– improve its housing,
– improve HRM by implementing individual career paths for staff members, improving mobility of tenured staff, and strengthen international scouting efforts,
– improve public relations by making its results more accessible to its constituting partners, and
– contribute to promoting public interest in mathematics and computer science.

Growth scenario. CWI intends to maintain its position as an independent research center, in between academia and more applied laboratories, with intensive relations with these and other societal partners. The Institute aims for a *moderate growth scenario* of about 10%.

During the review period CWI has grown by some 10% as well, largely as a result of its success in the BSIK program, which contributes M€1.5 to CWI's annual income over 2005. A continued expansion is, we feel, amply justified by the external factors mentioned above. It would require a slow increase in the basic funding to be provided by NWO, a continuation of the BSIK funding in some form after 2008, and a strong growth of hosted staff not on CWI payroll.

Conclusion. It is our conviction that CWI has been successful in its mission during the review period and is well prepared for the future.



CWI spin-off company DataDistilleries, acquired by SPSS in 2003, uses data mining technology for customer relationship management software for call centers.

From spin-offs to licences

Turning knowledge into business: with this motto CWI founded CWI Incubator BV in 2000. The start-up of innovative companies is a way of transferring CWI's knowledge into the heart of society. CWI Incubator was created to provide financial support and employment arrangements for CWI employees who want to start new businesses based on their research.

Although the economic climate has deteriorated since 2001, CWI Incubator's motto still holds. Its implementation has changed, however. Instead of starting new spin-off companies, emphasis has shifted towards licensing CWI technology to existing businesses.

A good example of a company building on CWI technology is DataDistilleries. This successful data mining software developer started in 1994 as a CWI spin-off and was acquired by US software company SPSS in 2003. Its applications run on CWI's Monet database kernel. The company is also involved in the MultimediaN project, which further reinforces its ties with CWI.

CWI research also forms the basis of the DocGen technology of the Software Improvement Group. This company was founded in 2000 with the help of researchers from CWI's Interactive Software Development and Renovation theme. DocGen automatically generates technical documentation directly from the source code of complex software systems.

Software developer Adaptive Planet has been using CWI's Manifold language since 2002. Manifold is a coordination language developed by researchers from CWI's Coordination Language theme, that manages the interaction of reusable software components.

In 2004 the bio start-up company PodiCeps signed a licence for the Argos software, developed by CWI's Visualization and 3D Interfaces theme. PodiCeps develops a chemical detection technique that can aid pathologists with cancer diagnosis. Argos measures characteristics of marked structures in cell nuclei that can be an indication of cancer and provides ways to present this information. In exchange for the licences CWI Incubator has acquired shares in both Adaptive Planet and PodiCeps.

Chapter 1

CWI: Centrum voor Wiskunde en Informatica

Centrum voor Wiskunde en Informatica (CWI) is the national research institute for mathematics and computer science of the Netherlands Organization for Scientific Research (NWO). Founded in 1946, CWI performs frontier academic research in the public interest on fundamental topics in mathematics and computer science. CWI has its offices on the campus of the Science Park Amsterdam, which is one of the largest concentrations of scientists in the country.

CWI functions as the research institute of the *Stichting Centrum voor Wiskunde en Informatica*, a not-for-profit foundation registered in Amsterdam. CWI's primary source of funding is the Dutch Ministry of Education, Culture and Science (OCW) through NWO. Additional funding is obtained through national and international programs and contract research.

The basic unit at CWI is the *theme*. A theme consists of up to five sub-groups, each working on related areas of a common discipline. Themes vary in size from four staff members in *pilot themes* to over twenty members in mature themes. Themes are administratively grouped into *clusters*. Each cluster is managed by a senior staff member, who is also a member of the Institute's management team. CWI also has five departments that provide administrative, technical and production support for CWI's researchers, and it maintains an internationally recognized library for mathematics and computer science.

CWI is both a producer and a consumer of research talent in the Netherlands. The Institute employs PhD students and postdocs and transfers the results of its research through numerous joint appointments or other relationships with Dutch universities. Researchers at CWI also participate directly in national and European programs. The transfer of results to national and European society, industry and academia is a key element of CWI's mission.

1.1 History

CWI was founded in 1946 as the *Mathematisch Centrum* (MC), the research institute of the foundation *Stichting Mathematisch Centrum*. In 1983, in recognition of the growing component of computer science research at the MC, the Institute changed its name to Centrum voor Wiskunde en Informatica. Along with this change, CWI reorganized its research into six departments, three with a mathematics character and three focused on computer science. In 1997, the departmental structure of the Institute was changed to the current theme-oriented focus. In 2001 the name of the Stichting Mathematisch Centrum was changed to Stichting Centrum voor Wiskunde en Informatica.

CWI's research focus has gone through several transitions in its 59-year history. Initially, the Institute was chartered to serve as a vehicle to transfer mathematical solutions to Dutch industry during post-war reconstruction. The applied nature of the Institute's charter made leading academics reluctant: some refused to join CWI because they feared it would become a consulting agency. The opposite turned out to be true. The MC regularly was able to introduce and develop new and fundamental scientific techniques that would later be transferred to universities as well as industry.

Some of CWI's early successes

First Dutch CPU cycles
(thanks to the ARRA and X series)

Programming languages for the world
(thanks to Algol60, 68 and Python)

Dry feet for Holland
(thanks to statistical models and computations developed at CWI)

Rest for the weary
(thanks to Dijkstra's shortest path algorithm, developed at CWI)

In the 1950s, the Institute was responsible for the introduction of advanced statistical techniques to Holland as a part of its computations on new dikes and the Delta works. The MC also developed the very first Dutch computer, the ARRA, soon to be followed by the X-series. In the 1960s and 1970s, along with its traditional role in the Dutch mathematics community, the Institute had a strong focus on the development of programming languages like Algol60 and Algol68. During the early 1980s, the Institute was active in many of the EU ESPRIT research initiatives and CWI took the lead nationally and within Europe in providing connectivity to the fast-growing Internet community: for nearly a decade, essentially all of the electronic mail and file traffic between Europe and the USA passed through the Institute's *mcvax*. Also, it co-developed the first international standard on computer graphics, GKS, selling hundreds of licenses of its C implementation.

In the 1990s, the Institute's work on synchronized multimedia, structured document design and language theory led to seminal contributions in many international standards, such as SMIL, XHTML and SVG. It also led to the development of the language Python, a jewel that was not immediately appreciated and which was perhaps transferred out too soon.

During the 1980s and 1990s the Institute was very successful in numerical, stochastic, and combinatorial analysis and algorithms, as applied to differential and integral equations, computational fluid dynamics, operations research, and mathematical physics. Major contributions concern multigrid methods, adaptive high-performance computing, and networks and matroids. Two small sized activities, yet jewels in CWI's crown, were the world record factoring of large numbers into primes, and special function analysis with a major contribution in the update of the omnipresent *Handbook of Mathematical Functions*. Noteworthy is also that several of the research themes have gained a high level of integration of mathematics and computer science.

In spite of the worldwide political and financial instability of the early 2000s, the Institute has remained successful in attracting research funding and in producing top-quality research results. CWI initiated one successful national knowledge-society grant (BSIK) and participated in two others, its researchers were awarded top national and

international honors, and the production of research output is at an all-time high. In the most recent CiteSeer listing three of the five most cited Dutch computer scientists in the Netherlands are employed by CWI.

1.2 Research mission and goals

CWI has a two-fold research mission:

1. To perform frontier research on selected topics in mathematics and computer science, and
2. To transfer new knowledge in these fields to society in general, and to trade and industry in particular.

CWI selects topics for its research that are scientifically challenging and socially relevant. The concentration of a large number of excellent researchers in computer science and mathematics provides the opportunity for synergistic relationships in many cross-over fields, such as pattern recognition, modeling, and simulation of logical and physical processes, cryptography, queueing theory, image processing, quantum complexity, logic programming, and combinatorial optimization.

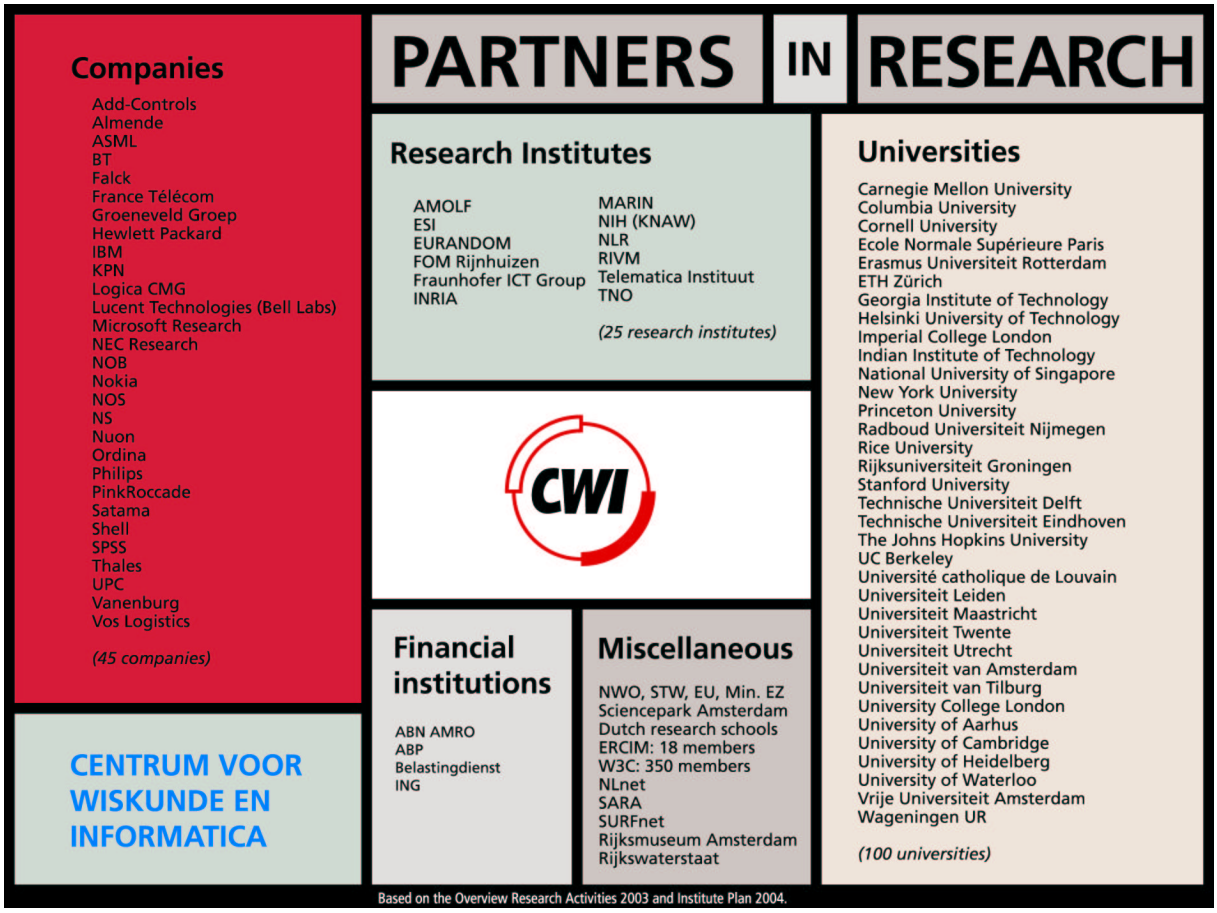
External recognition for CWI research

2000 Marcel Neuts Award - Michel Mandjes
2003 Cor Baayen Award - Ronald de Wolf
2003 Dantzig Prize - Lex Schrijver
2003 Fulkerson Prize - Bert Gerards
2003 Fulkerson Prize - Lex Schrijver
2003 Kolmogorov Medal - Paul Vitányi
2003 Gijs de Leve Award - Bert Zwart
2003 Peterich Prize - Willem Hundsdorfer
2004 Lanchester Prize - Lex Schrijver
2004 Minerva Prize - Ute Ebert

The relatively light-weight theme-based organization at CWI stimulates structural and ad hoc collaboration among disciplines, just as the infrastructure support at the Institute facilitates cooperation with partners outside CWI's walls.

Technology transfer, the second key component of CWI's mission, is structurally embedded in the organization. In the 1960s, CWI was actively spinning-off its research results to the commercial sector with the founding of Electrologica BV. The academic and super-computer center SARA was also spun off when running a CPU-cycle service bureau for academic Amsterdam was consuming too many CWI resources. In the last decade, more than ten companies have been launched based on work started at CWI, the majority of which are still active.

Along with employing excellent researchers, the Institute is also an important link in the supply-chain of academic talent in the Netherlands: many of the senior faculty at Dutch universities have had appointments at CWI, either during their dissertation research or as staff members. More than 25 CWI staff members currently hold part-time professorships at universities across the country.



1.3 CWI in national and international contexts

CWI does not operate in a vacuum. It exists within the extensive quilt of national, European and other international research activities in mathematics and computer science. This section will highlight CWI's major research and funding relationships.

1.3.1 CWI's position within the Netherlands

Research and advanced technical development within the Netherlands occurs across several channels. We highlight our role within the Dutch community in this section.

CWI and NWO. CWI is one of nine institutes funded by NWO. Each of these institutes has a permanent research character across the Dutch scientific spectrum, ranging from high-energy physics and astronomy to history and criminal justice. CWI is NWO's institute for mathematics and computer science. In NWO's typology of institutes, CWI is primarily *problem-oriented*. It also is a *meeting place* for researchers from the Netherlands and abroad, and provides *facilities* such as a comprehensive library and the Benelux W3C office. As with all NWO institutes, CWI's research focus and role are dynamic and change in response to the needs of its constituent community. This includes participating in directed competitive programs in addition to receiving block funding for long-term research. At the start of this new century, members of CWI's staff have been awarded seven Veni, Vidi and Vici distinguished researcher de-

velopment NWO grants (more than any other NWO institute), and CWI participates in two of the three mathematics clusters that have been selected for funding by NWO.

CWI and the Dutch university community. The relationship between CWI and the Dutch academic community dates back to 1946, when the Institute was founded. During the period of this evaluation, approximately ten PhDs were awarded per year at universities across the Netherlands based on research work performed at CWI. (As detailed elsewhere in this chapter, this rate compares favorably with similar institutes across Europe.) These degrees are usually awarded via professorships held at Dutch universities by CWI staff members.

NWO *Vernieuwingsimpuls* grant recipients at CWI

S.M. Bohte (Veni, 2002)
J.E. Frank (Veni, 2002)
M. Laurent (Vidi, 2002)
M.A. Peletier (Vidi, 2003)
H.M. Buhrman (Vici, 2003)
P.J. Collins (Vici, 2004)
P.D. Grünwald (Vidi, 2004)

Within the Netherlands, the core of university research effort is organized in inter-institution research schools. CWI participates in all research schools in mathematics and computer science and one in physics, ranging from the Thomas Stieltjes Institute for Mathematics to the Center for Plasma Physics and Radiation Technology.

CWI and EURANDOM. In addition to its participation in national research schools in mathematics and the many part-time faculty appointments of its staff, CWI maintains close ties with EURANDOM, a research institute for the study of stochastic phenomena, located in Eindhoven.

CWI and the TTIs. CWI is a founding consortium member for the Telematica Instituut, one of four Technological Top Institutes (TTIs) in the country. Since 1997, CWI researchers have participated in nine large-scale joint TTI projects.

CWI and the knowledge society. In 2003, the Dutch government funded nine major ICT initiatives in a research-industry partnership to strengthen the country's position as a knowledge-based society. CWI was the initiating partner of one of these grants (BRICKS), and it participates in two others (MultimediaN and VL-e). The BSIK initiative is a follow-on to the earlier ICES/KIS-1 and ICES/KIS-2 programs in which CWI was also an active participant.

CWI also actively participates in various programs from the Ministry of Economic Affairs to stimulate a research-industry partnership in the country. The Institute has participated in a range of national initiatives managed by SenterNovem (such as BTS, IS, WBSO and IOP). These programs fund research that is coordinated with the needs of the Dutch industrial community.

CWI and spin-off companies. In addition to participating in national programs to work with Dutch industry, CWI also actively transfers its results to the community in the form of spin-off companies. The Institute hosts a separate foundation for this purpose: *CWI Incubator BV* (CWI-Inc). CWI-Inc provides small-scale seed funding support for CWI-related start-ups in exchange for an equity position.

Proceeds from the growth of these companies are used to fund future ventures. Of the ten companies spun off during the past decade, seven are still active.

Table 1.1. CWI spin-offs, 1990–present

Year	Company	Business	Status
1990	DigiCash	*Electronic payments*	Ended, 1999
1994	General Design / Satama	*Web design*	Sold, 2000
	NLnet / UUnet	*ISP*	Active
1995	CAN Diensten	*Mathematical software*	Active
	Data Distilleries	*Data mining*	Sold, 2003
1997	Unipay Technologies	*Encryption, electronic authorization*	Active
1998	Eidetica	*Search systems*	Sold, 2002
	Oratrix Development	*Multimedia authoring*	Ended, 2002
2000	Software Improvement Group	*Legacy software improvement*	Active
2001	Epictoid	*Animation tools*	Ended, 2003
2002	Adaptive Planet	*Component SW, tools*	Active
2004	PodiCeps	*Tumor screening*	Active

CWI and CWI. In 2001, CWI was unable to prevent the national employment offices from changing their name to *Centrum voor Werk en Inkomen* and initiating wide national usage of the acronym CWI. This unhappy name coincidence is a source of short-term irritation to the administrative staff and a potential long-term problem for the Institute's identity within the Netherlands.

1.3.2 CWI in European and other international contexts

CWI has a strongly international character, hosting researchers from over twenty countries across the world (see Table 1.2). In addition, CWI has been an active participant in various European research initiatives. This section highlights a number of major contributions of the Institute and its researchers.

CWI and Brussels. From the inception of wide-scale European research support in the early 1980s, CWI has been successful in obtaining competitive funding from such European initiatives as ESPRIT, ACTS, TELEMATICS, BRITE, TMR, and IST. Within the period of this evaluation (1999–2004), CWI has participated or is still actively engaged in over twelve projects in the fifth and sixth Frameworks. CWI also participates in decentralized European programs, such as RTIPA and TT-Medal in EUREKA and its ITEA-labeled projects.

CWI and W3C. As the worldwide web was being spun, CWI's researchers took an active role in many of the World Wide Web Consortium (W3C) working groups. The Institute provided significant support for the XML, XHTML, XForms, SMIL and SVG recommendations developed by W3C. At present, several CWI researchers are on loan to W3C as senior staff members.

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 W3C office in 1998. In 2002, the scope of this office has expanded to serve the entire Benelux.

Table 1.2. Nationalities of CWI staff in FTE in 2004

Region	*FTE*	*%*	Region	*FTE*	*%*	FTE	%
Germany	12.6	23%	Ukraine	1.0	2%		
Spain	4.5	8%	Czech Republic	1.0	2%		
Rumania	4.0	7%	Austria	1.0	2%		
Great Britain	3.0	5%	Portugal	1.0	2%		
Russia	4.0	7%	Sweden	1.0	2%		
Hungary	3.0	5%	Finland	1.0	2%		
Italy	2.1	4%	Norway	0.0	0%		
Poland	3.6	7%	Turkey	0.0	0%		
France	0.8	1%	Greece	0.0	0%		
Belgium	2.8	5%	Lithuania	0.0	0%		
Bulgaria	7.0	13%	Slovenia	0.0	0%		
Serbia	2.0	4%	Croatia	0.0	0%		
					Europe	**55.4**	**80%**
					Americas	**7.2**	**10%**
					Asia	**6.0**	**9%**
					Australia	**1.0**	**1%**
					Africa	**0.0**	**0%**
					Total non-Dutch in FTE	**69.6**	**100%**

CWI and ERCIM. In 1989, CWI, GMD (Germany) and INRIA (France) founded the European Research Consortium for Informatics and Mathematics (ERCIM). ERCIM, which currently has 23 member organizations across Europe that represent a research community of over 12,000 scientists, coordinates scientific working groups on projects of common interest, supports a fellowship program for young PhDs, and sponsors the Cor Baayen Award (named after CWI's former scientific director and ERCIM's first president) for research excellence.

Between 1999 and 2004, CWI participated in ten ERCIM working groups and has hosted more than twenty young researchers as part of the ERCIM Fellowship program. In addition to supplying ERCIM's first president, CWI's Gerard van Oortmerssen was elected as ERCIM president for two consecutive terms while he was the Institute's general director.

CWI and ERCOM. CWI is a long-term participant in ERCOM, a subcommittee of EMS, the European Mathematical Society. ERCOM consists of the directors of European non-academic mathematics research institutes.

1.4 Organization structure

This section provides a brief overview of CWI's organization structure. We consider the general management responsibilities, the structure of the research component of CWI, and the structure of the support departments within the Institute.

1.4.1 CWI management structure

The research institute CWI is the operational unit of the not-for-profit foundation *Stichting Centrum voor Wiskunde en Informatica* (S-CWI). S-CWI is a legal entity, registered in

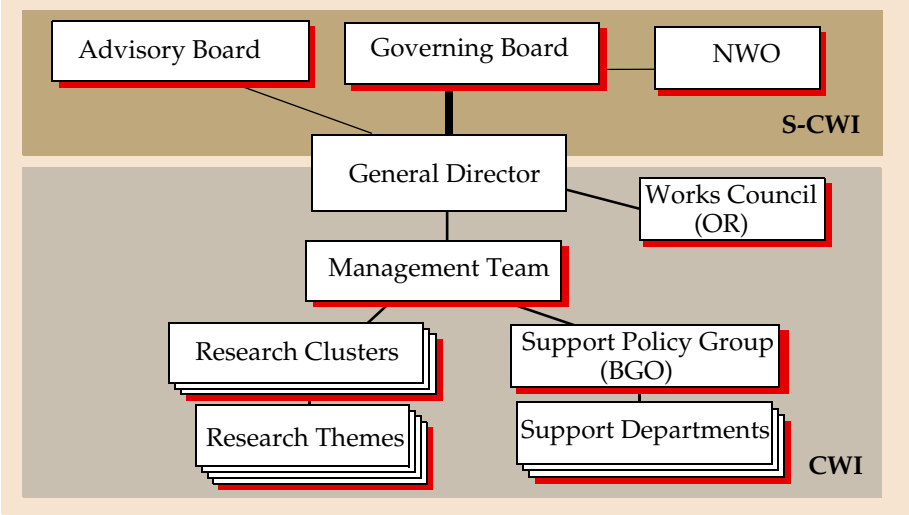


Figure 1.1. CWI management structure

Amsterdam.

Figure 1.1 illustrates the management structure of CWI. A Governing Board, an informal Advisory Board and NWO govern and support CWI's direct management in the context of their responsibilities within S-CWI. Within the Institute, the general director and the management team direct daily operations. The research themes are managed within research clusters; activities within the support departments are coordinated through the support policy group (BGO). Finally, the works council (OR) has a statutory responsibility to advise management.

Since the restructuring of CWI research management as of 1997, the implementation of the Institute's research policy is managed at theme level. Each theme leader is responsible for the quality of the theme's scientific output and for its financial health. Semi-annual theme evaluation meetings are held; these meetings, at which the scientific director, controller, cluster head and theme leader are present, focus on research strategy, staff planning and a financial analysis of the theme's operations.

The composition of the S-CWI governing board for the period 1999–2004 is given in Table 1.3. The composition of CWI's management team for the same period is given in Table 1.4. The details of each theme's management is provided later in this report.

1.4.2 CWI research structure

Research at CWI is theme based. A research theme typically begins as a pilot theme for a period of up to three years; during this time, an opportunity is provided to define a coherent research strategy, to attract projects and funding, and to attract personnel. At the end of the pilot period, the theme is evaluated and either promoted to a full research theme or discontinued.

Full research themes have a broad research charter within their area of study. In the normal course of the research life cycle, themes may be redefined, restructured or terminated. Themes are encouraged to seek partnerships with other research groups

Table 1.3. CWI Governing Board, 1996–present

Function	Dates	Person
Chair	3/1996 — 3/2003	Prof.ir. L.A.A.M. Coolen (KPN / UM)
	3/2003 — present	Prof.dr. P.W. Adriaans (UvA)
First vice-chair & secretary	3/1996 — 5/2002	Prof.dr. K.M. van Hee (Bakkenist / TUE)
	5/2002 — 3/2003	Prof.dr. P.W. Adriaans (Perot Systems / UvA)
	3/2003 — 4/2004	Prof.dr. H.A. van der Vorst (UU)
	6/2004 — present	Prof.dr. M.H. Overmars (UU)
Second vice-chair & treasurer	3/1996 — 3/2003	Prof.dr. H.A. van der Vorst (UU)
	4/2004 — present	Prof.dr.ir. C.J. van Duijn (TUE)
Members	3/1996 — 5/2002	Prof.dr. P.M.G. Apers (UT)
	3/1996 — 3/1999	Prof.dr.ir. J.H.A. de Smit (UT)
	5/2002 — 5/2004	Prof.dr. M.H. Overmars (UU)
	3/1999 — present	Prof.dr. F.A. van der Duyn Schouten (UvT)
	3/2003 — present	Ms.mr. S.J.M. Roelofs (ICT~Office)

inside CWI and externally.

Pilot and research themes are grouped into research clusters. A cluster typically consists of three to five themes. The cluster is primarily an administrative entity; it is based on discipline-related and pragmatic considerations. The heads of each research cluster serve as members of CWI's management team.

The following paragraphs give a broad overview of each cluster.

PNA – Probability, Networks and Algorithms. The research in PNA lies on the borderline of mathematics and computer science. The current focus is on discrete and probabilistic analysis, modeling, algorithms, and optimization (with analysis, discrete mathematics, game theory, logic, number theory, operations research, and stochastics as prime tools), and on their applications in technology, management, trade, and biology, in particular in information technology, operations management, finance, transport, communication, combinatorial and computational biology, medicine, textile trade, and the environment.

PNA currently hosts four full research themes and one pilot theme. The work and results of PNA are described in detail in Chapter 3.

SEN – Software Engineering. The research activities of SEN are focused on various aspects of software engineering, evolutionary systems and distributed multimedia systems. Typical research questions are the analysis and transformation of software systems, verification of embedded software, component-based development, competitive agents and multimedia architectures. The ambition is to cover the whole range of activities from fundamental concepts and prototype implementations to the validation of these concepts in practice.

SEN currently hosts four full research themes and one pilot theme. The work and results of SEN are described in detail in Chapter 4.

MAS – Modelling, Analysis and Simulation. The research area of MAS is applied and numerical mathematics. The emphasis lies on partial differential equations with

Table 1.4. CWI Management Team, 1997–present

Function	Dates	Person
Director	1999 — 5/2003 6/2003 — 10/2003 10/2003 — present	Dr.ir. G. van Oortmerssen Drs. W. Hutter Prof.dr. J.K. Lenstra
Controller	1999 — 6/1999 2/2000 — present	Drs. P. van der Veen D.G.C. Broekhuis
Leaders of research clusters		
Probability, Networks and Algorithms PNA	1999 — present	Prof.dr. A. Schrijver
Software Engineering SEN	1999 — 12/2001 1/2002 — present	Prof.dr. J.W. de Bakker Prof.dr. P. Klint
Modelling, Analysis and Simulation MAS	1999 — 8/2000 9/2000 — present	Prof.dr.ir. C.J. van Duijn Prof.dr. J.G. Verwer
Information Systems INS	1999 — present	Prof.dr. M.L. Kersten

mathematical analysis, scientific computing, computational fluid dynamics and computational electromagnetics as major activities across all three MAS themes. Smaller sized activities include control and system theory (discrete event systems, hybrid systems, realization theory, system identification theory) and asymptotics and special functions (with involvement in a major revision of the classical *Handbook of Mathematical Functions*).

MAS currently hosts three full research themes. The work and results of MAS are described in detail in Chapter 5.

INS – Information Systems. The research activities of INS are focused on various aspects of information systems. Current research topics include management of large multimedia datastores with probabilistic query processing features; methods and models for narrative story telling over multimedia stores; prototyping novel visualization techniques on concrete applications and devices; and theory-inspired investigation into the nature of new quantum computing paradigms. All research activities seek a balance between application inspired problems, the accompanying software architectures and experimentation, and the scientific modeling and analysis of the solutions invented.

INS currently hosts four full research themes. The work and results of INS are described in detail in Chapter 6.

1.4.3 CWI support structure

In addition to its four research clusters, CWI currently has six support departments: financial services, personnel, communications and publications, computer systems, housing and facilities, and the CWI library. The heads of the service departments, together with the controller and general director, form a separate support policy board (BGO). The structure and responsibilities of the support departments are discussed in Chapter 7.

Table 1.5. CWI staff, 1999–2005 (in FTE/year, *prognosis)

CWI Staff	1999	2000	2001	2002	2003	2004	*2005**
Total tenured staff	**55.3**	**53.2**	**49.4**	**52.2**	**53.0**	**54.5**	***55.0***
Non-tenured staff	24.0	28.0	26.1	27.0	30.9	26.3	*35.2*
CWI PhD students	27.3	34.2	41.5	43.1	45.8	55.8	*70.6*
Total research staff CWI payroll	**106.6**	**115.4**	**117.0**	**122.3**	**129.7**	**136.6**	***160.8***
Support staff	50.5	50.0	51.0	51.3	53.5	52.2	*51.3*
Total staff CWI payroll	**157.1**	**165.4**	**168.0**	**173.6**	**183.2**	**188.8**	***212.1***
Seconded PhD students	*16.3*	*12.0*	*10.6*	*6.1*	*5.2*	*5.2*	*4.2*
Other seconded staff	*20.9*	*24.4*	*22.4*	*17.4*	*14.5*	*16.4*	*11.0*
Total hosted staff	***194.3***	***201.8***	***201.0***	***197.1***	***202.9***	***210.4***	***227.3***

1.4.4 Employee works council

CWI also has a works council, the *ondernemingsraad* (OR), which consists of members chosen by the Institute's staff. The OR has a legal charter to advise management on significant policy issues that impact the Institute's long-term viability or which have a significant impact on the Institute's staff. The OR meets on a monthly basis and has bi-monthly meetings with the director. In 2004, the OR had seven members.

1.5 Cost-benefit overview

This section summarizes information on CWI's staff size and staff distribution. We also discuss the productivity of CWI's researchers. We close the section with a discussion of the financing of CWI's research activities.

1.5.1 Staffing

The staff in residence at CWI consists of several groups: tenured researchers with permanent appointments, non-tenured postdocs with temporary appointments, a support staff with permanent appointments, PhD students who are funded by projects coordinated at CWI, and a broad set of part-time or temporary staff members who are employed elsewhere and detached (or seconded) at the Institute. The tenured staff, non-tenured postdocs, support staff and the majority of the PhD students are CWI employees. At the beginning of the evaluation period, some of CWI's PhD students were formally employed by external funding agencies (such as NWO), but these numbers have been reduced in recent years because of an NWO policy change. The staffing levels for CWI during the evaluation period (along with a prognosis for 2005) are given in Table 1.5.

During the evaluation period, the size of the support staff has remained constant at approximately 51 FTE, representing 26% of the total hosted staff. The tenured staff has also remained relatively constant at about 53 FTE, also representing 26% of the total hosted staff. The number of non-tenured postdocs varied slightly between 24 and 31 FTE, representing between 12% and 15% of the total hosted staff. The number of seconded researchers averaged 19 FTE, representing approximately 9% of the hosted

staff. The number of PhD students in residence averaged approximately 50 FTE, or 25% of the hosted staff.

During the evaluation period, the number of staff directly employed averaged 172 FTE. Of these, over 70% were research staff members. Of the total hosted staff, 75% were research FTE. The difference between hosted FTE and directly employed FTE was, in the beginning of the period, strongly influenced by the PhD student employment policy of NWO. Table 1.6 shows the distribution of PhD students by employment type during the period.

Table 1.6. PhD students, 1999–2005 (in FTE/year, *prognosis)

PhD Students Hosted	1999	2000	2001	2002	2003	2004	*2005**
CWI PhD students	27.3	34.2	41.5	43.1	45.9	55.8	*70.6*
Seconded PhD students	16.3	12.0	10.6	6.1	5.1	5.4	*4.2*
Total hosted PhD students	***43.6***	***46.2***	***52.1***	***49.2***	***51.0***	***61.2***	***74.8***

Please note that Tables 1.5 and 1.6 provide information based on FTEs, not individuals. Since many seconded staff members have part-time appointments – typically one or two days per week – the actual number of researchers hosted at the Institute is significantly higher than the FTEs shown.

1.5.2 Productivity

During the same period, CWI's staff published an average of 300 academic publications per year, as well as an average of eight monographs, 10 PhD dissertations and 100 other professional publications and products. This is equivalent to approximately 2.4 academic publications per payroll research staff member, including PhD students. The research output is summarized in Table 1.7. More detailed summaries are given

Table 1.7. Aggregated scientific output, 1999–2004

Output class		1999	2000	2001	2002	2003	2004	Total
Academic	refereed journals and proceedings	216	306	265	258	316	317	1,678
	other journals and proceedings	17	11	21	28	27	42	146
	book chapters	10	17	14	12	10	12	75
	Total academic	**243**	**334**	**300**	**298**	**353**	**371**	**1,899**
Monographs		8	12	6	9	6	5	46
PhD dissertations		8	11	12	17	9	12	69
Professional publications/products		62	115	101	116	138	93	625

elsewhere in this report. A full publications summary and description of research out-

put is given on the companion CD-ROM to this report. As a further measure of productivity, Figure 1.2 compares CWI's output with that of the eight other ERCIM institutes that are similar in structure and mission to CWI. (This represents approximately half of ERCIM's members.) Figure 1.2, which shows averages of output over 2002 and 2003 – the years for which comparative data was available – illustrates CWI's relative size (Figure 1.2-a), the number of refereed publications per payroll research FTE (Figure 1.2-b), and the PhD production rate per tenured/non-tenured payroll research staff FTE (Figure 1.2-c).

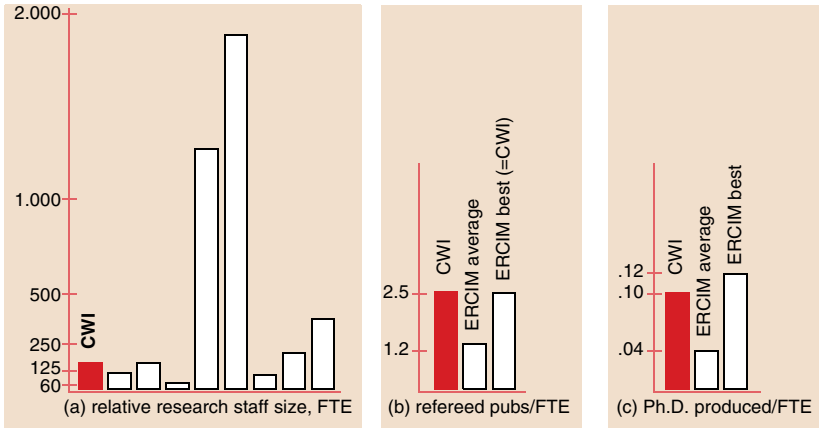


Figure 1.2. CWI productivity as compared with other ERCIM institutes, 2002–2003

There are plans within NWO to standardize on a citations reference system for its institutes. An initial journal-based system is in place for mathematics, but no similar system exists at the time of this writing for computer science. In the initial analysis of the mathematics community, CWI scores among the top research institutions nationwide in both the raw citations and impact categories.

1.5.3 Costs and funding

In the period 1999–2004, the annual operating budget was approximately M€14. The primary expense item for the Institute is personnel, which constitutes nearly 75% of costs. Other costs include housing, utilities, travel and equipment. During the period, CWI's primary source of funding was NWO, which provides approximately 65% of CWI's operating budget. Approximately 20% of the operating budget is covered by other research grants obtained from competitive funding sources and 5% is covered by direct research contracts. A final 5% is covered by a variety of sources, including special proceeds obtained from the sale of licenses or equity in spin-offs. CWI maintains a modest buffer fund to cover transient funding requirements.

A summary of expenses and funding for the period 1999–2004 is given in Table 1.8. The source of all figures are the financial statements approved by CWI's auditors. Amounts before 2002 have been converted to euros. Note that because of change in NWO accounting practices, slight deviations can be expected from the annual reports filed in each year.

Table 1.8. CWI financial summary, 1999–2004

Expenditures (k€)	1999	2000	2001	2002	2003	2004 est
Personnel costs	8,996	9,671	9,736	10,874	11,362	11,860
Other costs	4,007	4,988	4,099	3,128	3,285	2,997
Addition to reserves	151	734				58
Total	**13,154**	**15,393**	**13,835**	**14,002**	**14,647**	**14,915**

Funding (k€)	1999	2000	2001	2002	2003	2004 est
Direct funding	8,897	8,453	8,862	9,465	9,632	10,502
Research funding	2,567	3,458	3,118	2,628	2,396	3,749
Contracts	709	602	683	483	822	507
Other	982	2,881	345	306	269	157
Extraction from reserves			827	1,120	1,528	
Total	**13,155**	**15,394**	**13,835**	**14,002**	**14,647**	**14,915**

Expenditures (%)	1999	2000	2001	2002	2003	2004 est
Personnel costs	*69%*	*63%*	*70%*	*78%*	*78%*	*80%*
Other costs	*30%*	*32%*	*30%*	*22%*	*22%*	*20%*
Addition to reserves	*1%*	*5%*				*0%*
Total	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

Funding (%)	1999	2000	2001	2002	2003	2004 est
Direct funding	*68%*	*55%*	*64%*	*68%*	*66%*	*70%*
Research funding	*20%*	*22%*	*23%*	*19%*	*16%*	*26%*
Contracts	*5%*	*4%*	*5%*	*3%*	*6%*	*3%*
Other	*7%*	*19%*	*2%*	*2%*	*2%*	*1%*
Extraction from reserves			*6%*	*8%*	*10%*	
Total	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

The funding percentages per cluster of CWI's research budget are shown in Table 1.9. In the tables that provide data on externally funded projects per theme (Chapters 3–6) gross budgets are mentioned.

1.6 Reflections on the 1999 evaluation recommendations

The previous full external evaluation of CWI occurred in 1999, covering the period 1992–1998. As part of this review, each of CWI's scientific themes were rated, as was the Institute as a whole. In its reaction to the external evaluation, NWO's Council for Physical Sciences (GB-E) provided additional review comments and suggestions.

1.6.1 Summary of recommendations

CWI's fifteen research themes were rated based on the five-point scale of excellent, very good, good, satisfactory and unsatisfactory. Seven themes were rated as excellent, five were rated as very good and one was rated between very good and good. One theme was rated as good and one as unsatisfactory. CWI, as a whole, was rated as being very good, with an external impact that was very high.

Table 1.9. CWI funding percentages of research clusters, 1999–2004

Cluster	1999	2000	2001	2002	2003	2004
PNA	22.0%	20.6%	26.1%	25.4%	25.1%	21.6%
SEN	26.9%	30.6%	28.8%	27.9%	29.1%	33.4%
MAS	23.4%	20.4%	18.7%	19.4%	20.2%	18.8%
INS	27.7%	28.4%	26.4%	27.3%	25.6%	26.2%
Total	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**

The external reviewers were pleased with CWI's response to earlier review comments, its performance with respect to spin-off companies, and its new (in 1999) management structure. The committee was also supportive of CWI's efforts to gain more open access to external funding (specifically that related to the Telematics Institute) and it found the trend toward more temporary staff assignments positive.

The concerns of the committee were the fact that CWI's housing facilities provided little room to accommodate new staff, that CWI had a two-year postdoc policy that was seen as being rigid, and that the burden of theme members who were deemed as being unproductive often were not shared across the Institute (thus adversely impacting the performance of individual themes). The review committee also recommended that CWI analyze the potential for patent protection for its results and it noted its concern that CWI should not attempt to fill the void resulting from reductions within the Dutch industrial research community as this would threaten the fundamental nature of CWI's own research. The committee further felt that CWI's production of PhDs in the period was modest. Finally, the committee recommended that CWI investigate more systematic bilateral cooperation with international partners (as it had done with Germany's GMD).

In addition to the evaluation of the external review committee, the GB-E also provided a set of recommendations and suggestions. While most of these recommendations dealt with national funding issues, two items have broader relevance to this review. First, GB-E felt that CWI should concentrate on building fewer themes than the fifteen in place in 1999, with each of the resulting themes having a larger scope. Second, GB-E felt that CWI's 1999 staffing level was appropriate for the future and that no significant growth of the Institute was desired.

1.6.2 CWI's actions in response to the review recommendations

CWI was pleased with the strongly positive evaluation of its research groups. It also acted on the recommendations received from the external review committee and GB-E. In summary, all themes rated below very good have been discontinued, either via direct termination or internal reorganization. In the natural course of CWI's activities during the past six years, several other themes were reorganized or moved within the organization, several new pilot themes were created and several themes that existed in 1999 were terminated (usually as the result of staff changes in the Institute). The

detailed responses of each theme to individual comments, suggestions and recommendations from the 1999 review have been explicitly addressed within the research theme descriptions found elsewhere in this evaluation.

As for the more general concerns of the review committee, CWI undertook the following actions.

Housing. CWI has been in active consultation with NWO to develop plans and secure funding for new or expanded facilities for its researchers and research infrastructure. Since CWI is not in a position to finance physical plant expansion directly, this process is dependent on funding priorities that are beyond the Institute's control. We are pleased that plans for expanding CWI's facilities, including an expansion of space to house new staff members, are at an advanced stage. The Institute expects approval for its plans in 2005.

Postdoc employment policy. In contrast to the review committee's perception, CWI is able to offer flexible postdoc positions. Our standard policy is to offer an initial two-year contract, which can easily be renewed for two or, in exceptional circumstances, four years. Given the nature of postdocs and the need for temporary staff to find external employment when no permanent positions are available at CWI, a postdoc period of longer than six years is seen as undesirable.

Sharing the burden of unproductive staff. CWI is aware of its responsibility to actively monitor staff performance and to help position staff across the breadth of its research activities. The Institute relies on a pro-active HRM policy to maximize staff effectiveness. When a staff problem is signaled, the director, together with the personnel department, attempts to find an HRM solution that is tailored to the needs of the individual staff member. This includes possible placement within a support department, assistance in out-placement or early retirement, or the creation of a new position within another research group on a best-fit basis. CWI also maintains budgetary instruments to reduce the financial burdens on individual themes due to personnel issues. This policy has been broadly successful during the period.

Potential for patent protection. The issue of patent protection is under active study by CWI's governing organizations. While the merits of patenting publicly-financed research remains a highly debated issue, it is clear to CWI that it is not in a position to effectively manage the commercial exploitation of a patent portfolio directly: it has neither the staff nor the expertise to accomplish this task on its own. While the patent climate has changed considerably since these recommendations were made in 1999, the entire question of patentability remains an open issue.

The impact of a declining Dutch industrial research sector. CWI is acutely aware of the impact of the declining industrial research sector within the Netherlands. While such a decline provides a measure of opportunity for new projects at the advanced end of the industrial R&D spectrum, it also provides substantial threats in terms of a declining marketplace for placing and obtaining research staff members. CWI has no short-term plans to fill a substantial part of the industrial R&D void, but it does remain an active partner across the spectrum of national and European research organizations. CWI will continue to establish closer cooperation and ties with selected organizations

without jeopardizing its fundamental academic research character.

PhD production rate. CWI does not share the observations of the evaluation committee about the output rate of PhDs. As detailed in section 1.5.2, the production rate, which averages at approximately 10.5 degrees per year based on a research staff of approximately 150, is essentially the same or better than is found at similar institutes (such as INRIA or GMD/Fraunhofer). Since CWI is significantly smaller than some other national research centres, our absolute numbers are, of course, also smaller in magnitude.

Increased bilateral international research partnerships. As was discussed above, CWI remains active in participating in national and international partnerships that align with its mission of producing first-rate scientific research results. As on the Dutch national level, the European research landscape is in a state of flux. In this changing environment, CWI's strong participation as a founding member of ERCIM, its active participation in numerous European and other international research projects, and its policy of exchanging staff with partner organizations provides a sensible basis for future growth. We will continue to monitor developments in Europe with interest, but do not expect more formal ties with other Institutes at this time.

Increased size of a more limited number of research themes. CWI feels that one of its strengths is the effective structuring of its research components. Each of CWI's themes are managed by active researchers who contribute directly to the theme's research output. In order to pursue leading-edge research (which is often individual in nature) and have a light-weight management structure, CWI has opted to maintain its current policy of encouraging the positioning of highly-focused theme-based research. This provides both increased flexibility to start, develop and terminate themes, and it provides an achievable personal development path for the Institute's researchers. While we appreciate the potential for the greater critical mass larger themes provide, these benefits do not provide across-the-board advantages for the bulk of the research activities within the Institute. We feel that ample opportunities exist for topic-based cooperation among CWI's researchers, which contributes to a more dynamic context-based grouping of research strength with a significantly lower management overhead than would be provided by a structural bundling of existing themes when non-structural research overlap is present.

Overall staff size. In 1999, CWI employed a research staff of 107 FTE (and hosted a total of 144 research FTE). Since the previous evaluation, the Institute has been successful in attracting funding for large new research initiatives (both national and international). While a substantial increase in size by direct growth or acquisition is not in CWI's plans, and while a multi-campus model is not currently anticipated, CWI does expect to stabilize its staff size at a level consistent with the expected staff size that has resulted from its participation in the BRICKS, MultimediaN and VL-e research initiatives. This will result in an effective growth of its on-payroll research staff to approximately 160 FTE (and a hosted research staff of 175 FTE). A more modest growth in support staff (to remain at or below the level of 30%) is also anticipated.

1.6.3 Summary

It is CWI's policy to maintain a strong presence within the national and European research community by focusing on excellence in its staff and by directing its resources to solving new and socially relevant problems. We are encouraged by the positive review received in the past and accept the responsibility to maximize our resources in the future.

1.7 Structure of this self-evaluation

This evaluation report of CWI research is structured into seven chapters, of which this introduction has been the first. Chapter 2 provides an overview of CWI research strategy for the coming five years. Chapters 3, 4, 5 and 6 provide an overview of the research performed during the period 1999–2004 in each of CWI's clusters and themes. Chapter 7 provides an overview of the activities of CWI's six support departments in the period 1999–2004. Appendix A contains a summary of common acronyms.

Two companion volumes contain a selection of CWI publications over the review period. A companion CD-ROM gives detailed information for each of the research themes.

Chapter 2

Strategy 2005–2010

2.1 The research landscape

2.1.1 CWI's position

The research landscape in applied mathematics and computer science has changed drastically over the last five years. As a result of the emphasis on near-to-market research in EU framework programs, the internet bubble, and the push for early economic exploitation of scientific results, the long-term research infrastructure in Europe has suffered severe damage. So far, CWI and some of its ERCIM partners, notably France's INRIA and the Irish University Consortium, are holding their own against this threat.

NWO has created a seamless portfolio of programs to fund projects and to stimulate talented individuals. Through NWO and other offices, the Dutch government maintains a series of national research labs (AMOLF, Astron, CWI, ESI, EURANDOM, NIKHEF, and others) as well as a dedicated high-capacity network for research and education. In addition to this sizeable investment, it has made available M€800 over a six-year period to strengthen the country's position as a knowledge-based society.

Within this landscape CWI has maintained its prominent and unique position. Its core business remains *long-term research*. The combination of mathematics and computer science in a single institute favors a strong interaction between applied mathematics, applied logic, and computer science. Verification research, for instance, involves applied logic and algorithmics. Discrete algorithmics is also of great importance in CWI's groups in optimization, cryptology, quantum computing, and agent systems, while development of improved numerical algorithms is a unifying theme in the applied analysis cluster. Conversely, applied logic and mathematics find inspiration and challenges in many computer science disciplines, such as telecommunication, ERP, multimedia information systems, and software development. The modern mathematician cannot be a computer illiterate, while the computer scientist needs the methods and machinery from logic and mathematics.

Acting as a *meeting place* for young researchers from around the world, CWI stimulates interdisciplinary projects, not only combining mathematics and computer science as mentioned above, but also other fields, such as physics, economy, and the strategically important life sciences. CWI is one of the partners in the Telematics Institute, which was founded in 1998 in an attempt to create an institute at the meeting point of computer science, telematics, and e-commerce. Without giving up its own identity, CWI intends to participate in other such interdisciplinary initiatives.

Providing *facilities* for various organizations such as W3C and a comprehensive library of national importance is the third element in CWI's profile.

2.1.2 Visions and research agendas

Reflecting on the long-term strategy of an institute like CWI, we observe a slow but profound evolution of its field of research, which makes the potential impact of CWI on science and society at the beginning of the 21st century bigger than ever before. Algorithmics has pervaded many branches of mathematics, and advanced information processing is turning areas like physics, biology, sociology, cognitive science, economics, and linguistics into computational sciences. As the new century develops, more and more empirical sciences will absorb insights from mathematics and computer science. We are no longer just servants to the empirical disciplines, providing tools to process information, but have opened a direct dialog with them about the nature of their basic models and techniques. At the same time this dialog is a rich source of inspiration and opportunities for us. CWI sees it as an important challenge to play a vital role in the development of the national and international research landscape from this perspective.

Apart from this general development, CWI's research is influenced by a series of agendas. First, NOAG-i, the national research agenda for computer science 2001–2005, has identified seven themes: *algorithms and formal methods*; *software engineering*; *embedded systems*; *intelligent systems*; *multimedia*; *modeling, simulation, and visualization*; and *parallel and distributed computing*. NWO and BSIK, among others, have initiated corresponding funding programs, which are important to CWI. NOAG-i's successor, which is currently being drafted with strong CWI involvement, is expected to have a similar impact.

Other important agendas are the 2003 and 2004 ICT-Forum visions, the 2004 ICT-Forum report on ICT research and health care, and the upcoming research agenda for the EU 7th Framework Programme (FP7). Last but not least, the research agendas and advanced software products of IBM, Microsoft, Nokia, Philips, and other companies are of increasing importance. Government funded, easily accessible research has become a significant driver for product innovation. The Philips High Tech Campus is illustrative of an infrastructure that acts as a meeting place for research and innovation. CWI is a strong partner in these developments.

As far as mathematics is concerned, the future of mathematics research in the Netherlands was analyzed in a 1999 report by KNAW. This led to the 2002 national strategy for mathematics research, which in turn is leading to the establishment of national mathematics clusters (not to be confused with CWI's research clusters). CWI is a partner in two of the three clusters that are being created, in *non-linear dynamics in natural systems* and *discrete, interactive and algorithmic mathematics, algebra and number theory*.

Some topics that are expected to dominate the computer science research agenda for the near future are information security, ubiquitous computing, self-organizing software systems, and ambient intelligence. For applied mathematics important areas are non-linear dynamics, complex systems, computational science, and stochastic networks.

2.2 Mission and goals

As mentioned in Section 1.2, the mission of CWI is two-fold:

1. To conduct frontier research on selected topics in mathematics and computer science at a competitive international level, and
2. To transfer new knowledge in these fields to society in general, and to trade and industry in particular.

This mission, which has remained basically the same since CWI was founded in 1946, has gained in importance in view of the developments sketched in Section 2.1. Long-term research is a catalyst for continued economic growth. Institutes like CWI are breeding grounds for human capital, innovation, and education.

In accordance with its mission CWI has identified the following primary goals for the coming period:

To conduct advanced research. In particular:

- *To initiate new research,* and to introduce new areas of expertise in the country. Recent examples are the themes *Quantum Computing and Advanced Systems Research*, *Nonlinear Dynamics and Complex Systems*, *Cryptology and Information Security*, and *Convergent Media Interfaces*.
- *To address research problems of great societal relevance.* Examples are ICT research in health care, a potential new field for CWI whose importance was emphasized in a recent ICT-Forum report, and applications of mathematics and computer science in the life sciences.
- *To perform innovative contract research for industry.* Some current projects are "Impact of resource sharing on capacity and performance of multiservice wireless networks" for France Télécom and "An open next generation SMIL reference implementation" for Stichting NLnet.

To act as a breeding ground and meeting place for young researchers and academic staff. At any time, CWI employs a large number of PhD students and postdocs. A large percentage of current Dutch full professors in mathematics or computer science have held or hold (part-time) positions at CWI. The retirement of the first generation of computer scientists in five to ten years and the expected budget increase for computer science create a continuing need for a setting in which a new generation of researchers, temporarily shielded from teaching and administrative duties, can mature.

To foster close contacts between academia and corporate and government parties. CWI has strong contacts with Dutch-based multinational corporations such as AKZO, DSM, Philips, Shell, and Unilever, with Dutch banks and software companies, with Netherlands Railways (NS), France Télécom, and KPN, and with national institutes such as KNMI, NRL, MARIN, RIVM, TNO, and many others.

To play a leading role in mathematics and computer science policy making. CWI aims at playing a leading role in setting the national research agendas in applied mathematics and computer science. It currently holds the chairs of IPN, the organization

of Dutch computer science research schools, and ACI, NWO's computer science advisory committee; these bodies are involved in drafting the national research agenda for computer science (NOAG-i) for the period 2005–2010. It is also represented in OOW, the organization of Dutch mathematics research schools, and in ACW, NWO's mathematics advisory committee. Several of its staff members are active in KNAW. On an international level, CWI plays a role in many scientific societies and organizations, and it was represented on the Fields Medal jury.

2.3 Strengths, weaknesses, opportunities, threats

2.3.1 Strengths

Identity. In view of the global decline in long-term research capacity, CWI's mission of fundamental research has become more urgent than before. Its position in the Dutch applied mathematics and computer science landscape is unique. Its role as a central meeting point for researchers, the prominent participation of its researchers in organizations and discussions on a national as well as international level, the administrative support it provides to various mathematics and computer science societies, and the *de facto* national status of its library further attest to this.

Quality of staff. The competence of CWI's research staff is widely recognized.

Contacts. CWI has strong contacts and cooperations within the scientific world and with the public and private sector, both nationally and internationally. A large number of its former and current employees hold academic positions worldwide.

Theme-oriented organization. CWI's theme-oriented research organization supports a flexible and interdisciplinary research policy.

Financial structure. CWI's internal financial system is clearly structured, with budgets decentralized to the theme level. The combined transparency in research and finances is exploited by the management team to control budgets and research programs of all themes effectively.

2.3.2 Weaknesses

Housing. CWI's housing facilities are a point of concern. One of its primary goals is to act as a meeting place, which makes the situation even more urgent.

Software development. The development, distribution, and maintenance of major software systems, which is an important activity in some of CWI's research groups, taxes its capabilities.

HRM. Some of CWI's groups have a relatively large tenured research and programming staff. Also, collective labor agreements and external funding schemes sometimes hamper flexibility in HRM.

Public relations. With some exceptions, CWI's marketing, public relations, and popularization of the results obtained need improvement.

2.3.3 Opportunities

Global ICT developments. The rapid development of ICT technology in today's society is a rich source of opportunities for CWI.

Science Park Amsterdam. The increasing activity in the Science Park Amsterdam is creating favorable circumstances for new multidisciplinary research cooperations, in particular in the life sciences.

Strategic alliances. There are opportunities to reinforce or establish programmatic cooperation with ICT institutes devoted to short-term applied research whose areas of expertise complement those of CWI.

Industrial R&D. Industrial R&D has been shifting towards short-term goals. This creates opportunities for fundamental research by CWI that is needed by industry, but no longer conducted by it.

2.3.4 Threats

R&D climate. The overall political and corporate climate is not favorable for R&D, especially not for fundamental research, CWI's key activity.

Global ICT developments. The rapid pace of ICT development in combination with CWI's small size also has a drawback. The overwhelming technology push of the large multinational corporations leads to an innovation pace that is hard to follow and even harder to join.

External funding. CWI obtains about a quarter of its income from research grants that only partially cover the costs of the projects in question. It has to provide matching funds from its basic NWO subsidy, which reduces the budget for vision-driven research.

HRM. Both talented young researchers and senior staff members are hard to find. The latter often leave as a result of academic appointments, which is a major goal and success of CWI. The steadily declining interest in mathematics and theoretical computer science among younger people is a matter of grave concern to CWI, threatening recruitment, outflow, and societal support.

Identity. Reconfiguration of CWI by merging it with institutes for short-term research would be a threat to its unique identity, which is its major strength. Forging strategic alliances with such institutes as indicated above is a simpler, less risky alternative.

2.3.5 Analysis

CWI has a unique position and an excellent reputation. If anything, its mission has become more urgent since the previous review in 1999 in view of the global decline in long-term research capacity. There is certainly no lack of new research topics, but they have to be chosen carefully, since the scale and pace of developments, especially in ICT, make it hard to achieve sufficient critical mass. Strategic alliances with short-term oriented research institutes can help to alleviate this problem and to bridge the gap between theory and practice. Apart from this, CWI's housing facilities are a point of urgent concern, and some HRM issues and public relations need attention.

2.4 Strategy

2.4.1 Overall strategy

In view of the above goals and SWOT analysis, the Institute has adopted the following overall strategy for the period 2005–2010.

Reinforce CWI's prominent position in long-term fundamental research. Initiate new research in, for instance, multiscale analysis, hybrid systems, stochastic and dynamic networks, algebraic methods in optimization, probabilistic algorithms, algorithmic game theory, new computing paradigms, software systems tomography, self-organizing database systems, and knowledge elicitation.

Expand CWI's position in long-term applied research. Participate in applications of mathematics and computer science in, for instance, the life sciences and in health care related ICT research.

Strengthen CWI's involvement in ICT research for the humanities and social sciences. Participate in programs such as CATCH on cultural heritage and Stevin on language technology.

Forge strategic alliances with external parties. Reinforce or establish programmatic cooperation with short-term research oriented ICT institutes whose areas of expertise complement those of CWI. Try to find external parties interested in and capable of alleviating CWI's software development limitations.

Improve housing. Plans for expanding CWI's facilities are in an advanced stage. Adding a new wing to the current building is the preferred option.

Improve HRM. Implement individual career paths for staff members using, for instance, a tenure track process. Improve mobility of tenured staff by entering into transfer agreements with other parties. Strengthen international talent scouting efforts in cooperation with national laboratories and ERCIM partners.

Improve public relations. Each theme needs to make its results more accessible to CWI's constituents – potential partners, students, funding agencies, society, etc. The themes will develop demos for PR purposes; CWI's web presence will be improved.

Increase public interest. Contribute to promoting mathematics and computer science.

2.4.2 Knowledge transfer and cooperation with industry

In fundamental research, journal and conference publications, teaching, and PhD supervision are the classical knowledge transfer mechanisms. This is no different for CWI. Many of the Institute's staff members hold part-time full professor positions at universities, while at any time a large number of PhD students and postdocs hold temporary positions at CWI.

At least as important to CWI is the more direct and focused knowledge transfer resulting from joint projects with corporate partners (including CWI spin-offs), universities, research schools, and other research laboratories, from contract research (currently 6% of CWI's income), and from the creation of spin-offs.

The knowledge produced by CWI can be made even more productive by reinforcing or establishing programmatic cooperation with short-term research oriented ICT

institutes. This is one of the Institute's strategic goals for the coming five years. Another one is strengthening its marketing, public relations, and popularization efforts.

2.4.3 Human resource strategy

Job market. Both talented young researchers and senior staff members are hard to find. Especially mathematicians are in short supply. The declining interest in mathematics and theoretical computer science among younger people is an issue of grave concern. For this reason, the Institute considers it a matter of strategic importance to strengthen its international scouting efforts in cooperation with national laboratories and ERCIM partners, and to contribute to promoting public interest in mathematics and computer science.

Recruitment and career development. PhD students generally leave CWI after obtaining their doctorate. Tenured staff is largely recruited from among the most talented postdocs, using a stepwise selection process that resembles a tenure track system. It only rarely happens that an experienced researcher from outside the Institute is directly appointed to a tenured position. To improve the selection process as well as the career perspectives for the people involved, CWI is implementing a system of individual career paths for staff members. In comparison to university faculty, senior staff receives a somewhat lower salary but enjoys more autonomy and has to deal with less bureaucracy. CWI views the departure of its researchers to academic positions not as a loss but as a success, which also fosters relations with academia.

Mobility. Some of CWI's themes have a relatively large tenured research and programming staff. CWI will make an effort to improve mobility of tenured staff by entering into transfer agreements with academic as well as corporate parties.

2.4.4 Financial strategy

During the late 1990s, CWI was able to build up a financial buffer from positive results in research projects to cover transient short-term financing needs. This buffer was extended with the proceeds from the sale of equity in CWI spin-off companies, and with fees from licenses of CWI technology. In 1999, the buffer was approximately M€4. While this is a substantial amount for an organization the size of CWI, several factors have contributed to a steady depletion of the buffer since then.

A primary reason was a delay in the start of the EU's 6th Framework Programme and the one-year delay of the Dutch BSIK financing. Another significant factor was the change from cash basis accounting to accrual accounting mandated by the Dutch Government. Contributing factors were the rise in salaries resulting from new collective labor agreements and a rise in the cost of products and goods resulting from the introduction of the euro. The increase in base funding by NWO was insufficient to cover all these extra expenditures. The financial problems were compounded by a negative opinion on the Institute's VAT exemption that, if it survives our appeal, will result in an additional expense of k€450 per year.

One of the Institute's priorities during the coming period will be to strengthen its buffer fund. Guidelines in financial management hold that 15% to 20% of the turnover

Table 2.1. Target budgets 2005–2010 (all amounts in k€ of 2005)

Income	2005	2006	2007	2008	2009	2010
NWO basic funding	10,375	10,625	10,750	10,875	11,125	11,125
NWO funding housing & paid VAT*	950	1,450	1,450	1,450	1,450	1,450
NWO projects	1,625	1,625	1,625	1,625	1,625	1,625
National programs - BSIK	1,500	1,500	1,500	1,500	750	750
National programs - other	1,200	1,200	1,200	1,200	1,200	1,200
International programs	300	300	300	300	300	300
Liaison/contract research	425	400	400	400	400	400
Other income	275	275	275	275	275	275
Allowance depreciation before 2002	510	430	430	430	430	430
Total income	**17,160**	**17,805**	**17,930**	**18,055**	**17,555**	**17,555**

Expenses	2005	2006	2007	2008	2009	2010
Personnel expenses	12,600	12,700	12,800	12,900	12,900	12,900
Retirement/reduced payment funds	350	350	350	375	375	375
Material expenses	2,200	1,950	1,950	1,950	1,950	1,950
Non refundable VAT*	950	450	450	450	450	450
Depreciation - new housing	0	1,000	1,000	1,000	1,000	1,000
Depreciation - other	830	880	885	885	885	885
Total expenses	**16,930**	**17,330**	**17,435**	**17,560**	**17,560**	**17,560**

Prognosis	2005	2006	2007	2008	2009	2010
Annual result	**230**	**475**	**495**	**495**	**-5**	**-5**
Equity at year end	**376**	**851**	**1,346**	**1,841**	**1,836**	**1,831**

* Figures regarding VAT in 2005 include amounts of 2003 and 2004

of an organization should be kept as a financial reserve; for CWI this would mean a reserve of approximately M€2. While building this buffer will be a challenge – especially given the negative equity climate for CWI's spin-off companies – the Institute expects that the external projects in place for the coming years, together with a realistic level of base funding from NWO, will enable CWI to carry out its research mission and build an adequate financial reserve for the future.

Another issue of strategic concern is the continued trend toward matching funding in projects. External projects often require matching of between 30% to 70% of the project costs. Hence, CWI is unable to participate in all of the relevant research programs in the Netherlands and across Europe. While CWI is pleased that this issue now figures prominently in national policy discussions, the fact remains that at present matching obligations absorb a substantial portion of our base funding.

Table 2.1 provides a financial summary of CWI's expected expenses based on the projected funding situation during the coming six years.

2.4.5 Growth scenario

CWI's mission is, in brief, to perform fundamental research in mathematics and computer science in the public interest. It is motivated by the intrinsic quest for knowledge, which continuously renews itself, and by the need to enable further technological development, to support lasting economic growth, and to help facing environmental challenges. The Institute's *raison d'être* has become more important since the evalua-

tion of 1999 in view of the more pronounced role of mathematics and computer science as foundational disciplines as well as the global decline in long-term research capacity noted in Section 2.1.

In order to fulfill its mission, CWI intends to maintain its position as an independent research center, in between academia and more applied laboratories, with intensive relations with these and other societal partners, and requests to sustain a *moderate growth scenario* as indicated in Table 2.1.

During the review period CWI has grown by some 10%, largely as a result of its success in the BSIK program, which contributes M€1.5 to CWI's annual income over 2005. A continued expansion is, we feel, amply justified by the external factors mentioned above. It would require a slow increase in the basic funding to be provided by NWO. It would also require a continuation of the BSIK funding in some form after 2008. CWI suggests that a next BSIK tender has lean and efficient application procedures as well as granting criteria based upon quality and past performance, in accordance with NWO's tradition and in contrast to the present round.

CWI and the popular press

CWI's research has not gone unnoticed outside the scientific world. In 1999, the institute received considerable attention when an international team coordinated by CWI researcher Herman te Riele factored the RSA-155 challenge number. This achievement is equivalent to decoding data encrypted with the RSA-155 public-key cryptosystem, which is widely used to secure data transport, for example in the SSL internet security protocol. Media all over the world including *The New York Times*, *Le Monde*, and *The Sydney Morning Herald* published headlines like "Internet no longer secure".

In 2003 and 2004, several newspapers as well as international popular scientific journals like *New Scientist* and *Pour La Science* featured articles on Paul Vitányi's research on automated classification methods. This technique based on data compression calculates "the distance between Händel and Hendrix," as the Dutch newspaper *NRC Handelsblad* wrote. The same method can just as easily group related DNA sequences or languages, without prior knowledge of their nature.

Ute Ebert's discovery of the mechanisms behind the branching of sparks in 2002 featured in the news section of *Nature*. A year later, when Ebert won the Minerva Prize for best physics publication by a woman, the Dutch newspaper *De Volkskrant* published an extensive interview with her.

In 1952 the first Dutch computer was put into operation at the Mathematical Center, CWI's predecessor. 50 years later, many Dutch newspapers and websites paid attention to this event. The same happened when in 2003 the first open European internet connection, established at CWI, existed for 15 years.

Several Dutch newspapers featured articles on EUROPHLUKES. Goal is to compile a large database of photos of whales. CWI developed an algorithm that recognizes individual whales based on the shape of their tail fins.

Chapter 3

Research cluster PNA – Probability, Networks and Algorithms

General

Cluster leader

Prof.dr. A. Schrijver (1999–present)

Strategy and policy

PNA focuses on discrete and probabilistic analysis, modeling, algorithms, and optimization and on their applications in technology, management, trade, and biology, in particular in information technology, operations management, security, finance, transport, communication, combinatorial and computational biology, medicine, textile trade, and the environment.

Prime tools are found in a wide range of pure and applied mathematics: algebra, analysis, discrete mathematics, game theory, geometry, logic, number theory, operations research, and stochastics.

Much of PNA's research is on the borderline of mathematics and computer science, for instance, the projects on computational logic, computer-intensive methods in stochastics, computational complexity, network algorithms, automatic algorithms for still images, wavelet signal analysis, performance and control of computer-communication networks, and cryptology and information security.

PNA's first and foremost research objective is to make fundamental and applied contributions to problems and techniques in the above themes. Testing and implementing new techniques for practical use and developing algorithms also belong to the objectives. Algorithmics, networks, operations research, stochastics, and security are fields that are central to PNA and that connect the different themes.

Themes

- **PNA1:** *Networks and Logic - Optimization and Programming*.
- **PNA2:** *Advanced Communications Networks*.
- **PNA3:** *Stochastics*.
- **PNA4:** *Signals and Images*.
- **PNA5:** *Cryptology and Information Security*.

Developments

The pilot theme PNA4 started in January 1997 and was transformed to a regular theme in July 1999.

Table 3.1. Global staff survey of PNA0–PNA5 (*prognosis)

PNA		1999	2000	2001	2002	2003	2004	2005*
PNA0	CWI research staff						1.1	1.1
	Total research staff						*1.1*	*1.1*
PNA1	CWI research staff	5.9	5.7	7.4	7.4	8.0	7.4	9.9
	Total research staff	*8.7*	*8.9*	*10.7*	*9.7*	*8.9*	*8.6*	*11.9*
PNA2	CWI research staff	4.0	4.2	5.8	3.7	3.2	2.8	6.3
	Total research staff	*4.6*	*5.6*	*7.3*	*5.9*	*5.9*	*6.7*	*10.7*
PNA3	CWI research staff	4.2	3.7	6.2	6.1	5.1	3.7	2.7
	Total research staff	*8.5*	*7.9*	*9.7*	*8.1*	*5.9*	*5.3*	*3.9*
PNA4	CWI research staff	7.4	8.6	9.5	9.7	9.8	9.0	6.1
	Total research staff	*8.2*	*9.8*	*10.0*	*12.5*	*10.0*	*9.9*	*6.1*
PNA5	CWI research staff						2.3	7.1
	Total research staff						*2.4*	*7.4*

In January 2002 the former theme PNA2 was split up into a group focusing on systems and control, which is now part of theme MAS2, and a group focusing on performance and quality of service of communication networks, which forms the new pilot theme PNA2. It was decided that from January 2004 PNA2 continues as a regular theme.

In July 2004, a new pilot theme PNA5 started, which includes the group "Computational number theory and data security". This was part of theme MAS2.

Two small cluster projects, grouped under PNA0, are not discussed in this report.

Scientific challenges for PNA

The following challenges are currently playing a role at CWI in discussions on future research projects.

Network decomposition, visualization, and reliability. Many of today's questions can be described in terms of networks, and because of the computerization of modern life, the nature of most of these questions is computational. For designing practical software as well as for the fundamental understanding of the underlying computational issues we need to clarify our picture of these networks: how can they be visualized such that they become computationally more transparent and accessible, how can we break them into pieces to facilitate the organization of computational work, and how reliable are they? In spite of the work that has been done, some of the main challenges remain: the practical implementation of the techniques found so far, the balance between network users with different characteristics (like urgency and quality of service), and the role of forbidden substructures of networks that inhibit decomposition.

Ad hoc networks. A complicating feature of real-world networks, like those of mobile phones and wireless computers, is that they are hyper-dynamic: they vary quickly and unpredictably over time. Decisions on how to schedule or route tasks over these

ad hoc networks have to be made within a split second after one learns, often only partially, their actual structure. When these decisions are to be implemented the network will already have changed. Predicting and improving the performance of such *ad hoc* networks is extremely challenging. It also requires new techniques in queueing theory.

Lévy processes. Queueing theory is close to the theory of Lévy processes, and interesting contributions could follow from combining these branches. So far, these research lines have hardly interacted, perhaps due to the fact that queueing has been used mainly in operations research (telecommunication, logistics, manufacturing), whereas Lévy processes have been applied in finance and insurance. Admittedly, Lévy processes are somehow limited, as they require the stochastic processes involved to have independent increments – a restrictive requirement in many applications – but they offer an extremely rich mathematical framework, as witnessed by, e.g., the seminal book by Bertoin (1996) and the new book by Applebaum (2004). Particularly motivated by phenomena in finance, interesting new problems were stated (e.g., option pricing), some of which have been solved.

Critical percolation. Among the main events in probability in recent years are the spectacular breakthroughs in critical percolation and related processes. Key roles were played by stochastic Loewner evolutions, introduced by Schramm and further developed by him, Lawler and Werner, and by Smirnov's proof of conformal invariance and Cardy's formula. These results are restricted to a small class of two-dimensional models. It is still an important challenge to get a satisfactory description of the near-critical behavior of a large class of spatial stochastic processes. Besides these tools, which involve a mixture of complex function theory, conformal mapping, stochastic calculus, and combinatorics, new multiscale techniques of Kesten, Sidoravicius, and co-workers look very promising.

Information security. Evaluating and certifying security systems become increasingly important and need to take the computing infrastructure into account. Mathematical techniques play an important role in this growing area. How hard is integer factorization, and how secure are elliptic curve based cryptosystems? It may not be realistic to expect great progress on these famous and difficult problems, but cryptologists always have them in the back of their minds, and use them as a test for any new ideas that emerge. The recent breakthrough in primality testing confirms that one should always be prepared for the unexpected.

Optimization challenges. In spite of the successful approaches to integer programming with the help of linear programming, better, alternative, methods for solving integer programming are needed. One research direction is based on lattice techniques to more efficiently search the solution space, another is to find better approximations. Theoretical investigations over the last twenty years teach that there is indeed an approach that approximates integer programming problems even better than linear programming does. This is semidefinite programming. Theory moreover teaches that it should be computationally as tractable as linear programming. In practice, however, semidefinite programming problems become already quite hard for only a few dozen variables, while linear programming software can often deal with millions of variables.

Narrowing this gap is a big challenge. One of the promising approaches is to use the theory of invariants to reduce the size of semidefinite programming problems by eliminating the high degree of symmetry that such problems may have.

3.1 Theme PNA1 – Networks and Logic - Optimization and Programming

Research in	Combinatorics, algorithms, mathematical optimization and mathematical logic
Started in	January 1997
Theme leader	Prof.dr.ir. A.M.H. Gerards (1999–present)
MSC-CR classification	05-xx [Combinatorics] 90-xx [Operations research, mathematical programming] D.3.2 [Language classifications] D.3.3 [Language constructs and features]

Table 3.2. Staff of PNA1, 1999–2005 (in FTE/year, *prognosis)

PNA1		1999	2000	2001	2002	2003	2004	2005*
Leader:	*A.M.H Gerards*	*0.2*	*0.20*	*0.20*	*0.2*	*0.2*	*0.2*	*0.20*
Researchers:	*K.R. Apt*	*0.8*	*0.80*	*0.80*	*0.8*	*0.4*	*0.0*	*0.40*
	A.M.H Gerards	*0.8*	*0.60*	*0.60*	*0.6*	*0.6*	*0.6*	*0.60*
	M. Laurent	*0.7*	*0.68*	*0.61*	*0.7*	*0.7*	*0.7*	*0.80*
	A. Schrijver	*0.4*	*0.40*	*0.40*	*0.4*	*0.4*	*0.4*	*0.40*
Programmers:	*A.G. Steenbeek*	*0.9*	*0.90*	*0.87*	*0.6*	*0.6*	*0.6*	*0.85*
Total tenured staff		**3.8**	**3.6**	**3.5**	**3.3**	**2.9**	**2.5**	**3.3**
Non-tenured staff		2.1	1.6	1.1	1.3	2.3	0.8	2.6
CWI PhD students		0.0	0.5	2.8	2.8	2.8	4.1	4.0
Total research staff CWI payroll		**5.9**	**5.7**	**7.4**	**7.4**	**8.0**	**7.4**	**9.9**
Seconded PhD students		*1.0*	*0.4*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
Other seconded staff		*1.8*	*2.8*	*3.3*	*2.3*	*0.9*	*1.2*	*2.0*
Total hosted research staff		***8.7***	***8.9***	***10.7***	***9.7***	***8.9***	***8.6***	***11.9***

Table 3.3. Scientific output of PNA1

Output class		1999	2000	2001	2002	2003	2004	Total
Academic	refereed journals and proceedings	24	29	29	23	37	19	161
	other journals and proceedings	1	0	5	5	6	0	17
	book chapters	0	2	0	1	0	2	5
Total academic		**25**	**31**	**34**	**29**	**43**	**21**	**183**
Monographs		2	2	2	1	2	1	10
PhD dissertations		0	1	0	1	0	1	3
Professional pub./products		3	9	15	11	5	3	46

Table 3.4. Funding percentages of PNA1

PNA1	1999	2000	2001	2002	2003	2004	Average
Direct NWO	74.0%	75.2%	72.5%	76.0%	64.7%	66.2%	71.4%
Other research funds	5.1%	9.1%	13.8%	14.6%	18.5%	16.7%	13.0%
Grants/contracts	9.5%	9.6%	5.2%	4.9%	9.0%	13.2%	8.6%
Other	11.4%	6.1%	8.5%	4.5%	7.8%	3.9%	7.0%
Total	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**

3.1.1 Senior researchers

Ms. Dr.ir. K.I. Aardal (as of March 15, 2004), Prof.dr. K.R. Apt, Prof.dr.ir. A.M.H. Gerards, Ms. Dr. M. Laurent, Prof.dr. A. Schrijver.

3.1.2 Research orientation, highlights, and future directions

Mission and research area. The modern technological and computerized society is largely combinatorial and many of its questions are computational: real-world problems often ask for searching a desirable solution among a finite number of candidates. However, this finite number is typically astronomical. Therefore, these problems are hard; but society needs their solutions. Motivated by this algorithmic challenge, PNA1 does research in combinatorics and algorithms, mathematical optimization, and mathematical logic: the motivation comes from society; the research is fundamental.

The techniques that the theme develops use methods from mathematics (algebra, geometry, graph theory, mathematical logic, topology), mathematical optimization (combinatorial, linear, integer, and semidefinite optimization) and computer science (computational complexity, logic and constraint programming).

A well-known approach to combinatorial computational problems is integer linear programming: it describes the collection of candidate solutions by a system of linear inequalities in integer variables. Solving such systems is hard, but when variables are allowed to be fractional it is easy, by linear programming. For this reason a much used approach is to design the linear inequalities such that dropping the integrality conditions is a not too dramatic relaxation. This is the topic of polyhedral combinatorics, one of the central themes of PNA1. An in-depth account of this area can be found in Schrijver's three-volume book *Combinatorial Optimization–Polyhedra and Efficiency* (1882+cx pages, Springer-Verlag, Berlin, 2003). This work, which was awarded the 2004 Lanchester Prize, gives a complete description of all results and methods in polyhedral combinatorics with many elegant proofs; it has over 4,000 references and contains detailed historical surveys tracing back several centuries, disclosing the often forgotten origins of what we know today. While writing this book several new results were obtained. Just one example is Schrijver's combinatorial algorithm to minimize a submodular function. Submodular functions are very general modeling tools in combinatorial optimization. The algorithm resolved a long-standing conjecture. This work was awarded a 2003 Fulkerson Prize.

More recently this linear programming approach to hard computational problems

has been improved by describing the candidate solutions as semidefinite matrices satisfying certain linear constraints; thus tighter relaxations can often be obtained, yielding better approximations. This "semidefinite" programming plays a growing role in optimization in the recent years; it is a major topic in today's PNA1 research. In 2002, Laurent was awarded a five-year Vidi research grant from NWO to support her research in this area. It focuses on the following directions: the molecular conformation problem: reconstruct a molecule in 3D given distances between some pairs of its atoms; the construction of tight semidefinite relaxations for hard combinatorial computational problems; the approximation of the global minimum of a multivariate polynomial over a basic closed semi-algebraic set: the semidefinite programming approach to this problem stems from real algebraic geometry and relies on relaxing the nonnegativity of a polynomial, which is hard to test, to the existence of a decomposition of the polynomial as a sum of squares of polynomials, which is a semidefinite program. Schrijver applies the theory of C^*-algebras to obtain upper bounds for the size of binary codes in terms of reasonably sized semidefinite programs. These bounds are sharper than Delsarte's classical linear programming bounds which are based on commutative C^*-algebras.

Another approach to hard computational problems is constraint programming. Also this is investigated by the theme, including possible cross-fertilization with integer programming. One of the main building blocks of any constraint programming system are constraint solvers. These are algorithms to solve or simplify sets of constraints. Apt has shown that rule-based programming is a most useful approach to develop efficient and flexible constraint solvers. These contributions to constraint programming are reported in his book *Principles of Constraint Programming* (407+xiv pages, Cambridge University Press, 2003). It provides a systematic introduction to the subject. The main thesis of the book is that constraint programming is about formulating problems as constraint satisfaction problems and about solving them in a programming language using general or domain specific methods. Apt's book stresses the connections between rule-based programming and constraint programming. Van Hoeve investigated the application of techniques from mathematical programming (in particular combinatorial optimization and integer and semidefinite programming) to constraint programming. For his work on the use of network flow techniques to design efficient propagation algorithms for the "soft all-different constraint" he received the best student paper award at the conference CP2004.

Many real-world problems can be modeled by networks (graphs) and matrices. Therefore, graph theory and network optimization have always been central topics of this theme. Often a particular algorithm only applies to a particular problem if the modeling network or matrix can be visualized in a certain sense; planarity (cross-free 2D-visualization) and total unimodularity are important examples. Schrijver studied linkless 3D-visualizations, a natural and promising extension of planarity. It is one of the outcomes of the famous Robertson-Seymour graph minor project that, under reasonable conditions, there is a bounded size obstruction to certify easily that a network cannot be made visual. It is expected that also matrices over finite fields have this nice structure. With Geelen (Waterloo, Ontario) and Whittle (Victoria, New Zealand), Ger-

ards forms a team working on establishing such structure theory. Among their main results so far are that the conjecture holds for matrices with low branch-width and that any matrix over some finite field with high branch-width contains an arbitrarily large square grid. This also has implications for Rota's conjecture, which says that for every finite field a bounded sized obstruction exists to certify easily that a matroid–a certain matrix-like object–cannot be visualized as a matrix over the field. The grid result mentioned before implies that, if Rota's conjecture were false, counterexamples would exist with arbitrarily large square grids; the team also showed on the other hand that counterexamples cannot contain large projective spaces. The two results narrow the gap a bit. A related recent result of the team is that for every finite field a certificate exists for a matroid not to be representable as a matrix over the field, that can be verified in polynomial time. Geelen, Gerards and Kapoor received a 2003 Fulkerson Prize for their article establishing Rota's conjecture for the four-element field.

Future directions. The general research strategy and directions remain; most activities will be continued, but some are changed at this moment. The research on constraint programming and its interactions with integer programming is coming to an end. Integer programming research will become more computational; recently the group was strengthened by a senior researcher (Aardal) in this area.

A new direction is algorithmic game theory: To study algorithmic aspects of creating rules for autonomous agents so that a commonly desirable outcome is achieved in spite of the selfish behavior of each agent. This approach has been successfully used in economics and more recently was applied to various aspects of electronic commerce, notably auctions and various negotiation mechanisms, for instance between users of communication networks. It is also highly relevant to grid computing. The game theoretic issues in these network settings prompt questions in combinatorial optimization.

The semidefinite programming research will focus on exploring two roads taken by PNA1 recently: The interaction with real algebraic geometry and the application of semidefinite programming and the theory of C^*-algebras to computationally hard combinatorial problems. Research on the structure of matrices will continue towards its present objectives. Investigating combinatorial algorithms in molecular biology is also an area in which the theme is taking its first steps. This will be expanded over the coming years.

Knowledge transfer and consultancy. It is our policy to participate in national and international training initiatives and that senior members hold positions at Dutch universities. All senior members are involved in such training activities; four of them are professors at Dutch universities.

Consultancy is not a primary activity of the theme, but PNA1 has always been involved in such projects. The theme has a long tradition in developing software for the Dutch railways; the railway companies NS and Railned use timetabling software by Schrijver and Steenbeek. A recent algorithm of Schrijver's finds the efficient routing for rolling stock of NS; the innovation is that it efficiently handles trains that vary in composition over the day and are split and recombined along their route. The theme

also develops software for, till now three, Dutch medical schools to plan student internships at hospitals. The theme will continue doing consultancy whenever it feels it can make a difference.

3.1.3 Implementation of the 1999 recommendations

- PNA1 is taking its first steps in investigating combinatorial algorithms in molecular biology. First funding became available through BRICKS.

3.1.4 Overview of the results

See Table 3.3 on page 37 for a numerical overview. A list of all publications can be found in the PNA1 sections of *CWI Overview Research Activities 1999–2003* (CD-ROM).

A selection of major publications

1 K.R. APT (1999). The essence of constraint propagation. *Theoretical Computer Science* **221** (1-2), 179–210.

2 A. SCHRIJVER (1999). Bipartite edge-coloring in $O(\Delta m)$ time. *SIAM Journal on Computing* **28**, 841–846.

3 K.R. APT (2000). The role of commutativity in constraint propagation algorithms. *ACM Transactions on Programming Languages and Systems (TOPLAS)* **22**, 6, 1002–1036.

4 J.F. GEELEN, A.M.H. GERARDS, A. KAPOOR (2000). The excluded minors for GF(4)-representable matroids. *Journal of Combinatorial Theory Series B* **79**, 247–299.

5 A. SCHRIJVER (2000). A combinatorial algorithm minimizing submodular functions in strongly polynomial time. *Journal of Combinatorial Theory Series B* **80**, 346–355.

6 K.R. APT, E. MONFROY (2001). Constraint programming viewed as rule-based programming. *Theory and Practice of Logic Programming* **1** (6), 713–750.

7 M. LAURENT (2001). On the order of a graph and its deficiency in chordality. *Combinatorica* **21**, 543–570.

8 J.F. GEELEN, A.M.H. GERARDS, G. WHITTLE (2002). Branch width and well-quasi-ordering in matroids and graphs. *Journal of Combinatorial Theory Series B* **84**, 270–290.

9 J. GEELEN, B. GERARDS, G. WHITTLE (2003). *Excluding a Planar Graph from GF(q)-representable Matroids*. Research Report 03-4, School of Mathematical and Computing Series, Victoria University of Wellington.

10 M. LAURENT (2003). A comparison of the Sherali-Adams, Lovász-Schrijver and Lasserre relaxations for 0-1 programming. *Mathematics of Operations Research* **28**, 470–496.

11 K.I. AARDAL, A.K. LENSTRA (2004). Hard equality constrained integer knapsacks. *Mathematics of Operations Research* **29**, 724–738.

12 E. DE KLERK, M. LAURENT, P. PARRILO (2004). *A PTAS for the Minimization of Polynomials of Fixed Degree over the Simplex.* Preprint.

13 A. SCHRIJVER (2004). *New Code Upper Bounds from the Terwilliger Algebra*. Preprint.

PhD theses

- T. Fleiner (Thesis advisors: A.M.H. Gerards, A. Schrijver, University: TUE, Date: November 8, 2000, Title: *Stable and crossing structures*)
- R. Gennari (Thesis advisor: K.R. Apt, University: UvA, Date: December 2, 2002, Title: *Mapping Inferences*)
- S. Brand (Thesis advisor: K.R. Apt, University: UvA, Date: December 3, 2004, Title: *Rule-based Constraint Propagation: Theory and Applications*)

PhD defences in 2005: D. Gijswijt (UvA, Thesis advisor: A. Schrijver), G. Maróti (TUE, Thesis advisor: A.M.H. Gerards), W.J. van Hoeve (UvA, Thesis advisor: K.R. Apt), P. Zoeteweij (Thesis advisors: K.R. Apt, F. Arbab (SEN3)).

Table 3.5. Some major externally funded projects of PNA1

Acronym	Full name	Dates		k€	Source
SPCO	Semidefinite programming and combinatorial optimization	1/2003	4/2008	600	NWO Vidi
ADONET	Algorithmic optimization discretization	1/2004	4/2008	250	EU (RTN)
AMORE	Algorithmic methods for optimizing the railways in Europe	3/2000	2/2004	150	EU (RTN)

3.1.5 Context

The researchers of PNA1 collaborate with researchers from institutes all over the world: Microsoft Research (Seattle), University of Waterloo (Ontario), Universität Klagenfurt, Georgia Tech, ETH Zürich, Princeton University, Singapore University, Victoria University (New Zealand), and more.

The theme maintains strong relationships with Dutch and European training institutions and networks: Since many years it participates in teaching national graduate courses for EIDMA, LNMB, Stieltjes and OZSL, and in European Research Training Networks as DONET and ADONET (on discrete optimization) and AMORE (on railway optimization). Two members of PNA1 are professors at UvA and two at TUE.

PNA1 participated in Dutch-Russian and Dutch-Hungarian research cooperation projects of NWO. It took a leading role in the "ERCIM working group on constraints" and was active in the EU working groups DEDUGIS, for logic-programming and constraint based software for GIS applications, and COTIC, for the design of declarative logic languages based on concurrent constraint programming.

Its reseachers are involved in BRICKS projects on bio-informatics and on logistic networks and supply chain optimization. Within CWI the theme cooperates with SEN3 on constraint programming, with SEN4 in the BRICKS project in logistic networks and supply chain optimization and with INS4 in the BRICKS project in bio-informatics. Other opportunities for cooperation within CWI are with SEN4, on algorithmic game theory, and with PNA5 on cryptology.

3.1.6 Scientific reputation

Awards

- In 2002, M. Laurent was awarded a five-year Vidi research grant from NWO for her research project "Semidefinite programming and combinatorial optimization".
- In 2002, A. Schrijver received an honorary doctorate degree in mathematics from the University of Waterloo, Ontario, Canada.
- In 2003, A.M.H. Gerards received, together with two former CWI researchers, the Delbert Ray Fulkerson prize of the American Mathematical Society and the Mathematical Programming Society for their paper "The excluded minors for GF(4)-representable matroids". See page 41.
- In 2003, A. Schrijver received the George B. Dantzig prize of the Mathematical Programming Society and the Society for Industrial and Applied Mathematics for his complete work in optimization.
- In 2003, A. Schrijver received the Delbert Ray Fulkerson prize for his paper "A combinatorial algorithm minimizing submodular functions in strongly polynomial time". See page 41.
- In 2004, W.J. van Hoeve, a PhD student, received the best student paper award at the conference CP2004, September 27–October 1, Toronto, for his paper "A hyper-arc consistency algorithm for the soft alldifferent constraint".
- In 2004, A. Schrijver received the Lanchester Prize of INFORMS, for his book *Combinatorial Optimization–Polyhedra and Efficiency*, for the best publication in operations research in 2003.

Memberships of committees and other professional activities

For a more extensive survey, please see the PNA1 section of the *CWI Overview Research Activities 1999–2003* (CD-ROM).

K.I. Aardal	four editorships, four memberships of boards, steering committees, advisory groups
K.R. Apt	full professor at UvA, four editorships, three memberships of boards, steering committees, advisory groups
A.M.H. Gerards	full professor at the TUE, two editorships, three memberships of boards, steering committees, advisory groups
M. Laurent	three editorships, one membership of boards, steering committees, advisory groups
A. Schrijver	full professor at UvA, member of KNAW (Royal Netherlands Academy of Arts and Sciences), nine editorships, eight memberships of boards, steering committees, advisory groups

Other items of significant interest. In 2001, the Moscow Center for Continuous Education published a Russian translation of the 1997 book *Geometry of Cuts and Metrics* by M. Laurent and M.M. Deza.

3.2 Theme PNA2 – Advanced Communication Networks

Research in	Queueing theory and performance analysis, traffic theory, telecommunications networking, network economics
Started in	January 1997 under the name Traffic and Communication - Performance and Control. As of 2002, PNA2 got its current name and scope
Theme leader	Prof.dr.ir. J.H. van Schuppen (1999–2001) Prof.dr. M.R.H. Mandjes (2002–present)
MSC classification	60-xx [Probability theory and stochastic processes], 60K25 [Queueing theory], 68M20 [Performance evaluation], 90B18 [Communication networks], 60F10 [Large deviations]

Table 3.6. Staff of PNA2, 1999–2005 (in FTE/year, *prognosis)

PNA2		1999	2000	2001	2002	2003	2004	2005*
Leader:	*J.H. Van Schuppen*	*0.2*	*0.2*	*0.20*				
	M.R.H. Mandjes				*0.20*	*0.2*	*0.20*	*0.2*
Researchers:	*J. van den Berg*	*0.1*	*0.1*	*0.10*	*0.10*			
	S.C. Borst	*0.6*	*0.6*	*0.45*	*0.40*	*0.4*	*0.40*	*0.4*
	M.R.H. Mandjes		*0.2*	*0.80*	*0.48*	*0.4*	*0.48*	*0.6*
	R.D. van der Mei						*0.60*	*0.8*
	R. Núñez-Queija						*0.25*	*0.5*
	J.H. van Schuppen	*0.8*	*0.6*	*0.60*				
Total tenured staff		**1.7**	**1.7**	**2.2**	**1.2**	**1.0**	**1.9**	**2.5**
Non-tenured staff		0.0	0.7	1.6	1.5	1.4	0.6	2.2
CWI PhD students		2.3	1.8	2.0	1.0	0.8	0.3	1.6
Total research staff CWI payroll		**4.0**	**4.2**	**5.8**	**3.7**	**3.2**	**2.8**	**6.3**
Seconded PhD students		*0.0*	*0.0*	*0.0*	*0.8*	*1.0*	*1.0*	*1.0*
Other seconded staff		*0.6*	*1.4*	*1.5*	*1.4*	*1.7*	*2.9*	*3.4*
Total hosted research staff		***4.6***	***5.6***	***7.3***	***5.9***	***5.9***	***6.7***	***10.7***

3.2.1 Senior researchers

Prof.dr.ir. S.C. Borst, Prof.dr. M.R.H. Mandjes (as of October 1, 2000), Prof.dr. R.D. van der Mei (as of April 1, 2004), Dr. R. Núñez-Queija.

3.2.2 Research orientation, highlights, and future directions

Mission and research area. Communication networks are expanding at an unprecedented rate, in terms of traffic volume, number of users, as well as the range of applications. The use of the Internet and wireless services has undergone an explosive growth. Network operators anticipate further expansion, fueled by the emergence of all-optical networking as well as the convergence of wireless and Internet access, along with a fundamental trend towards service integration. Future communication networks are expected to accommodate a variety of new services with a broad range

Table 3.7. Scientific output of PNA2

Output class		1999	2000	2001	2002	2003	2004	Total
Academic	refereed journals and proceedings	16	19	34	13	30	25	137
	other journals and proceedings	0	0	1	1	0	3	5
	book chapters	0	3	0	0	0	1	4
	Total academic	**16**	**22**	**35**	**14**	**30**	**29**	**146**
Monographs		1	0	0	0	0	0	1
PhD dissertations		0	1	0	0	1	0	2
Professional pub./products		8	18	12	2	27	15	82

Table 3.8. Funding percentages of PNA2

PNA2	1999	2000	2001	2002	2003	2004	Average
Direct NWO	79.0%	88.2%	79.6%	79.0%	59.2%	58.6%	73.9%
Other research funds	17.2%	8.0%	19.1%	6.1%	17.8%	19.5%	14.6%
Grants/contracts	0.0%	0.0%	0.0%	4.9%	14.2%	7.7%	4.5%
Other	3.8%	3.8%	1.3%	10.0%	8.8%	14.2%	7.0%
Total	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**

of Quality of Service (QoS) requirements. This motivates the research effort in QoS-enabling mechanisms, and, more specifically, QoS-differentiation mechanisms. It can also be expected that the role played by ICT becomes more substantial, and as a result application servers and software systems will have an important impact on the end-to-end QoS.

These trends in telecommunication networking have given rise to a range of fundamental and somewhat more applied scientific problems. The research carried out in the theme PNA2 is strongly motivated by these trends, and covers a broad spectrum of mathematical methods. These range from probability theory (stochastic processes, limit theorems, convergence results, large deviations), via applied probability (queueing theory, transform methods, sample-path techniques, stochastic operations research), to stochastic modeling (traffic theory, telecommunications networking, performance modeling, numerical techniques, advanced simulation methods).

The research in PNA2 can be divided into four application domains.

Performance analysis of wireline communication networks. Analysis is mainly done by using methods from stochastics, in particular queueing theory (asymptotic theories such as large deviations, transform methods, sample-path results, Markov chain analysis). There is a strong connection with network traffic analysis (heavy tails, long-range dependence, and their impact on system performance).

Queueing-theoretic analysis for dimensioning, engineering, and operating integrated-services wireless networks. Complicating issues are user mobility, interference problems, intrin-

sically limited bandwidth, and highly random propagation characteristics that widely vary over time and across spatially distributed users. Processor sharing queues, and other non-standard scheduling disciplines, are of crucial interest here.

Analysis of approaches for providing differentiated QoS. On the one hand, operators may rely on scheduling and priority mechanisms. On the other hand, in an environment with distributed control by end users, operators may use pricing as a means to provide users with the proper incentives to ensure a desirable allocation of network resources.

Performance of distributed ICT systems. It was observed that performance issues of application servers and software systems are becoming increasingly important, and have a significant impact on the end-to-end delay. These ICT systems give rise to rich classes of (layered) queueing models.

The research of PNA2 directly relates to the above application domains. We now list the main highlights.

The analysis of *Gaussian queues*, i.e., queues fed by Gaussian traffic, has been attracting increasing attention in the applied probability and queueing research communities, motivated by their wide-spread use in many application domains. Focusing on the field of communication networking, the intrinsic flexibility of the Gaussian traffic model has proven to be particularly useful. Its capability of covering a broad range of highly relevant correlation structures has made it one of the leading paradigms in traffic modeling. Notably, the class of Gaussian models contains long-range dependent processes such as fractional Brownian motion (fBm). The subject of Gaussian queues has become a major theme in PNA2's research, particularly in the second part of the evaluation period, also reflected by the appointments of Dębicki (2001–2003) and Mannersalo (2004) as postdocs, and the intensive collaboration with I. Norros (VTT, Finland). This increased focus on Gaussian queues resulted in a substantial series of articles. The research of PhD students Dieker (exact large-buffer asymptotics; to appear) and Van Uitert (tandem and priority queues, with Mandjes; *Annals of Applied Probility*, to appear) were significant contributions to this field. Some fundamental results could be directly applied in a project on bandwidth provisioning funded by the Telematica Instituut.

Long-range dependence and *heavy tails* can also be embedded in more traditional queueing models, such as models of the GI/G/1 type (with heavy-tailed service times), and queues fed by on-off sources (with heavy-tailed on-times). The paper by Zwart, Borst and Mandjes (*Ann. of Appl. Prob.*, 2004) can be regarded as culmination of a series of classical articles (with contributions of Boxma, Cohen, Jelenković, Pakes, Veraverbeke, and others), in that it has reached the highest level of generality: characterization of the large-buffer asymptotics a queue fed by heterogeneous on-off sources with regularly varying on-times. The collaboration with P. Jelenković (Columbia University) and O.J. Boxma (TUE) has appeared very fruitful. Much progress was achieved also in the *large deviations analysis* of the many-sources domain; in this respect it is worth mentioning the paper by Mandjes and Kim (*Queueing Syst.*, 2001) in which insensitivity for small buffers is shown. Mandjes (*Stoch. Mod.*, 1999) was awarded the 2000 best pa-

per award of the journal *Stochastic Models* (Marcel F. Neuts award) for the paper "Rare event analysis of the state frequencies of a large number of Markov chains".

A third strand of research concerns the development of mathematical models for *integration* of multiple types of traffic over a common resource. Núñez-Queija's thesis (2000) was a major milestone, with a special focus on the integration of streaming (constant rate) and elastic (adaptive) traffic. As prioritization becomes useful only when a differentiated pricing policy is imposed, Mandjes (*Computer Networks*, 2003) and Núñez-Queija also considered the integration setting from a micro-economic (e.g., game-theoretic) point of view.

The survey of Borst, Boxma, Núñez-Queija, Zwart (*Perf. Eval.*, 2003) can be considered as an account of the impact of the *service discipline* on the user-level performance. Detailed studies of different service disciplines have been a major research theme. Considerable progress was made for random-order-of-service by Borst, Núñez-Queija *et al.* (*Oper. Res. Lett.*, 2003; *Queueing Syst.*, 2004), foreground-background scheduling, and shortest-remaining-processing-time. Where Zwart and Boxma (Queueing Syst., 2000) showed that processor sharing is quite benign for heavy-tailed jobs, Mandjes and Zwart (preprint, 2004) show the opposite behavior for light-tailed jobs. Van Uitert's thesis (2003) gives a complete view on asymptotic results for generalized processor-sharing queues. Recent work by Núñez-Queija focuses on discriminatory processor-sharing (DPS).

Another important research topic concerns the application of fundamental queueing-theoretic results in the setting of *wireless networks*. Borst studied channel-aware scheduling strategies, as an effective mechanism for improving throughput performance in wireless data networks by exploiting channel fluctuations. While previously these strategies have mostly been explored at the packet level for a static user population, he focused on the performance at the flow level in a dynamic setting with random finite-size service demands. Then the user-level performance follows from a multi-class processor-sharing model where the total service rate varies with the total number of users, leading to explicit formulas for several performance measures. Borst's paper "User-level performance of channel-aware scheduling algorithms in wireless data networks" was awarded the best paper award of the conference Infocom 2003. Two consultancy projects with France Télécom have resulted in an intensive collaboration with T. Bonald and A. Proutière (impact of mobility; Infocom, 2004).

PNA2 also focused on the application of several fundamental results in *wireline networking*. Much of this effort was embedded in the national project on end-to-end QoS (EQUANET; partners: TNO Telecom, Lucent, TUE, UT). The quantitative evaluation methods developed in this project heavily rely on Núñez-Queija's work on DPS. Van der Mei's broad view on telecommunications networking, particularly in conjunction with the ICT aspects of end-to-end QoS, had a crucial impact on the direction of the chosen solutions. The team members' knowledge on TCP performance was of crucial importance in EQUANET; we mention the work on congestion-dependent queues (a prominent subject in Bekker's PhD project), in which area successful collaborations with O. Kella (Hebrew University, Israel), W. Scheinhardt (UT) and D. Mitra

(Lucent Techn./Bell Labs) can be reported. Van der Mei used advanced processor-sharing models to evaluate TCP performance (*Perf. Eval.*, 2003).

A particular feature relevant in the context of end-to-end QoS for next-generation *ICT systems* is the fact that many applications cross multiple domains. The need to realize end-to-end QoS over multiple domains raises new research challenges. In this context, significant progress was made in the development of methodologies for obtaining simple and explicit, but accurate approximations for the end-to-end delay by Van der Mei (*Perf. Eval.*, 2002 and 2005). In addition, research on the performance of ICT systems raised new challenges regarding systems with hardware-software interaction, which in many cases leads to the formulation of hierachical queueing models, i.e., where a server at one layer may be a customer at another layer. Very recently, in this context, pioneering results have been obtained by Van der Mei (several papers are under review), with successful collaborations with, e.g., O.J. Boxma (TUE) and N. van Dijk (UvA).

3.2.3 Implementation of the 1999 recommendations

- In 2002, J.H. van Schuppen stepped down as theme leader after his five-year term and joined the restructured theme MAS2 with his project group Control and System Theory.
- M.R.H. Mandjes, who joined PNA2 in 2000, succeeded Van Schuppen. PNA2 became a pilot theme Advanced Communication Networks consisting of the closely related subthemes Wireline Networks, Wireless Networks, and Network Economics. In 2004 PNA2 became a full-fledged theme.
- Several new staff were appointed.

3.2.4 Overview of the results

See Table 3.7 on page 45 for a numerical overview. A list of all publications can be found in the PNA2 sections of *CWI Overview Research Activities 1999–2003* (CD-ROM).

Selection of major publications

1 R.D. VAN DER MEI (2000). Polling systems with switch-over times under heavy load: moments of the delay. *Queueing Systems* **36**, 381–404.

2 R.D. VAN DER MEI, R. HARIHARAN, P.K. REESER (2001). Web server performance modeling. *Telecommunication Systems* **16**, 361–378.

3 R. NÚÑEZ-QUEIJA (2002). Queues with equally heavy sojourn time and service requirement distributions. *Annals of Operations Research* **113**, 101–117.

4 S.C. BORST (2003). User-level performance of channel-aware scheduling algorithms in wireless data networks. *Proc. Infocom 2003*. Extended version to appear in: *IEEE/ACM Transactions on Networking*.

5 K. DĘBICKI, M. MANDJES (2003). Traffic with an fBm limit: convergence of the stationary workload process. *Queueing Systems* **46**, 113–127.

6 T.L. OLSEN, R.D. VAN DER MEI (2003). Periodic polling systems in heavy-traffic: distribution of the delay. *Journal of Applied Probability* **40**, 305–326.

7 E. ALTMAN, K. AVRACHENKOV, R. NÚÑEZ-QUEIJA (2004). Perturbation analysis for denumerable Markov chains with application to queueing models. *Advances in Applied Probability* **36**, 839–853.

8 S.C. BORST, A. MANDELBAUM, M.I. REIMAN (2004). Dimensioning large call centers. *Operations Research* **52**, 17–34.

9 O.J. BOXMA, S. FOSS, J.-M. LASGOUTTES, R. NÚÑEZ-QUEIJA (2004). Waiting time asymptotics in the single server queue with service in random order. *Queueing Systems* **46**, 35–73.

10 M. MANDJES, P. MANNERSALO, I. NORROS, M. VAN UITERT (2004). Large deviations of infinite intersections of events in Gaussian processes. Preprint.

11 A.P. ZWART, S.C. BORST, M. MANDJES (2004). Exact asymptotics for fluid queues fed by multiple heavy-tailed on-off flows. *Annals of Applied Probability* **14**, 903–957.

12 M. MANDJES, M. VAN UITERT (2005). Sample-path large deviations for tandem and priority queues with Gaussian inputs. To appear in: *Annals of Applied Probability*.

PhD theses

- R. Núñez-Queija (Thesis advisor: O.J. Boxma, Co-advisor: S.C. Borst, University: TUE, Date: January 20, 2000, Title: *Processor-sharing Models for Integrated-services Networks*)
- A.P. Zwart (part-time) (Thesis advisor: O.J. Boxma, Co-advisor: S.C. Borst, University: TUE, Date: September 11, 2001, Title: *Queueing Systems with Heavy Tails*), Cum laude.
- N.K. Boots (external) (Thesis advisors: H.C. Tijms, M.R.H. Mandjes, University: VU, Date: February 5, 2002, Title: *Rare Event Simulation in Models with Heavy-tailed Random Variables*)
- M.J.G. van Uitert (Thesis advisor: S.C. Borst, Co-advisor: O.J. Boxma, University: TUE, Date: November 24, 2003, Title: *Generalized Processor Sharing Queues*)
- N.D. van Foreest (external, UT) (Thesis advisor: M.R.H. Mandjes, Co-advisor: W.R.W. Scheinhardt, University: UT, Date: December 17, 2004, Title: *Queues with Congestion-dependent Feedback*)

Table 3.9. Some major externally funded projects of PNA2

Acronym	Full name	Dates		k€	Source
BRICKS PDC2	Quality of service in communication networks	1/2004	12/2009	400	BSIK
EQUANET	End-to-end quality-of-service in next generation networks	12/2002	2/2005	200	SENTER
FLORIN	Analysis of wireless networks	1/2003	7/2006	150	France Télécom

3.2.5 Context

The researchers of PNA2 have scientific interaction with, amongst others, Bell Laboratories/Lucent Technologies (Murray Hill NJ, USA), INRIA (Rocquencourt/Sophia Antipolis, France), Microsoft Research (Cambridge, UK, and Redmond WA, USA), Statistical Laboratory/Computer Science Laboratory of the University of Cambridge (UK), Helsinki University of Technology (Finland), VTT Information Technology (Espoo, Finland), Tel-Aviv University (Israel), Columbia University (New York, USA), and Wrocław University (Poland).

PNA2 participates in the training institutions LNMB and Stieltjes. It is also member of the sixth framework European "network of excellence" EURO-NGI "Design and Engineering of the Next Generation Internet", in which it is mainly involved in the work package "Dynamics of networks under new traffic paradigms". It received a Van Gogh grant, together with INRIA, Sophia-Antipolis. It is also involved in the national research initiative Netherlands Graduate School in Stochastics. PNA2 also leads the BRICKS project "Quality of Service in Communication Networks" (other partners: UT and TUE).

PNA2 is partner in the SENTER/NOVEM-funded project EQUANET (mentioned above), and the TI-funded project M2C-QoS (with UT). Partners in the Dutch industrial research community are TNO Telecom (Delft), Lucent Technologies (Hilversum, Enschede), Philips Research (Eindhoven) and SURFnet (Utrecht). PNA2 also consulted with WorldCom in a project on bandwidth provisioning for IP backbone links, and with France Télécom in a project on wireless networks.

Three senior members of PNA2 are full professors (Borst at TUE, Mandjes at UvA and Van der Mei at VU), and one holds an assistant-professorship (Núñez-Queija at TUE). Borst also has an affiliation with Bell Labs (Murray Hill NJ, USA), and Mandjes with EURANDOM (Eindhoven).

Several researchers visit PNA2 on a regular basis. Prof.dr.ir. O.J. Boxma has an 0.1 FTE affiliation with PNA2. His presence at CWI has several valuable scientific spin-offs (collaborations with various group members, joint supervision of PhD students, interaction with EURANDOM). Also Prof.dr. R.J. Boucherie (UT), Dr.ir. W.R.W. Scheinhardt (UT), and Dr. A.P. Zwart (TUE) visit CWI on a frequent basis (0.2 FTE affiliations).

3.2.6 Scientific reputation

Awards

- 2000: M.R.H. Mandjes was awarded the best paper award of the journal *Stochastic Models* (Marcel Neuts award) for the paper "Rare event analysis of the state frequencies of a large number of Markov chains".
- 2001: S.C. Borst was awarded best paper award by the Operations Research Society of Israel for the paper "Dimensioning large call centers".
- 2003: S.C. Borst was awarded the best paper award of the conference Infocom 2003 for the paper "User-level performance of channel-aware scheduling algorithms in wireless data networks".

- 2003: A.B. Dieker was runner-up for the master thesis award of the Netherlands Society for Statistics and Operations Research (VVS); the thesis is entitled "Simulation of fractional Brownian motion" and was supervised by M.R.H. Mandjes.
- 2003: A.P. Zwart was awarded the Gijs de Leve prize for the best PhD thesis in the mathematics of operations research during the period 2000–2002.

Memberships of committees and other professional activities

For a more extensive survey, please see the PNA2 section of the *CWI Overview Research Activities 1999–2003* (CD-ROM).

S.C. Borst	full professor at TUE, three editorships (and one guest-editorship), four memberships of boards, steering committees, advisory groups, organizer of one conference, member of five program committees
M.R.H. Mandjes	full professor at UvA (as of August 1, 2004; from October 1, 2000 full professor at UT), one editorship, four memberships of boards, steering committees, advisory groups, organizer of one conference, member of six program committees
R.D. van der Mei	full professor at VU, two editorships (and one guest-editorship), one membership of boards, steering committees, advisory groups, (co-)organizer of two conferences, member of four program committees
R. Núñez-Queija	one guest-editorship, member of one program committee

3.3 Theme PNA3 – Stochastics

Research in	Probability, statistics and related fields
Started in	January 1997
Theme leader	Prof.dr. M.S. Keane (until December 1999)
	Prof.dr. J. van den Berg (as of December 1999)
MSC classification	60-XX [Probability theory and stochastic processes]
	62-XX [Statistics]
	37-XX [Dynamical systems and ergodic theory]

Table 3.10. Staff of PNA3, 1999–2005 (in FTE/year, *prognosis)

PNA3		1999	2000	2001	2002	2003	2004	2005*
Leader:	*M.S. Keane*	*0.18*						
	J. van den Berg	*0.02*	*0.20*	*0.20*	*0.20*	*0.20*	*0.20*	*0.2*
Researchers:	*J. van den Berg*	*0.70*	*0.70*	*0.70*	*0.70*	*0.60*	*0.60*	*0.6*
	K.O. Dzhaparidze	*0.80*	*0.80*	*1.00*	*1.00*	*1.00*	*1.00*	*1.0*
	R. Helmers	*1.00*	*1.00*	*1.00*	*1.00*	*0.58*		
	M.S. Keane	*0.52*	*0.20*	*0.80*	*0.27*			
Programmers:	*R. van der Horst*	*0.75*	*0.75*	*0.75*	*0.75*	*0.75*	*0.56*	
Total tenured staff		**4.0**	**3.7**	**4.5**	**3.9**	**3.1**	**2.4**	**1.8**
Non-tenured staff		0.2	0.0	0.8	1.2	1.0	0.5	0.6
CWI PhD students		0.0	0.0	0.9	1.0	1.0	0.8	0.3
Total research staff CWI payroll		**4.2**	**3.7**	**6.2**	**6.1**	**5.1**	**3.7**	**2.7**
Seconded PhD students		*1.0*	*2.3*	*1.8*	*1.0*	*0.3*	*0.0*	*0.0*
Other seconded staff		*3.3*	*1.9*	*1.7*	*1.0*	*0.5*	*1.6*	*1.2*
Total hosted research staff		***8.5***	***7.9***	***9.7***	***8.1***	***5.9***	***5.3***	***3.9***

Table 3.11. Scientific output of PNA3

Output class		1999	2000	2001	2002	2003	2004	Total
Academic	refereed journals and proceedings	5	10	7	7	9	7	45
	other journals and proceedings	0	0	0	2	0	0	2
	book chapters	0	1	0	1	2	0	4
	Total academic	**5**	**11**	**7**	**10**	**11**	**7**	**51**
Monographs		0	0	0	0	0	0	0
PhD dissertations		1	1	3	1	0	0	6
Professional pub./products		4	6	10	3	2	0	25

3.3.1 Senior researchers

Prof.dr. J. van den Berg, Dr. K.O. Dzhaparidze, Dr. R. Helmers (until mid-2003), Prof.dr. M.S. Keane (until April 2002).

Table 3.12. Funding percentages of PNA3

PNA3	1999	2000	2001	2002	2003	2004	Average
Direct NWO	79.4%	77.6%	77.0%	79.1%	79.8%	73.7%	77.8%
Other research funds	0.0%	0.1%	14.3%	14.5%	17.4%	16.9%	10.5%
Grants/contracts	4.5%	7.8%	3.2%	1.4%	0.0%	0.0%	2.8%
Other	16.1%	14.5%	5.5%	5.0%	2.8%	9.4%	8.9%
Total	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**

3.3.2 Research orientation, highlights, and future directions

Research area and highlights. Chance and uncertainty (or randomness) play an essential role in many phenomena and processes in nature, technology and society. Stochastics is the mathematical discipline that deals with the modeling and analysis of such phenomena. PNA3's research in stochastics is fundamental but motivated and inspired by real-world problems.

Before the departure of Keane and Helmers (in 2002 and 2003, respectively) the scope of PNA3's research was very broad, ranging from ergodic theory and dynamical systems via probability and stochastic analysis to modern mathematical and applied statistics.

Ergodic theory and dynamical systems is an area where ideas and techniques from mathematical analysis and probability are fruitfully combined. Hard problems often become more understandable by interpreting them in the framework of this area. A central question (in which several members of PNA3 are interested, each from a somewhat different perspective) is how fast the dependencies between random quantities assigned to different locations (in space or time) decay as a function of the distance. Another question, sometimes related to the former, is whether there is a suitable code between a system (process) of interest and some particularly nice system. Van den Berg and co-workers have studied mixing properties and finitary codes for a class of random fields. Keane and co-workers have constructed so-called finitary codes for certain processes arising from random walks in random scenery.

Another class of random walks, so-called reinforced random walks, has a very different flavor. These walks are non-Markovian and most standard techniques break down. Keane and Rolles (PhD student at that time) produced a substantial advance, showing a limit theorem valid for any finite graph, as well as recurrence for a large class of one-dimensional cases.

Keane (with co-workers) also studied a problem in geometric probability concerning convolutions and linear combinations of pseudo-isotropic distributions. Their paper on this work won a Polish prize (first prize in the Marek Kuczma Contest).

One of the most active fields in modern probability is Percolation and Interacting Particle Systems (IPS). The above mentioned reinforced random walk, although strictly speaking not an IPS, has much of its flavor. (Although it has only one particle, this has a non-trivial "self-interaction".) A well-known and fundamental example of IPS is the Coalescing Random Walks process. In this model particles move around randomly,

and stick together when they meet. Bramson and Griffeath showed in the early eighties (in an article that became a classic) how the particle density asymptotically decays with time. However, their method breaks down under small modifications of the model, for instance when meeting particles stick with a probability smaller than 1. Two papers by Van den Berg and Kesten (Cornell University) produce major progress on this problem by presenting a robust method, combining analytic, combinatorial and probabilistic techniques.

A relatively new branch of IPS is the study of Self-Organized Criticality, an intriguing subject that has received much attention in the physics literature but which is still poorly understood. An important class of models where such behavior is believed to take place are the so-called excitable media (e.g., forest-fires, and neural transmission). Recent work by Van den Berg and co-authors shows that even the one-dimensional case is considerably more subtle than suggested in the literature: results obtained by physicists in the early ninetees need significant correction. For the two-dimensional problems, which are much harder, Van den Berg and co-authors have proved connections with critical percolation. Two-dimensional critical percolation in itself was also investigated by Van den Berg and co-workers: lowest crossings were studied, and an analogue for SLE was discussed.

Stochastic Löwner Evolution, introduced by Schramm in 1999 and developed further by Schramm, Lawler, Werner and Smirnov, has had a revolutionary impact on 2D percolation and other spatial processes. PNA3 has invested much time and energy in the organization of a study group on this subject (during 2003 and early 2004), which was actively attended by mathematicians and physicists from several institutes.

The recent research by Dzhaparidze aims to develop a new methodology to obtain a better understanding of the structure of general second order random processes with stationary increments. Such processes arise in many fields of stochastic modeling, either directly, or as building blocks for more complicated models. A well-known example is the fractional Brownian motion (fBm), which plays an important role in various application areas, including telecommunication networks and mathematical finance where long-range dependence phenomena are encountered.

Spectral analysis of the fBm, carried on in a number of recent papers by Dzhaparidze and co-worker has uncovered a powerful methodology to deal at once with much more general si-processes, by making use of the Krein-de Branges spectral theory of vibrating strings.

The research by Helmers (with various co-workers), in modern statistics, in the above-mentioned period falls into two different parts: saddlepoint/Edgeworth expansions, and statistical estimation of Poisson intensities. As to the former, saddlepoint approximations for the trimmed and studentized trimmed mean were established, and simple explicit forms of the (empirical) Edgeworth expansions for these statistics were obtained. As to the latter, under certain assumptions on the observation of a cyclic Poisson process with unknown period, consistency of a new kernel type estimator of the intensity was obtained; moreover, the asymptotic bias, variance and mean-squared error of the estimator were computed. Helmers also published on nonparametric esti-

mation of the period, and on other topics (the bootstrap, and inference on rare errors).

Future directions. PNA3 plans to increase focus on spatial probability, mostly on problems motivated by physics and biology. In particular, we want to emphasize important aspects and subfields in which expertise in the Netherlands is still rare. Examples are topics where a combination of probabilistic and advanced analytic/geometric tools are needed, as in SLE (see below), and rigorous multiscale analysis of random spatial processes.

An important aim of PNA3 is to signal new international developments and, when there is a need, make these better known in the Netherlands by means of study groups, research initiatives and, at a later stage, advanced graduate courses. An example is the earlier mentioned study group on Stochastic Löwner Evolution, one of the most important new subjects in probability (and mathematics in general).

To be able to achieve its objectives, PNA3 needs at least one new permanent member in the very near future. In accordance with the above arguments, candidates should have excellent mathematical skills, and bring substantial new expertise to the Netherlands.

Knowledge transfer. All PNA3 members were involved in teaching and/or in the supervision of PhD students. PNA3 was also involved in consultancy, secondments and advisory work for Philips Research, Hewlett-Packard and EURANDOM (Keane), Rijkswaterstaat (Helmers), a small internet company (Van den Berg), and UvA (Van den Berg and Helmers).

3.3.3 Implementation of the 1999 recommendations

- In spite of the recommendations (and the departure of two members from the theme), no new senior researcher has been appointed.

3.3.4 Overview of the results

See Table 3.11 on page 52 for a numerical overview. A list of all publications can be found in the PNA3 sections of *CWI Overview Research Activities 1999–2003* (CD-ROM).

Selection of major publications

1 R. GER, M.S. KEANE, J.K. MISIEWICZ (2000). On convolutions and linear combinations of pseudo-isotropic distributions. *Journal of Theoretical Probability* **13**, 977–995.

2 J. VAN DEN BERG, H. KESTEN (2002). Randomly coalescing random walks in dimension $d \geq 3$. V. SIDORAVICIUS (Ed.). *In and Out of Equilibrium*, Birkhäuser, 1–45.

3 J. VAN DEN BERG, A. JÁRAI (2003). The lowest crossing in 2D critical percolation. *Ann. Probab.* **31**, 1241–1253.

4 K.O. DZHAPARIDZE, P.J. SPREIJ, E. VALKEILA (2003). Information processes for semimartingale experiments. *Ann. Probab.* **31** (1), 216–243.

5 R. HELMERS, IW. MANGKU, R. ZITIKIS (2003). Consistent estimation of the intensity function of a cyclic Poisson process. *J. Multivariate Anal.* **84**, 19–39.

6 M.S. KEANE, J.E. STEIF (2003). Finitary coding for the 1-D T, T^{-1}–process with drift. *Annals of Probability* **31**, 1979–1985.

7 J. VAN DEN BERG, A. JÁRAI (2004). On the asymptotic density in a one-dimensional self-organized critical forest-fire model. To appear in *Comm. Math. Phys.*

8 K.O. DZHAPARIDZE, J.H. VAN ZANTEN (2004). A series expansion of fractional Brownian motion. *Probab. Theory Relat. Fields* **130** (1), 39–55.

9 R. HELMERS, B-Y. JING, G. QIN, W. ZHOU (2004). Saddlepoint approximations to the trimmed mean. *Bernoulli* **10** (3), 465–501.

10 A. JÁRAI, F. REDIG (2004). Infinite-volume limits of high-dimensional sandpile models. To appear in *Probab. Theory Relat. Fields*.

PhD theses

- D. White (Thesis advisors: R.W.J. Meester and M.S. Keane, University: UU, Date: September 20, 1999, Title: *Percolation through Fractals, Backbends and Dynamic Lily Ponds*)
- M.R. Vervoort (Thesis advisor: M.S. Keane, Co-advisor: M. van Lambalgen, University: UvA, Date: September 19, 2000, Title: *Games, Walks and Grammars: Problems I've Worked on*)
- IW. Mangku (Thesis advisor: M.S. Keane , Co-advisor: R. Helmers, University: UvA, Date: January 22, 2001, Title: *Estimating the Intensity of a Cyclic Poisson Process*)
- B. Lemmens (Thesis advisors: M.S. Keane, S.M. Verduyn Lunel, University: VU, Date: June 7, 2001, Title: *Iteration of Non-expansive Maps under the 1-Norm*)
- J.H. van Zanten (Thesis advisor: M.S. Keane, Co-advisor: K.O. Dzhaparidze, P.J.C. Spreij, University: UvA, Date: October 24, 2001, Title: *Martingales and Diffusions, Limit Theory and Statistical Inference*)
- S.W.W. Rolles (Thesis advisor: M.S. Keane, University: UvA, Date: March 20, 2002, Title: *Random Walks in Stochastic Surroundings*)

Table 3.13. Some major externally funded projects of PNA3

Acronym	Full name	Dates		k€	Source
DPP	Dynamic percolation phenomena at and near criticality	2002	2004	105	NWO
DYNSTOCH	Research training network	1999	2004	170	EU
NWO-SOC	Mathematical models of biological and physical processes with self-organized critical behavior	2001	2004	100	NWO

3.3.5 Context

PNA3 has scientific contacts with researchers from many institutes, e.g., Cornell University, IMPA (Rio de Janeiro), Technical University Gothenburg, Rutgers University, Cambridge University, UC Berkeley, Technical University Budapest, and universities in Helsinki and Paris. In the period of this evaluation PNA3 members participated

in the European network DYNSTOCH and in a Dutch-Hungarian (NWO-OTKA) co-operation program. All PNA3 members were involved in teaching activities at Dutch universities or graduate programs.

Van den Berg participates in a recently started BRICKS project.

PNA3 is involved in a recent proposal to start a Netherlands Graduate School in Stochastics.

3.3.6 Scientific reputation

Awards

The paper "On convolutions and linear combinatorics of pseudo-isotropic distributions" by R. Ger, M. Keane and J.K. Misiewicz won the first prize in the Polish Marek Kuczma contest in 2001.

Memberships of committees and other professional activities

For a more extensive survey, please see the PNA3 section of the *CWI Overview Research Activities 1999–2003* (CD-ROM).

J. van den Berg	full professor at VU (since mid-2003), (co-)organizer of five conferences in the period 1999-2004; 30 invited lectures, three long-term visits (to Georgia Tech, the Erwin Schrödinger Institute, and the Isaac Newton Institute); member of six PhD committees; coordinator of a Dutch-Hungarian cooperation program
K.O. Dzhaparidze	organizer of one conference, member of the FWA committee Amsterdam, member of the EU program DYNSTOCH; ten invited lectures; co-advisor and member of several thesis committees
R. Helmers	(co-)organizer of a conference, membership of a steering committee (Limperg Institute); advisorship (PWC); project leader of a Dutch-Indonesian cooperation project; 16 invited lectures
M.S. Keane	full professor at UvA, member of KNAW, foreign member of the Chilean Academy of Sciences, three editorships, numerous invited lectures and memberships of boards, steering committees, advisory groups

3.4 Theme PNA4 – Signals and Images

Research in	Image and signal processing, spatial stochastics, stochastic geometry, wavelets, mathematical morphology
Started in	Pilot: January 1997, theme: January 1999
Theme leader	Dr.ir. H.J.A.M Heijmans
MSC classification	42C40 [Wavelets], 42A38 [Fourier and Fourier-Stieltjes transforms and other transforms of Fourier type] 60D05 [Geometric probability, stochastic geometry, random sets], 60G55 [Point processes] 62M30 Spatial processes, x 62M40 [Random fields; image analysis], 62H30 [Classification and discrimination; cluster analysis] 68T37 [Reasoning under uncertainty] 68T45 [Machine vision and scene understanding], 68U10 [Image processing] 94A08 [Image processing (compression, reconstruction, etc.)]

3.4.1 Senior researchers

Dr.ir. H.J.A.M. Heijmans, Prof.dr. M.S. Keane (1999), Dr. A.A.M. Kuijk (1999–2001), Dr. M.N.M. van Lieshout (1999–present), Dr. E.J.E.M. Pauwels (1999-10–present), Dr. B.A.M. Schouten (2002-05–present), Dr. N.M. Temme (1999).

Table 3.14. Staff of PNA4, 1999–2005 (in FTE/year, *prognosis)

PNA4		1999	2000	2001	2002	2003	2004	2005*
Leader:	*H.J.A.M. Heijmans*	*0.20*	*0.20*	*0.20*	*0.20*	*0.20*	*0.20*	*0.20*
Researchers:	*H.J.A.M. Heijmans*	*0.60*	*0.80*	*0.80*	*0.80*	*0.80*	*0.80*	*0.80*
	M.S. Keane	*0.10*						
	A.A.M. Kuijk	*1.00*	*1.00*	*0.33*				
	M.N.M. van Lieshout	*1.00*	*0.85*	*0.80*	*0.80*	*0.80*	*0.80*	*0.80*
	E.J.E.M. Pauwels	*0.15*	*0.68*	*0.85*	*0.85*	*0.85*	*0.85*	*0.85*
	N.M. Temme	*0.60*						
Programmers:	*A.G. Steenbeek*	*0.10*	*0.10*	*0.10*	*0.40*	*0.40*	*0.40*	*0.40*
	P.W. de Zeeuw	*0.90*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*
Total tenured staff		**4.7**	**4.6**	**4.1**	**4.1**	**4.1**	**4.1**	**4.1**
Non-tenured staff		0.0	1.0	3.3	3.6	4.4	4.3	2.0
CWI PhD students		2.7	3.0	2.1	2.0	1.3	0.6	0.0
Total research staff CWI payroll		**7.4**	**8.6**	**9.5**	**9.7**	**9.8**	**9.0**	**6.1**
Seconded PhD students		*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
Other seconded staff		*0.8*	*1.2*	*0.5*	*2.8*	*0.2*	*0.9*	*0.0*
Total hosted research staff		***8.2***	***9.8***	***10.0***	***12.5***	***10.0***	***9.9***	***6.1***

3.4.2 Research orientation, highlights and future directions

Mission and research areas. Rapid advances in communication, web technology and sensor technology, as well as the relentless increase in computational power have led

Table 3.15. Scientific output of PNA4

Output class		1999	2000	2001	2002	2003	2004	Total
Academic	refereed journals and proceedings	17	14	15	17	29	17	109
	other journals and proceedings	0	0	1	2	1	0	4
	book chapters	0	0	0	2	1	1	4
	Total academic	**17**	**14**	**16**	**21**	**31**	**18**	**117**
Monographs		1	2	1	0	0	0	4
PhD dissertations		0	1	1	0	1	0	3
Professional pub./products		2	7	8	17	17	20	71

Table 3.16. Funding percentages of PNA4

PNA4	1999	2000	2001	2002	2003	2004	Average
Direct NWO	81.1%	80.0%	76.3%	70.9%	70.4%	66.7%	74.3%
Other research funds	11.4%	14.6%	22.8%	28.1%	29.6%	27.0%	22.2%
Grants/contracts	1.3%	2.1%	0.4%	0.0%	0.0%	0.0%	0.6%
Other	6.2%	3.3%	0.5%	1.0%	0.0%	6.3%	2.9%
Total	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**

to an exponential growth in the amount of visual data readily available. However, the usefulness of these resources is largely determined by their accessibility, and in order to be effective, this needs to be based on *image content and semantics.* The Semantic Web and (semantic) web technologies focus on the manipulation and interpretation of meta-data once they have been provided in a standardized format (e.g., XML), but the actual *extraction* of such meta-data from computationally accessible "low-level" features still poses tremendous scientific challenges. The Signals and Images group therefore conducts research on the geometrical and statistical properties of image models that are tied to their visual content. This necessitates a multi-disciplinary approach which draws on fields as diverse as PDEs, mathematical morphology, information theory, (spatial) stochastic processes, statistical modeling and estimation theory, machine learning, information retrieval, and cognition. In turn, the expertise developed in this group is being applied to vision problems in astronomy, remote sensing, video communications, industrial inspection and machine vision.

Research is organized in three subthemes. The subtheme *Image Understanding, Retrieval and Indexing* (PNA4.1) investigates mathematical methodologies to generate content-specific descriptions of images and video, for the purpose of robust indexing, understanding and retrieval from large databases. *Image Representation and Analysis* (PNA4.2) deals with multiresolution signal and image representations in general, and methods in wavelet analysis, mathematical morphology, and image scale-spaces in particular. In addition, it addresses specific applications such as image and video cod-

ing and compression, data fusion and image analysis. *Stochastic Geometry* (PNA4.3) is concerned with modeling and analysis of random geometric structures using techniques from spatial statistics and stochastic and integral geometry. Recently, PNA4 has also branched out to biometry where challenging image and signal processing problems are emerging. Extensive contacts are maintained with the academic world, other national institutes (NLR, TNO) and industry. External financing comes from NWO and STW programs, EU FP5 and FP6, and NATO.

Research highlights.

Image Understanding, Retrieval and Indexing. Development of a content-based image-retrieval engine. Development of principled clustering algorithms with applications in image segmentation. Establishing the ERCIM Working Group on Image and Video Understanding. Initiation of EU project BIOVISION. Acquisition and successful completion of FP5 EU IST project FOUNDIT and FP5 Concerted Action EUROPHLUKES. Acquisition and coordination of EU FP6 NoE MUSCLE.

Image Representation and Analysis. Construction of adaptive wavelets by update lifting schemes that do not require bookkeeping. New compression algorithms using non-linear binary wavelets. Investigation of a new 3D wavelet-based video codec using temporal motion-compensated lifting schemes. Design of region-based image fusion schemes. Completion of PhD and student's best paper award at the Fifth International Conference on Information Fusion by G. Piella Fenoy. Acquisition and successful completion of EU project MASCOT.

Stochastic Geometry. Introduction and application of a variety of Markov object models that allow both clustering and regularity. Edited book on stochastic geometry, and completed book on Markov point processes and their applications. Developed perfect simulation algorithms for the penetrable spheres model and extrapolation/interpolation problems. Clustering methods based on point processes using either a Bayesian or a variational approach. Construction of J-functions for multivariate and marked point processes. Acquisition and successful completion of NWO project on inference for random sets, acquisition of STW project on sequential spatial processes.

Future directions. The spectacular increase in the amount of digital image/video files and datastreams will continue unabatedly. The theme's research therefore focuses on finding generic and mathematically principled solutions for the analysis and manipulation of semantic image content. The group comprises research teams whose expertise in image analysis and spatial statistics are complementary and together constitute a powerful tool to address the many challenges in image and signal understanding. Apart from the obvious scientific interest, developing a versatile vision system will impact on many other scientific and commercial activities. Examples that spring to mind include managing specialized databases in astronomy (e.g., automated surveys for LOFAR), microscopy, e-commerce (e.g., FOUNDIT project), surveillance and photo-identification (EUROPHLUKES project). Through EUROPHLUKES we have gained considerable expertise in the photo-ID of endangered ceteceans (whales, dolphins and porpoises). This research will be extended in an ongoing *Wiskunde Toegepast* project.

As photo-ID is a crucial first step in a number of important ecological projects (e.g., estimation of population parameters), we intend to capitalize on our collaboration with large European and American research groups in marine biology to become one of the prime centers for photo-ID in biodiversity studies.

A second emerging theme is the use of advanced statistical methodology in the analysis of multimedia documents. Especially noteworthy are the many applications of statistical learning to adaptive multimedia processing. This is hardly surprising: many problems in image analysis (e.g., segmentation, saliency detection, recognition etc.) can be recast as statistical questions related to clustering, outlier detection, classification, model estimation and change point detection. Conversely, the complexity and exacting constraints in image analysis make it a rich source of problems in spatial stochastics. The interplay between statistics, machine learning and multimedia understanding is the main tenet of MUSCLE, an FP6 NoE coordinated by our group.

Another avenue of research that we have started to explore focuses on the role of sensory integration and cognition in image and signal interpretation. There are many applications in which bottom-up processing for a single modality (such as vision) proves too brittle. Robustness can be improved by injecting prior or high-level knowledge (e.g., certain geometric configurations are more likely than others) and/or by incorporating information gleaned from other sensors (e.g., combining voice and face recognition modules). Again, this gives rise to interesting statistical problems, particularly in Bayesian reasoning and classification. Furthermore, it allows us to integrate the recent work on biometric sensing. To gather critical mass for this initiative, we are coordinating an IP proposal for the FP6 Call 4 on Cognition (IST-Unit E).

Knowledge transfer. Heijmans was ASCI lecturer on "Mathematical Morphology" (1999–2003), taught an undergraduate course *Stochastiek voor Informatici* (UL, 1999) and participated in "Vakantiecursus 2000." Van Lieshout taught an undergraduate course on probability (UU, 1999), and gave an invited talk on "Analyse van beelden en andere ruimtelijke data" at the Nationale Wiskunde Dagen (February 4-5, 2000). Pauwels lectures at the Catholic University Brussels and supervised eight MSc theses at Leuven University (Belgium). From 1999 till 2002, Oonincx taught a course "Fourier Analysis", tutored a master course on "Mathematics and Sound" at UvA, and acted as MSc thesis advisor. Schouten acted as lecturer at the Utrecht School of Art and Technology (USAT). Kuijk was advisor for the Computer Graphics Group at Philips Research (May-December 1999, 2 days/week). Between 1999 and 2001 M.S. Keane was advisor for Philips Research Laboratories, Eindhoven (1 day/week), Hewlett-Packard Laboratory, Bristol (1 month/year) and EURANDOM, Eindhoven (0.5 day/week).

Van Lieshout co-organized the session Mathematical Statistics, VVS Statistische Dag, UvA (April 15, 2003). Pauwels was guest editor for ERCIM News 55: Special issue on Machine Perception. He spoke at the NSF-ERCIM Workshop (Luxembourg) and was invited speaker at the ICT Kennis Congres (The Hague, September 5, 2003). Schouten delivered a keynote lecture "The future of biometrics in Europe" at the European Biometrics Forum (Dublin, 2003). Van Lieshout gave an invited lecture on "Lo-

cally scaled Markov point processes" at the Wiskunde Colloquium, Philips Research, Eindhoven. At the Conference on Digital Image Computing in Sydney (December 10-12, 2003) Heijmans gave an invited plenary lecture on "Data hiding for image security". In 2004, Pauwels was invited member of the FP6 Expert Meeting on Knowledge and Content Technologies (Luxembourg, April 20-21). He also gave a presentation "Computer-Assisted Datamining in Image Databases" at CEBIT Hannover (March 22), and was an invited expert for the Semantic Web Panel at the European Commission's IST 2004 Event in The Hague (November 17-19). Further knowledge transfer occurs through frequent talks at conferences and workshops, a bi-weekly Signals and Images Seminar, a bi-weekly Spatial Stochastics Seminar (in collaboration with J. van den Berg, PNA3), as well as the bi-monthly PNA Colloquium (in collaboration with A. Schrijver).

3.4.3 Implementation of the 1999 recommendations

- The tenured staff was extended with E.J.E.M. Pauwels in 2001, who heads the subtheme Image Understanding, Retrieval, and Indexing
- An IOP project was acquired.
- The methodological orientations were continued.

3.4.4 Overview of the results

See Table 3.15 on page 59 for a numerical overview. A list of all publications can be found in the PNA4 sections of *CWI Overview Research Activities 1999–2003* (CD-ROM).

Selection of major publications

1 O. BARNDORFF-NIELSEN, W.S. KENDALL, M.N.M. VAN LIESHOUT (eds). (1999). *Stochastic Geometry, Likelihood and Computation*, Boca Raton: Chapman and Hall/CRC Press.

2 E.J. PAUWELS, G. FREDERIX (1999). Finding Salient Regions in Images: Nonparametric Clustering for Image Segmentation and Grouping. *Computer Vision and Image Understanding* **75** (1/2), 73–85.

3 B.A.M. SCHOUTEN, P.M. DE ZEEUW (1999). Feature extraction using fractal codes. D.P. HUIJSMANS, A.W.M. SMEULDERS (eds). *Visual Information and Information Systems, Third International Conference, Visual'99*, Amsterdam, LNCS **1614**, Springer, 483-492.

4 J. GOUTSIAS, H.J.A.M HEIJMANS (2000). *Mathematical Morphology*, IOS Press, Amsterdam.

5 M.N.M. VAN LIESHOUT (2000). *Markov Point Processes and their Applications*. London/Singapore: Imperial College Press/World Scientific Publishing.

6 B.A.M. SCHOUTEN, P.M. DE ZEEUW (2000). Image databases, scale and fractal transforms. *Proceedings of International Conference on Image Processing (ICIP 2000)*, CD-ROM ISBN 0-7803-6300-0.

7 G. PIELLA FENOY, H.J.A.M. HEIJMANS (2002). Adaptive lifting schemes with perfect reconstruction. *IEEE Trans. Signal Processing* **50**, 1620–1630.

8 R. KESHET, H.J.A.M. HEIJMANS (2003). Adjunctions in pyramids, curve evolution and scale spaces. *International Journal on Computer Vision* **52**, 139–151.

9 P.J. OONINCX, P.M. DE ZEEUW (2003). Adaptive lifting for shape-based image retrieval. *Pattern Recognition* **3**, 2663–2672.

10 P. GREGORI, M.N.M. VAN LIESHOUT, J. MATEU (2004). Mixture formulae for shot noise weighted point processes. *Statistics and Probability Letters* **67**, 311–320.

11 V. KREINOVICH, E.J. PAUWELS, S.A. FERSON, L.GINZBURG (2004). A feasible algorithm for locating concave and convex zones of interval data and its use in statistics-based clustering. *Numerical Algorithms* **37**,225–232.

12 M.J. HUISKES, ERIC J. PAUWELS (2005). Indexing, Learning and Content-based Retrieval for Special Purpose Image Databases. M. ZELKOWITZ (ed.). *Advances in Computers*, Academic Press.

PhD theses

- P.J. Oonincx (Thesis advisor: T.H. Koornwinder, Co-advisor: N.M. Temme, University: UvA, Date: February 9, 2000, Title: *Mathematical Wavelet Analysis: Wavelets, Wigner Distribution and a Seismic Application*)
- B.A.M. Schouten (Thesis advisor: M.S. Keane, University: UvA, Date: March 23, 2001, Title: *Giving Eyes to ICT! Or: How Does a Computer Recognize a Cow?*)
- G. Piella Fenoy (Thesis advisor: P.W. Hemker, Co-advisor: H.J.A.M. Heijmans, University: UvA, Date: October 30, 2003, Title: *Adaptive Wavelets and their Application to Image Fusion and compression*)
- **Future theses:** G. Frederix (External, Thesis advisor: L. Verstraelen, Co-advisor: E.J. Pauwels, April 2005) and L. Kamstra (Thesis advisor: J.B.T.M Roerdink, RUG, Co-advisor: H.J.A.M Heijmans). September 2005).

Table 3.17. Some major externally funded projects of PNA4

Acronym	Full name	Dates		k€	Source
MASCOT	Meta-data for advanced scalable video coding tools	5/2001	4/2003	220	EU / IST
MUSCLE	Multimedia understanding through semantics, computation and learning	3/2004	2/2008	320	EU / FP6
PERS	Inference for random sets	1/2001	12/2002	106	NWO

3.4.5 Context

The *Signals and Images* research group enjoys extensive contacts and interactions with Dutch universities and research institutes. This collaboration takes various forms: From 2001 through 2004 Prof. A. Smeulders (UvA) was a scientific advisor to the group.

Several group members taught specialized degree courses at various universities. Between 2001 and 2004 Van Lieshout was secretary and treasurer of the section Mathematical Statistics of the Dutch Society for Statistics and Operational Research (VVS). In addition, she was a member of the steering committee "Complex stochastic models" of the European research institute EURANDOM (Eindhoven) from 1998 till 2003, and co-organizes the annual meeting "Bijeenkomst Stochastici" held in Lunteren.

The *Signals and Images* research group is also well-embedded in the European research area through a large number of European projects (for a more detailed list see below) and its active participation in ERCIM (European Research Consortium for Informatics and Mathematics), in which it chairs one of the working groups (Image and Video Understanding). The group was also a member of ERCIM Vital Statistics Task force (2000–2004).

Through joint publications and project collaboration the group has an established global scientific network. We mention in particular collaboration with Chalmers, Aalborg, Warwick, Western Australia, Wageningen, ITC, Utrecht, Glasgow, Strathclyde, Augsburg, Aarhus, Castellon, INRIA, ICRISAT, Texas A&M, Torun, Leuven University, Europe Media Lab Dublin, University College London, College of the North Atlantic in Maine, The Johns Hopkins University, CSIRO Sydney. From August 1, 2003 till March 31, 2004, H. Heijmans was on sabbatical at the latter institute.

The group also has extensive collaboration with industrial partners both in the Netherlands (mainly through end user committees for STW projects) and internationally (mostly via European projects – see list below). In addition, M.S. Keane acted as a consultant for Philips and Hewlett-Packard (Bristol). In 2001 A. Kuijk was an advisor for the group Computer Graphics at Philips Research for two days a week. Afterwards, he joined the CWI spin-off Epictoid.

3.4.6 Scientific reputation

Awards

- M.S. Keane: foreign member of the Chilean Academy of Sciences, October 1999.
- M.N.M. van Lieshout: elected member of the International Statistical Institute (2004).
- B.A.M. Schouten: CD-ROM "Giving Eyes to ICT", Bronze World Medal for Design in the Category New Media, sub-category Information and Education, 2001, New York Arts Festival, New York, USA.

Memberships of committees and other professional activities

For Keane, see section 3.3, for Temme, see section 5.1 For a more extensive survey, please see the PNA4 section of the *CWI Overview Research Activities 1999–2003* (CD-ROM).

H.J.A.M. Heijmans	senior member of IEEE, four editorships, four memberships of boards, steering committees, advisory groups
A.A.M. Kuijk	member of one program committee

M.N.M. van Lieshout	member of one program committee, four boards, steering committees, advisory groups, one MSc committee, six organizing committees, seven PhD committees (five as external examiner)
E.J.E.M. Pauwels	coordinator of four international projects, chair of one working group, member of four program committees, two PhD committees, co-advisor of two PhD students
B.A.M. Schouten	member of three boards, steering committees, advisory groups, reviewer for one research program

3.5 Pilot Theme PNA5 – Cryptology and Information Security

Research in	Cryptology
Started in	June 2004
Theme leader	Prof.dr. R.J.F. Cramer (2004–present)
MSC-CR classification	94A60 [Cryptography], 11Yxx [Computational number theory], 11T71 [Algebraic coding theory; cryptography], 94A15 [Information theory], 81P68 [Quantum computation and quantum cryptography] E.3 [Data encryption], E.4 [Coding and information theory], F.2 [Analysis of algorithms and problem complexity], G.2 [Discrete mathematics]

3.5.1 Senior researchers

Prof.dr. R.J.F. Cramer, Dr.ir. H.J.J. te Riele (as of September 1, 2004).

Table 3.18. Staff of PNA5, 1999–2005 (in FTE/year, *prognosis)

PNA5		1999	2000	2001	2002	2003	2004	2005*
Leader:	*R.J.F. Cramer*						*0.12*	*0.2*
Researchers:	*H.J.J. te Riele*						*0.27*	*0.8*
	R.J.F. Cramer						*0.35*	*0.6*
Total tenured staff							**0.7**	**1.6**
Non-tenured staff							0.4	1.0
CWI PhD students							1.2	4.5
Total research staff CWI payroll							**2.3**	**7.1**
Seconded PhD students							*0.0*	*0.0*
Other seconded staff							*0.1*	*0.3*
Total hosted research staff							***2.4***	***7.4***

Table 3.19. Scientific output of PNA5

Output class		1999	2000	2001	2002	2003	2004	Total
Academic	refereed journals and proceedings						7	7
	other journals and proceedings						0	0
	book chapters						1	1
Total academic							**8**	**8**
Monographs							0	0
PhD dissertations							0	0
Professional pub./products							1	1

Table 3.20. Funding percentages of PNA5

PNA5	1999	2000	2001	2002	2003	2004	Average
Direct NWO						100.0%	100.0%
Other research funds						0.0%	0.0%
Grants/contracts						0.0%	0.0%
Other						0.0%	0.0%
Total						**100.0%**	**100.0%**

3.5.2 Research orientation, highlights and future directions

Mission and research area. The PNA5 theme was established on June 1, 2004 and is concerned with fundamental as well as practice-oriented cryptology and information security. Broadly speaking, cryptology provides and analyzes the core techniques for securing digital transactions and information systems from hackers and malicious corruption in general. It also explores the fundamental limits of what can be achieved securely. Examples of core cryptographic tools are encryption schemes and digital signature schemes, which enable secure communications. Information security uses cryptographic tools to build secure systems, such as fire-walls and secure internet protocols.

One focal point of the new theme is secure computation. This area deals with the general problem of two or more parties who, in the absence of a trusted third party, wish to achieve a joint task securely even though they are mutually distrustful and wish to keep sensitive, private information secret from each other. This is sometimes called multi-lateral security, as opposed to unilateral security in the case of secure communications. Standard methods from secure communications typically do not suffice in order to achieve multi-lateral security, and so this area relies on its own, dedicated set of basic cryptographic tools. As a specific example, consider the problem where two companies consider a merger, but only if their joint customer base is "large enough," i.e., the bases are disjoint enough. However, before the merger is actually established, it may certainly be in their commercial interest to continue to hide their trade secrets from one another. In principle, secure computation resolves this paradoxical situation and allows the parties to determine whether their joint base is large enough without requiring them to expose their respective secrets to one another. Oblivious transfer is the core cryptographic technique upon which the solution is based. More generally, practical applications of secure computation include profile matching, secure and private aggregate database access, electronic voting or auctions, and threshold cryptography. Moreover, the mathematical theory of secure computation offers a multitude of important theoretical challenges.

Other priority topics are the Number Field Sieve project for factoring large integers, which is relevant to the security of the widely used RSA cryptosystem, as well as other issues in computational number theory with relevance for cryptology, discrete tomography, and public key cryptography (chosen ciphertext security for encryption, digital signatures), information theoretically secure cryptography (secret key es-

tablishment from correlated randomness by public discussion, privacy amplification, bounded storage model, secret sharing, secure multi-party computation), quantum cryptography (key exchange, protocols), formal security analysis as well as applied information security (security in mobile networks).

Research in cryptology is often at the interface of mathematics and computer science, and typically draws on methods from theoretical computer science (e.g., complexity theory, formal methods, algorithms), number theory, geometry, discrete mathematics, as well as information theory and quantum physics.

Future directions. At the time of writing, PNA5 consists of two senior researchers (Cramer/Te Riele), one postdoc (S. Fehr), three PhD students (plus one vacancy), as well as guests. As of September 1, 2004, PNA5 includes the Computational Number Theory project of Te Riele, which used to be part of MAS2. For more information on Te Riele and this project, please refer to the section on MAS2.

Several applications for external project funding are pending, and more will be filed in 2005. It will depend on the extent to which these are granted whether all scheduled research projects below can be commenced within the next two to four years.

The research agenda for PNA5 includes the following projects (in arbitrary order):

Practical secure computation. This project focuses on core cryptographic techniques which do not yet belong to the standard toolkit of the security engineer, as opposed to methods for secure communication.

Cryptanalysis through computational number theory. Work on the Number Field Sieve will be continued, which is relevant to the security of the widely used RSA cryptosystem.

Algebraic & combinatorial aspects of secure multi-party computation. The relation between linear secret sharing schemes with (strong) multiplication on the one hand, and matroids and error correcting codes on the other hand will be explored.

Quantum cryptographic protocols Special attention will be devoted to the study of cryptographic methods, such as zero knowledge protocols, that may withstand an adversary that has access to a quantum computer.

Information-theoretically secure cryptography. This project concerns secret key establishment from correlated randomness by public discussion, privacy amplification, encryption in the bounded storage model, and secret sharing, as well as mass-scale secure and private storage and message transmission.

Public-key cryptography: foundations and practice. This project deals in particular with the study of number-theoretical public key encryption schemes that withstand adaptive chosen ciphertext attack, as well as identity-based cryptosystems based on certain pairing on elliptic curves. This work is important in emerging industry standards. Extending the class of NP-languages for which practical NIZK (non-interactive zero-knowledge) proofs are known is another priority.

Applied information security. Security and user privacy in mobile networks will be the focus.

Formal security analysis. This project deals with formal reasoning about security: ex-

pressing the security of complex systems in terms of the security of its less complicated components.

Discrete tomography. Further development of algorithms in discrete tomography for 3D problems and for problems with gray values, i.e., more than two pixel values.

Knowledge transfer

- R.J.F. Cramer is full professor at UL and teaches cryptology.
- R.J.F. Cramer received funding from STW for one postdoc and two PhD students in a joint project with Philips Research and TUE, to start in 2005.
- A new national Seminar on Research in Information Security and Cryptology was kicked off in October 2004. An international workshop on Secure Multi-Party Protocols was organized in Amsterdam in 2004. A Special Semester on Mathematical Aspects of Cryptology is co-organized in 2005 in Barcelona, in collaboration with the Polytechnical University of Catalunya.

3.5.3 Overview of the results

See Table 3.19 on page 66 for a numerical overview.

Selection of major publications

1 R.J.F. CRAMER, V. SHOUP (2003). Design and analysis of practical public-key encryption schemes secure against adaptive chosen ciphertext attack. *SIAM Journal on Computing* **33**,167–226.

2 R.J.F. CRAMER, I. DAMGAARD (2004). Secret-key zero-knowledge and non-interactive verifiable exponentiation. *Proceedings of Theory of Cryptography Conference (TCC '04)*, MIT, Cambridge, USA, Springer-Verlag LNCS **2951**, 223–237.

3 R.J.F. CRAMER, I. DAMGAARD, Y. ISHAI (2005). Share conversion, pseudorandom secret-sharing schemes and applications to secure distributed computing. *Proceedings of Theory of Cryptography Conference (TCC '05)*, MIT, Cambridge, USA, Springer-Verlag LNCS.

3.5.4 Context

PNA5 has attracted Prof.dr. A.K. Lenstra (Lucent Bell Labs/TUE) as scientific advisor per September 1, 2004, for an initial period of 4 years. In the academic year 2004–2005 PNA5 has a visiting professor from TUE for 0.4 FTE, and throughout the winter semester of 2004 a visiting PhD student from Aarhus University.

There is potential for collaboration between PNA5 and PNA1, INS4, PNA4, SEN2.

Close contacts with academia and industry include ETH Zürich, Aarhus University, Katholieke Universiteit Leuven, Philips Research, Eindhoven, TUE, UL, New York University, IBM Zürich Research Laboratory, IBM T.J. Watson Research Center, Lucent Bell Labs, Technion (Haifa), MIT, Polytechnical University Catalunya, NTT (Japanese TNO Telecom), Columbia University.

3.5.5 Scientific reputation

Memberships of committees and other professional activities

For H.J.J. te Riele, see section 5.2

R.J.F. Cramer	full professor at UL, "junior member" of KNAW (De Jonge Akademie), four editorships, four memberships of boards, steering committees, advisory groups

Chapter 4

Research cluster SEN – Software Engineering

General

Cluster leader

Prof.dr. J.W. de Bakker (1999–2001)
Prof.dr. P. Klint (2002–present)

Strategy and policy

SEN focuses its research on various aspects of software engineering, evolutionary systems and multimedia applications. Typical research questions are analysis and transformation of software systems, verification of embedded systems, component-based development, competitive agents, and multimedia players.

Table 4.1. Global staff survey of SEN0–SEN5 (*prognosis)

SEN		1999	2000	2001	2002	2003	2004	2005*
SEN0	CWI research staff		0.0	0.0	0.0	0.0	0.0	0.0
	Total research staff		*0.8*	*0.8*	*0.8*	*0.8*	*0.8*	*0.8*
SEN1	CWI research staff	10.7	13.8	9.4	7.6	8.2	12.4	15.8
	Total research staff	*11.1*	*13.9*	*9.8*	*8.2*	*11.6*	*13.6*	*16.3*
SEN2	CWI research staff	7.5	9.4	9.4	10.9	10.1	9.7	10.2
	Total research staff	*10.1*	*12.1*	*12.8*	*13.0*	*10.4*	*11.3*	*11.7*
SEN3	CWI research staff	7.0	7.1	8.6	10.5	11.4	11.2	9.1
	Total research staff	*9.2*	*9.2*	*11.2*	*12.0*	*13.5*	*13.0*	*10.9*
SEN4	CWI research staff	5.3	6.8	10.5	7.9	8.0	9.2	9.0
	Total research staff	*6.9*	*8.4*	*11.3*	*8.0*	*8.7*	*9.6*	*9.4*
SEN5	CWI research staff						1.8	7.0
	Total research staff						*1.8*	*7.0*

The ambition is to cover the whole range of activities from fundamental concepts and prototype implementations to the application of these concepts in practice. For fundamental research, many cooperations exist with Dutch universities and international partners.

In addition to scientific publications, demonstrations and prototype systems are important outcomes of the research in this cluster. These prototypes find their way to

researchers worldwide. Applications and technology transfer are mostly realized in cooperation with external partners or via the creation of spin-off companies.

Themes

- **SEN1:** *Interactive Software Development and Renovation*.
- **SEN2:** *Specification and Analysis of Embedded Systems*.
- **SEN3:** *Coordination Languages*.
- **SEN4:** *Evolutionary Systems and Applied Algorithmics*.
- **SEN5:** *Convergent Media Interfaces*.

A cluster project under SEN0 is devoted to the bibliography of Aad van Wijngaarden (former director of CWI).

Developments

1. SEN has created two spin-off companies: The Software Improvement Group (a spin-off of SEN1 started in 2000), and Adaptive Planet (a spin-off of SEN3, started in 2002).
2. SEN5 was created as a pilot theme in 2004.

Scientific challenges for SEN

The following challenges are currently playing a role at CWI in discussions on future research projects.

Software systems tomography. Like in computer tomography – where slices of the human body taken by means of an MRI or X-ray scan are synthesized into a three-dimensional model for a specific purpose like brain surgery – we intend to develop techniques for *software systems tomography*. This is a four-stage process. First, facts are extracted from the raw source code of the application or from an execution trace. Next, these facts are used to build a specific model that will enable us to answer specific questions about the system regarding its architecture, low-level coding properties, concurrency behavior, security properties, adherence to protocol standards, and more. Next, verification techniques are applied to answer specific questions for the given model. Depending on the questions, we will combine static analysis, (parallel) model checking, and theorem proving techniques. Finally, visualization techniques will give insight into the answers that are found and how they relate to the original system's source code.

Coordination and reconfiguration of distributed components. Coordination and dynamic reconfiguration naturally arise in many software (and other) systems, such as dynamically evolving agent societies, system biology, enterprise architectures, and business processes. They gives rise to many scientific challenges, including the coordination of interaction among autonomous agents; compositional reasoning about emergent behavior in distributed concurrent systems; dynamically reconfigurable architectures necessitated by mobility; and their mathematical foundation. All these represent core challenges that for the next five years will remain at the forefront of research on software intensive and other complex systems.

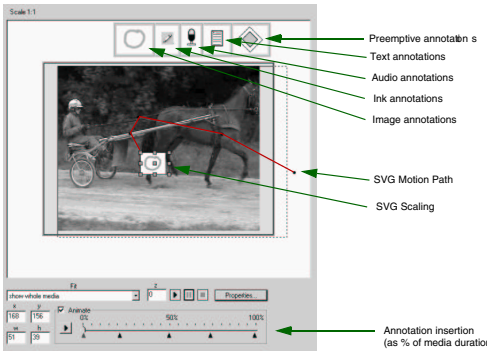


Figure 4.1. An animation interface is shown for use with medical images. A SMIL-based multimedia file is constructed containing a base media extended with peer-level audio, text, image or animation annotations.

Figure 4.2. From SEN project *Ideals*: analyzing 14 million lines of C source code that control ASML's Twinscan^{TM} waferstepper.

Fundamental adaptive solutions for repeated games in competitive multi-agent systems. ICT applications are facing a paradigm shift: from monolithic applications with central control to many independent self-interested ("non-cooperative") parties connected by distributed networks and interacting in a dynamic and *ad hoc* way. The terms for these interactions are set via, for instance, negotiations, auctions, and market mechanisms. These occur repeatedly, either sequentially, simultaneously, or even in a completely unstructured way, as repeated competitive games. We aim at deriving fundamental adaptive solutions for self-interested agents playing in repeated competitive games, in a generic and substantial way, with a focus on techniques from computational intelligence and adaptive algorithms. Furthermore, competitive multi-agent systems will be designed for applications like transportation logistics, patient planning in health care, and communication networks.

Making distributed time-based media transfer correct and transparent. The convergence of consumer, business and computer devices brings with it a number of significant challenges in how complex information must be created, protected, distributed, and shared. A first – and fundamental – challenge is modeling the interactions of multiple information streams (such as images and audio or video, multilingual audio and text) as they transit through a distributed network of heterogeneous servers and clients. Languages that support the declarative description of information interaction and models and methods that can be used to verify a host of aspects of information integrity (including content security and logical correctness) within the temporal framework of the underlying information are of vital importance. A second challenge is reducing the authoring burden of creating presentations containing multilevel rich media content. The creation process needs modeling support that is aware of the diversity of the underlying infrastructure.

4.1 Theme SEN1 – Interactive Software Development and Renovation

Research in	Software evolution, software transformation, generic language technology, domain-specific languages, knowledge engineering
Started in	1997
Theme leader	Prof.dr. P. Klint (1997–present)
CR classification	D.2 [Software engineering]

4.1.1 Senior researchers

Dr. M.G.J. van den Brand, Prof.dr. A. van Deursen, Prof.dr. D.J.N. van Eijck (as of January 1, 2004), J. Heering, Prof.dr. P. Klint.

Table 4.2. Staff of SEN1, 1999–2005 (in FTE/year, *prognosis)

SEN1		1999	2000	2001	2002	2003	2004	2005*
Leader:	*P. Klint*	*0.20*	*0.2*	*0.2*	*0.2*	*0.20*	*0.2*	*0.2*
Researchers:	*M.G.J. van den Brand*	*0.75*	*1.0*	*1.0*	*0.0*	*0.63*	*0.4*	*0.4*
	A. van Deursen	*1.00*	*1.0*	*1.0*	*1.0*	*0.80*	*0.8*	*0.8*
	D.J.N. van Eijck						*0.8*	*0.8*
	J. Heering	*1.00*	*1.0*	*1.0*	*1.0*	*1.00*	*1.0*	*1.0*
	P. Klint	*0.40*	*0.4*	*0.4*	*0.2*	*0.20*	*0.2*	*0.2*
Total tenured staff		**3.4**	**3.6**	**3.6**	**2.4**	**2.8**	**3.4**	**3.4**
Non-tenured staff		3.0	4.3	0.8	0.6	1.6	3.0	3.4
CWI PhD students		4.3	5.9	5.0	4.6	3.8	6.0	9.0
Total research staff CWI payroll		**10.7**	**13.8**	**9.4**	**7.6**	**8.2**	**12.4**	**15.8**
Seconded PhD students		*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
Other seconded staff		*0.4*	*0.1*	*0.4*	*0.6*	*3.4*	*1.2*	*0.5*
Total hosted research staff		***11.1***	***13.9***	***9.8***	***8.2***	***11.6***	***13.6***	***16.3***

Table 4.3. Scientific output of SEN1

Output class		1999	2000	2001	2002	2003	2004	Total
Academic	refereed journals and proceedings	12	25	11	19	15	19	101
	other journals and proceedings	0	0	8	1	4	14	27
	book chapters	0	1	1	4	1	0	7
	Total academic	**12**	**26**	**20**	**24**	**20**	**33**	**135**
Monographs		0	2	3	0	0	1	6
PhD dissertations		0	1	0	2	2	0	5
Professional pub./products		10	6	10	9	9	17	61

Table 4.4. Funding percentages of SEN1

SEN1	1999	2000	2001	2002	2003	2004	Average
Direct NWO	67.9%	69.7%	82.1%	94.4%	74.4%	61.9%	75.0%
Other research funds	26.5%	23.7%	14.3%	4.8%	20.3%	35.9%	20.9%
Grants/contracts	5.6%	6.6%	2.6%	0.8%	0.0%	1.6%	2.9%
Other	0.0%	0.0%	1.0%	0.0%	5.3%	0.6%	1.2%
Total	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**

4.1.2 Research orientation, highlights, and future directions

Mission and research area. Our society increasingly depends on large, interacting, computer systems. The rapidly changing computerization needs are, however, not matched by our abilities to build and maintain such systems. The development, understanding and evolution of large software systems is a key economic and societal problem. The mission of this theme is to advance the state of the art in these three areas.

The development of large software systems is addressed by generating components on the basis of domain-specific languages, by explicitly describing the cooperation protocols of components, by explicitly packaging subsystems, and by exploring methods for unit testing and daily builds. Key questions are related to capturing the variability of software systems and controlling the process for configuring, building and distributing them. The software implementation activities in this theme form a test bed for these new techniques.

Software understanding is addressed by developing new techniques for the analysis and exploration of software systems. Key questions are how to traverse programs for extracting facts, how to describe the desired analysis, how to collect the results of the analysis and how to visualize them. Real systems use multiple source languages, and fact extraction and analysis should therefore be done in a language-parametric fashion.

The evolution of software systems is approached by applying program analysis techniques to study the evolutionary aspects of a system. The results of program understanding are also used for program transformations that form the basis for fully automatic system renovation. Description and automation of these transformations and finding the commonality in program transformations for different languages are research topics. The correctness of these transformations is also a major concern.

The general research approach is to bring together established fundamental notions such as modularization, term rewriting, and program generation with pragmatic needs such as component-based development and understanding or transforming legacy systems. Formal language definitions play an important role in this approach. They describe the syntax and semantics of a domain-specific or programming language and form the basis for the analysis and transformation of software in existing languages, for the generation of specific tools, and for the development of domain-specific languages. The aim is to realize truly *generic language technology* that can be applied in

many problem areas.

Research highlights. Problems regarding documentation generation (DocGen), type inference, code smell detection, architecture extraction, clone detection, and aspect mining were solved for various languages (COBOL, Java, C, SDL). Program transformations were applied to the optimization of numerical C++ code in coordinate-free style, adaptation of COBOL programs, COBOL data reverse engineering, and Java test code refactoring.

With the increased versatility of our language processing techniques it becomes more important to consider how to manage the knowledge about languages and application domains. The notion of a Language Design Assistant was introduced to structure and better understand the development process of and knowledge contained in language definitions. We also made progress in characterizing domain-specific languages and using feature diagrams for characterizing domain models.

We introduced the notion of *grammar engineering* to recognize the central role that grammars play in software engineering projects (including our own). This included work on grammar recovery and grammar refactoring. Techniques for Generalized LR parsing were further improved and extended with *island grammars* (for parsing only areas of interest in source code when a complete language grammar is not available) and disambiguation based on term rewriting.

Our basic computing paradigm remains term rewriting but it has been extended in various ways to meet our main challenges. Traversal functions were added to enable the concise specification of source code traversals for analysis, fact extraction, and transformation. Source code layout and program annotations can now be preserved during rewriting. A start was made with the use of relational techniques for the processing and refinement of source code facts in a language-parametric way.

Major progress was made with the modernization and extension of the ASF+SDF Meta-Environment (including Generalized LR parsing and parser generation, pretty-printing, static checking, compilation, library functions, user-interface, and connections with the Emacs and Vim editors and the integrated development environment Eclipse). Various code generators (ApiGen, JJForester, JJTraveler) were developed that take a grammar as input and generate a tree processor in C or Java as output that provides basic tree access as well as global visitors. In this way hybrid applications can be built that are partly based on ASF+SDF specifications and partly on hand written C or Java code. Our software engineering process was improved by the introduction of various tools (DailyBuild, AutoBundle, and PackageBase).

Future directions. Our main ambition remains to advance the state of the art in the development, understanding and evolution of large software systems. In addition to solving the problems we encounter in practice, we will strengthen and extend the research sketched above with research on finding and describing language-parametric program transformations, on the integration of analysis techniques based on term rewriting and relations, and on the problems posed by grammar engineering.

Knowledge transfer. Four senior researchers are associated with organizations for

higher education (in Amsterdam, Delft, and Utrecht) and are involved in teaching regular courses.

In 2000 the Software Improvement Group was created to develop and market SEN1's research results. Its main activities are documentation generation and software assessment. Our results are also used by various banking groups (ABN AMRO, Fortis, ING), and software services firms (e.g., Cap Gemini, First Result). Many joint projects with industrial partners have been completed or are in progress: ABN AMRO (documentation generation, program transformation), ASML (aspect mining), Baan (software knowledge management and delivery), Chipsoft (software delivery), Exact (software delivery), First Result (application generation), Lucent (understanding), Nokia Research (understanding), PinkRoccade (maintenance), and Planon (software delivery).

Examples of the use of our technology in academia are the Action Semantics Environment (programming language semantics, Aarhus), the CHI compiler (mechanical engineering, Eindhoven), ELAN (rewriting, Nancy), Stratego (program transformation, Utrecht), μCRL toolset (model checking, Eindhoven and Amsterdam), MathML generation (typesetting, Nancy), CASL (specification language, Bremen), and TOM (pattern matching, Nancy). Several of our tools (aterms, toolbus, sglr) are included in the Debian linux distribution.

4.1.3 Implementation of the 1999 recommendations

- The research group SEN1.3 (Interactive Visualization Environments) headed by R. van Liere left SEN1 by the end of 2000 to staff the restructured theme INS3.
- In 2004, J. van Eijck (till 2000 INS3, INS cluster from 2000–2004) joined SEN1 with the project group SEN1.4 (Concept Based Reasoning and Knowledge Engineering).

4.1.4 Overview of the results

See Table 4.3 on page 74 for a numerical overview. A list of all publications can be found in the SEN1 sections of *CWI Overview Research Activities 1999–2003* (CD-ROM).

Selection of major publications

1 M.G.J. VAN DEN BRAND, H.A. DE JONG, P. KLINT, P.A. OLIVIER (2000). Efficient annotated terms. *Software, Practice & Experience* **30** (3), 259–291.

2 T.B. DINESH, M. HAVERAAEN, J. HEERING (2001). An algebraic programming style for numerical software and its optimization. *Scientific Programming* **8** (4), 247–259 (Special issue on Coordinate-Free Numerics).

3 M.G.J. VAN DEN BRAND, J. HEERING, P. KLINT, P.A. OLIVIER (2002). Compiling language definitions: The ASF+SDF compiler. *ACM Transactions on Programming Languages and Systems* **24** (4), 334–368.

4 P. KLINT, C. VERHOEF (2002). Enabling the creation of knowledge about software assets. *Data and Knowledge Engineering* **41** 2–cw3158, 141–158.

5 M.G.J. VAN DEN BRAND, P. KLINT, J.J. VINJU (2003). Term rewriting with traversal functions. *ACM Transactions on Software Engineering and Methodology* **12** (2), 152–190.

6 D.J.N. VAN EIJCK (2003). Parser combinators for extraction. *Proceedings of the Fourteenth Amsterdam Colloquium*, ILLC, UvA, 99–104.

7 M. MERNIK, J. HEERING, A.M. SLOANE (2003). When and how to develop domain-specific languages. Preprint.

8 M. BRUNTINK, A. VAN DEURSEN, R. VAN ENGELEN, T. TOURWÉ (2004). An evaluation of clone detection techniques for identifying cross-cutting concerns. *Proceedings International Conference on Software Maintenance (ICSM 2004)*, IEEE Computer Society. (Best paper award.)

9 A. VAN DEURSEN, J. VISSER (2004). Source model analysis using the JJTraveler visitor combinator framework. *Software Practice & Experience* **34** (14), 1345–1379.

10 A. VAN DEURSEN, C. HOFMEISTER, R. KOSCHKE, L. MOONEN, C. RIVA (2004). Symphony: View-driven software architecture reconstruction. *Proceedings of the IEEE/IFIP Working Conference on Software Architecture (WICSA '04)*, IEEE Computer Society.

11 K. DOETS, D.J.N. VAN EIJCK (2004). *The Haskell Road to Logic, Maths and Programming*. King's College Publications, London.

PhD theses

- E. Saaman (external) (Thesis advisors: G.R. Renardel de Lavalette, P. Klint, University: RUG, Date: November 24, 2000, Title: *AFSL: Another Formal Specification Language*)
- S.M. van Dongen (Thesis advisors: M. Hazewinkel, D.J.N. van Eijck, Co-advisor: M.G.J. van den Brand, University: UU, Date: May 29, 2000, Title: *Graph Clustering by Flow Simulation*)
- P.A. Olivier (Thesis advisor: P. Klint, Co-advisor: M.G.J. van den Brand, University: UvA, Date: December 5, 2000, Title: *A Framework for Debugging Heterogeneous Applications*)
- R. van Liere (Thesis advisor: P. Klint, University: UvA, Date: March 4, 2001, Title: *Studies in Interactive Visualization*)
- M. Pauly (Thesis advisors: J. van Benthem, D.J.N. van Eijck, University: UvA, Date: December 13, 2001, Title: *Logic for Social Software*)
- T. Kuipers (Thesis advisor: P. Klint, Co-advisor: A. van Deursen, University: UvA, Date: February 26, 2002, Title: *Techniques for Understanding Legacy Software Systems*)
- L.M.F. Moonen (Thesis advisor: P. Klint, Co-advisor: A. van Deursen, University: UvA, Date: December 5, 2002, Title: *Exploring Software Systems*)
- R. Nouwen (external) (Thesis advisors: D.J.N. van Eijck, H. de Swart, University: UU, Date: November 21, 2003, Title: *Plural Pronominal Anaphora in Context: Dynamic Aspects of Quantification*)
- J. Heguiabehere (external) (Thesis advisor: D.J.N. van Eijck, Co-advisor: M. de Rijke, University: UvA, Date: December 4, 2003, Title: *Building Logic Toolboxes*)
- M. de Jonge (Thesis advisor: P. Klint, Co-advisor: A. van Deursen, University: UvA, Date: 2003, Title: *To Reuse or to Be Reused*)

- J.M.W. Visser (Thesis advisor: P. Klint, Co-advisor: R. Lämmel, University: UvA, Date: 2003, Title: *Generic Traversal of Typed Source Code Representations*)

Table 4.5. Some major externally funded projects of SEN1

Acronym	Full name	Dates		k€	Source
DSL/TI	Domain-specific languages	1999	2002	1,300	TI
Ideals	Idiom design for embedded applications on a large scale	2003	2006	850	SENTER
CaLCE	Computer-aided life cycle enabling	9/2003	8/2006	1,145	SENTER

4.1.5 Context

SEN1 currently has joint projects with, among others, Dutch software companies Exact BV, Planon BV, ChipSoft BV, PinkRoccade Public BV, and Software Improvement Group BV (SEN1 spin-off), with ASML (lithographic equipment for IC production) and IBM, and with researchers at many Dutch and foreign universities. It also has strong contacts with major Dutch banks, such as ABN AMRO, Fortis, and ING.

The cooperation with the HvA, VU and UvA is particularly close, and this has led to the Software Engineering Amsterdam (SEA) initiative to create a "critical mass" in SE research and education. External funding for SEA is currently being applied for.

The SEN1 spin-off Software Improvement Group BV is active in all fields of software renovation: adaptation, integration and rebuilding of existing software systems.

See Section 4.1.2 for further details.

4.1.6 Scientific reputation

Awards

- A. van Deursen (with M. Bruntink) received two best paper awards: for the paper "Predicting class testability using object-oriented metrics" at the Fourth IEEE International Workshop on Source Code Analysis and Manipulation (SCAM 2004) and for the paper "An evaluation of clone detection techniques for identifying cross-cutting concerns" at the International Conference on Software Maintenance (ICSM 2004).
- P. Klint received two IBM Eclipse Innovation Awards for the MetaEclipse and KernelMetaEclipse projects.

Memberships of committees and other professional activities

For a more extensive survey, please see the SEN1 section of the *CWI Overview Research Activities 1999–2003* (CD-ROM).

M.G.J. van den Brand	lecturer at Hogeschool van Amsterdam, organizer of one conference, member of six program committees
A. van Deursen	full professor at TUD, organizer of five conferences, member of twelve program committees

D.J.N. van Eijck	full professor at UU, scientific director Dutch Graduate School in Logic (until November 2002), chairman VSNU visitation committee for Artificial Intelligence (Fall 2001 and Spring 2002), member of two program committees
J. Heering	organizer of two conferences, member of five program committees
P. Klint	full professor at UvA, member scientific council INRIA, member scientific directorate Schloss Dagstuhl, president European Association for Programming Languages and Systems (EAPLS), member of two editorial boards, member of eleven program committees

4.2 Theme SEN2 – Specification and Analysis of Embedded Systems

Research in	Software and System – verification and validation
Started in	January 1997
Theme leaders	Prof.dr.ir. J.F. Groote (1997–September 2000)
	Prof.dr. W.J. Fokkink (September 2000–September 2004)
	Dr. J.C. van de Pol (September 2004–present)
MSC classification	68Q60 [Specification and verification]
	68Q85 [Models/methods for distributed computing]
	68T15 [Theorem proving (deduction, resolution)]

Table 4.6. Staff of SEN2, 1999–2005 (in FTE/year, *prognosis)

SEN2		1999	2000	2001	2002	2003	2004	2005*
Leader:	*J.F. Groote*	*0.20*	*0.13*					
	W.J. Fokkink		*0.07*	*0.20*	*0.2*	*0.2*	*0.13*	
	J.C. van de Pol						*0.07*	*0.2*
Researchers:	*W.J. Fokkink*	*0.50*	*0.73*	*0.63*	*0.6*	*0.6*	*0.40*	*0.2*
	J.F. Groote	*0.60*	*0.40*					
	J.W. Klop	*0.60*	*0.40*	*0.48*	*0.2*	*0.2*	*0.20*	*0.2*
	J.C. van de Pol	*0.67*	*1.00*	*1.00*	*1.0*	*1.0*	*0.93*	*0.6*
Programmers:	*B. Lisser*	*1.00*	*1.00*	*1.00*	*1.0*	*1.0*	*1.00*	*1.0*
Total tenured staff		**3.6**	**3.7**	**3.3**	**3.0**	**3.0**	**2.7**	**2.2**
Non-tenured staff		1.6	2.9	2.1	3.2	2.6	2.0	3.0
CWI PhD students		2.3	2.8	4.0	4.7	4.5	5.0	5.0
Total research staff CWI payroll		**7.5**	**9.4**	**9.4**	**10.9**	**10.1**	**9.7**	**10.2**
Seconded PhD students		*1.4*	*1.1*	*1.2*	*0.1*	*0.0*	*0.5*	*1.0*
Other seconded staff		*1.2*	*1.6*	*2.2*	*2.0*	*0.3*	*1.1*	*0.5*
Total hosted research staff		***10.1***	***12.1***	***12.8***	***13.0***	***10.4***	***11.3***	***11.7***

Table 4.7. Scientific output of SEN2

Output class		1999	2000	2001	2002	2003	2004	Total
Academic	refereed journals and proceedings	9	23	25	20	16	33	126
	other journals and proceedings	4	0	3	5	8	8	28
	book chapters	0	0	6	0	0	0	6
	Total academic	**13**	**23**	**34**	**25**	**24**	**41**	**160**
Monographs		1	2	0	0	0	0	3
PhD dissertations		3	1	1	3	0	3	11
Professional pub./products		6	16	6	0	13	0	41

4.2.1 Senior researchers

Prof.dr.ir. J.F. Groote (tenured till September 2000, seconded since then), Prof.dr. W.J. Fokkink, Prof.dr. J.W. Klop, Dr. J.C. van de Pol.

Table 4.8. Funding percentages of SEN2

SEN2	1999	2000	2001	2002	2003	2004	Average
Direct NWO	66.1%	68.7%	71.5%	73.6%	80.4%	64.3%	70.7%
Other research funds	12.6%	26.6%	21.7%	19.6%	16.8%	32.2%	21.6%
Grants/contracts	18.3%	3.3%	3.8%	5.6%	2.9%	2.2%	6.0%
Other	3.0%	1.4%	3.0%	1.2%	0.0%	1.3%	1.7%
Total	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**

4.2.2 Research orientation, highlights, and future directions

Mission and research area. The main research of this theme is concentrated on techniques for *improving the quality of software in embedded systems*. For this purpose we study and develop formal techniques for the unambiguous description, design and analysis of systems and software. We work with a wide range of analysis techniques and resources to verify that programmed systems exhibit their expected functionality. We employ methods from algebra (process algebra, term rewriting) and logic (temporal logic, timed automata). For the analysis of systems, dedicated tools for automated theorem proving, model checking, mechanical proof checking, state-space analysis and reduction, simulation, testing and visualization are developed and used. An important vehicle is the language μCRL: micro Common Representation Language and its associated toolset. In order to assess the viability of various techniques and tools, we carry out experiments in the realm of fundamental distributed algorithms, embedded and hybrid control systems, and network protocols. Industrial application of our techniques, in the form of case studies, is an important activity.

Research highlights.

Fundamental research. SEN2 has a strong tradition in process theory (Bergstra, Klop, Baeten, Vaandrager, Van Glabbeek, Groote, Fokkink). Our (former) group members made many contributions to the *Handbook of Process Algebra* (2001). As a spin-off, the formalism μCRL (process algebra with data) was developed in the 1990s. Much research was devoted to the foundations of this formalism, culminating in three theses within the evaluation window (Luttik, Usenko, Van der Zwaag). Recent years have shown new fundamental research in process theory, viz. SOS theory (structural operational semantics). The work of Groote, Van Glabbeek and Fokkink on SOS specification formats received a worldwide reputation.

Awards. Special attention deserves the foundational work of J.W. Klop. His many years of research on term rewriting materialized in the recently published 900-page handbook *Term Rewriting Systems*. In 2003, this godfather of the Dutch term rewriting school was appointed as a member of KNAW. The honorary doctorate from the University of East-Anglia in 2002 showed the international recognition for his achievement. Another valuable achievement is that W. Fokkink got the chair in theoretical computer science at VU (2001).

Verification by theorem proving and model checking. The μCRL toolset, started by

Groote, provides an environment for research experiments in formal verification. Several tools and techniques are integrated in one architecture. The research of Van de Pol, Blom and several PhD students in this area tries to fight complexity of verifying distributed systems *by all means*: developing new proof methods, combining model checking and theorem proving algorithms, exploiting distributed hardware. We can only mention a selection of the results: **(1) Proof methods.** The *cones and foci theorem* provides a systematic method to prove that an implementation meets its specification. The framework is implemented in the American theorem prover PVS, and provides completely mechanized protocol verifications, such as the Sliding Window Protocol. Other achievements are an *abstract interpretation framework* and the *partial-order reduction by confluence* technique for process algebra. In both methods theorem proving is used to achieve a symbolic state space reduction. The reduced state space is then subjected to model checking, using e.g., the French toolset CADP. (**2) Theorem prover support.** A special-purpose theorem prover to solve Boolean combinations over data specifications is under development. This gave rise to several publications on extensions of BDDs and resolution to settings with equality and data. It is used to discharge proof obligations of the methods mentioned before. (**3) Distributed tools.** Recently, we developed new distributed verification algorithms, an upcoming research area. This research gave us a lead in distributed state space reduction. It widens the applicability of model checking to state spaces that only fit in the memory of dozens of computers. For this research, a cluster of computers was acquired by SEN2 in collaboration with two other research groups at CWI.

Applied research. We applied our research to real systems in industrial contexts, in two large and many smaller projects. These case studies result in finding and explaining errors, and improving the design of systems in various phases of the engineering cycle (requirements analysis, design, testing). The theses of Romijn (NWO/EW), Griffioen (NWO/EW), Pang (STW/Progress) and Orzan (STW/Progress) report on results, experiences, new methods, and limitations.

Future directions. We will be active in various upcoming research areas. The aim is to keep a leading position in verification technology based on state space reduction, by combining brute force and symbolic reasoning methods. Moreover, we will focus on a number of relevant application domains. Finally, through strategic alliances and choices we want to lower the threshold for industrial application of formal methods.

Distributed model checking is a core technology, in which we want to play a leading role. We already developed distributed state space reduction algorithms. These are effective, and we currently have no competitors worldwide. We want to extend this expertise to enumerative distributed model checking algorithms, which is an active and upcoming area with many open problems. Van de Pol will organize the PDMC workshop in 2005.

Symbolic reasoning is a core technology we want to extend and apply systematically. The idea is to apply theorem proving and constraint solving in order to detect and prove invariants, confluence properties and state mappings at the level of system

specifications. The goal is to optimize specifications so that the generated state space will be minimal.

Security protocols is an upcoming application area, driven by societal needs. We will develop and verify black-box security algorithms, especially for mobile and wireless networks. Actually, we have already started with security protocol verification. S. Mauw (seconded from TUE) works on specification of security properties and dedicated verification algorithms. Cederquist (ERCIM fellow) and Dashti (NWO/EW) work on e-commerce protocols and a BRICKS PhD will start soon. W. Fokkink coordinates the CWI security platform, and is involved in Sentinels and SAFE-NL.

Traffic control is another application area on which we want to focus. A concrete application is railway safety, which we know from earlier projects on interlocking specification languages and verification of small rail yards. The current European integration of the national railway safety systems gives a new impulse to the precise specification of interlockings. We want to develop a completely automated proof methodology that scales to the verification of large railway yards.

Finally, we strive for a wide applicability of our technology by gearing the techniques towards existing artifacts in industry, such as UML models and actual software. To this end we will collaborate with SEN1. Also, we will apply testing techniques to distributed systems. The ITEA project TT-MEDAL is already devoted to testing. Finally, we support several activities to develop a main-stream specification language, such as GenSpect at TUE (this integrates process algebra and Petri nets) and LOTOS-NT at INRIA-Vasy (this integrates process algebra with modern imperative languages).

Knowledge transfer. Besides publications, our knowledge is transferred via projects with industrial partners, secondments, courses at universities, and involvement in various national initiatives.

The SVC project (Systems Validation Center), 1999–2002, was a collaboration with, among others, the Telematica Instituut, UT, CMG, KPN and Lucent. We assisted in the automated verification of telecommunication devices. In the European ITEA project TT-MEDAL (started in 2003) we apply formal test generation techniques to industrial systems. The technology – based on UML 2.0 and TTCN-3 – is applied at industrial partners, such as Nokia (telecommunication), DaimlerChrysler (car industry), ProRail (railway safety), and LogicaCMG. In smaller projects (based on NWO/STW/Progress projectcs and bilateral contracts), we collaborated with various industrial and governmental partners, including Philips (IEEE 1394 Firewire and bus bridges), Thales (SPLICE, command and control systems), NLR, Royal Navy (Lynx helicopter data acquisition unit), Weidmüller and AddControls (distributed truck lift system), ASML (wafer steppers).

Our senior members have been seconded at various other institutes. From 1998-2004, J.W. Klop was seconded at RU. W.J. Fokkink was seconded at VU (until September 2004), J.C. van de Pol is senior lecturer at TUE (from May 2004), and J.F. Groote was seconded to TUE (–September 2000). Our research is taught at various universities by members of the group. Among the many courses we mention: J.F. Groote

(TUE): "Verification and testing", "Design and analysis of embedded systems", "Requirement Analysis, Design and Verification"; W.J. Fokkink (VU): "Distributed Algorithms", "Protocol Validation"; J.W. Klop (VU, RU): "Term Rewriting Systems", "Process Algebra".

Finally, we are involved in various national initiatives, such as SENTINELS, SAFENL, and the organization of a Dutch testing day, a Dutch security day, and a Dutch Proof Tools Day.

4.2.3 Implementation of the 1999 recommendations

- In 2000, J.F. Groote left CWI for a full time professorship at TUE. W.J. Fokkink succeeded him.
- The recommended pilot theme Software Testing Technologies was not created.
- J.C. van de Pol joined the tenured staff and heads the subtheme Distributed Systems.
- In 2004, W.J. Fokkink left CWI for a full time professorship at VU. J.C. van de Pol succeeded him.

4.2.4 Overview of the results

See Table 4.7 on page 81 for a numerical overview. A list of all publications can be found in the SEN2 sections of *CWI Overview Research Activities 1999–2003* (CD-ROM).

Selection of major publications

1 I. BETHKE, J.W. KLOP, R.C. DE VRIJER (2000). Descendants and origins in term rewriting. *Information and Computation* **159**, 59–124.

2 W.J. FOKKINK, J.F.TH. KAMPERMAN, H.R. WALTERS (2000). Lazy rewriting on eager machinery. *ACM Transactions on Programming Languages and Systems* **22** (1), 45–86.

3 J.F. GROOTE, J.P. WARNERS (2000). The propositional formula checker HeerHugo. *Journal of Automated Reasoning* **24**, 101–125.

4 J.W. KLOP, V. VAN OOSTROM, R.C. DE VRIJER (2000). A geometric proof of confluence by decreasing diagrams. *J. Logic Computat.* **10** (3), 437–460.

5 J.F. GROOTE, M. RENIERS (2001). Algebraic process verification. J.A. BERGSTRA, A. PONSE, S.A. SMOLKA (Eds.). *Handbook of Process Algebra*, Elsevier, Amsterdam, 1151–1208.

6 S.C.C. BLOM, J.C. VAN DE POL (2002). State space reduction by proving confluence. *Proceedings of CAV 2002*, LNCS **2404**, 596–606.

7 J. HOOMAN, J.C. VAN DE POL (2002), Formal verification of replication on a distributed data space architecture. *Proceedings of ACM Symposium on Applied Computing 2002*.

8 J.F. GROOTE, H. ZANTEMA (2003). Resolution and binary decision diagrams cannot simulate each other polynomially. *Journal of Discrete Applied Mathematics* **130** (2), 157–171.

9 J.W. KLOP et al. (2003). *Term Rewriting Systems*, Cambridge Tracts in Theoretical Computer Science, **55**, Cambridge University Press, xxii+884 pages.

10 L. ACETO, W.J. FOKKINK, R.J. VAN GLABBEEK, A. INGOLFSDOTTIR (2004). Nested semantics over finite trees are equationally hard. *Information and Computation* **191** (2), 203–232.

11 B. BADBAN, J.C. VAN DE POL (2004, to appear). Zero, Sucessor and Equality in BDDs. Accepted for *Annals of Pure and Applied Logic*.

12 B. BLOOM, W.J. FOKKINK, R.J. VAN GLABBEEK (2004). Precongruence formats for decorated trace semantics. *ACM Transactions on Computational Logic* **5** (1), 26–78.

PhD theses

- M.A. Reniers (Thesis advisors: J.C.M. Baeten, L.M.G. Feijs, University: TUE, Date: June 7, 1999, Title: *Message Sequence Chart: Syntax and Semantics*)
- J.P. Warners (Thesis advisors: J.F. Groote, J. van Leeuwen, Co-advisor: H. van Maaren, University: TUE Date: September 14, 1999, Title: *Non-linear Approaches to Satisfiability Problems*)
- J.M.T. Romijn (Thesis advisors: H. Brinksma, F.W. Vaandrager, University: UT, Date: October 15, 1999, Title: *Analysing Industrial Protocols with Formal Methods*)
- D. Griffioen (Thesis advisor: F.W. Vaandrager, University: RU, Date: May 10, 2000, Title: *Studies in Computer Aided Verification*)
- S.C.C. Blom (Thesis advisor: J.W. Klop, University: VU, Date: March 6, 2001, Title: *Term Graph Rewriting – Syntax and Semantics*)
- S.P. Luttik (Thesis advisors: J.A. Bergstra, J.F. Groote, University: UvA, Date: April 3, 2002, Title: *Choice Quantification in Process Algebra*)
- M.B. van der Zwaag (Thesis advisor: J.A. Bergstra, University: UvA, Date: October 11, 2002, Title: *Models and Logics for Process Algebra*)
- Y.S. Usenko (Thesis advisors: J.F. Groote, W.J. Fokkink, University: TUE, Date: December 2, 2002, Title: *Linearization in μCRL*)
- J. Pang (Thesis advisor: W.J. Fokkink, University: VU, Date: October 26, 2004, Title: *Formal Verification of Distributed Systems*)
- N. Ioustinova (Thesis advisor: W.J. Fokkink, Co-advisor: N. Sidorova, University: VU, Date: November 4, 2004, Title: *Abstractions and Static Analysis for Verifying Reactive Systems*)
- S.M. Orzan (Thesis advisor: W.J. Fokkink, Co-advisor: J.C. van de Pol, University: VU, Date: November 25, 2004, Title: *On Distributed Verification and Verified Distribution*)

4.2.5 Context

Through secondments and part-time appointments, our group has close connections with VU (Klop, Fokkink), RU (Klop), TUE (Groote, Van de Pol) and UvA (Bergstra, Ponse). We have also had joint projects with UT and the system engineering group of TUE.

Table 4.9. Some major externally funded projects of SEN2

Acronym	Full name	Dates		k€	Source
SVC	Systems validation center	1999	2002	1,000	TI
KTV-FM	Kleine technologie verkenning formal methods	2002		45	RNLN
TT-MEDAL	Tests & testing methodologies with advanced languages	2004	2005	700	ITEA Senter

Internationally, we have a Dutch-French collaboration project (SenVa) with the Vasy group at INRIA, mainly on interoperability of each other's tool sets. We are active members of two working groups in ERCIM, "Formal methods for industrial critical systems" and "Dependable Software-intensive Systems". Besides, we have many contacts with individual international researchers, as proven by joint papers, conference organization, and mutual research visits.

4.2.6 Scientific reputation

Awards

- J.W. Klop received an honorary doctorate from the University of East-Anglia on July 11, 2002.
- J.W. Klop was appointed as a member of KNAW in September 2003.
- J.W. Klop is a CWI Fellow since December 2003.

Memberships of committees and other professional activities

For a more extensive survey, please see the SEN2 section of the *CWI Overview Research Activities 1999–2003* (CD-ROM).

W.J. Fokkink	full professor at VU, member of 17 program committees, twelve PhD reading committees, four times thesis advisor
J.F. Groote	full professor at TUE, three memberships of boards, steering committees, advisory groups
J.W. Klop	full professor at VU, member of KNAW, two editorships, three memberships of boards, steering committees, advisory groups
J.C. van de Pol	associate professor at TUE, member of five program committees, three boards, three PhD reading committees, co-advisor

4.3 Theme SEN3 – Coordination Languages

Research in	Coordination and software composition; component based software engineering; formal specification and verification methods; mathematical foundations of computation, coalgebra.
Started in	January 1997
Theme leader	Prof.dr. J.J.M.M. Rutten (1997–present)
MSC-CR classification	05A15, 4A72, 18D20, 54E35, 68N15, 68N99, 68Q05, 68Q10; 68Q45; 68Q55; 68Q60, 68Q70; 68Q85 C.2, D.1, D.3, F.1, F.3, F.4, J.3

Table 4.10. Staff of SEN3, 1999–2005 (in FTE/year, *prognosis)

SEN3		1999	2000	2001	2002	2003	2004	2005*
Leader:	*J.J.M.M. Rutten*	*0.2*	*0.2*	*0.2*	*0.2*	*0.2*		*0.2*
	F. Arbab						*0.2*	
Researchers:	*F. Arbab*	*1.0*	*1.0*	*1.0*	*1.0*	*1.0*	*0.8*	*1.0*
	J.W. de Bakker	*0.3*	*0.3*	*0.3*	*0.4*			
	F.S. de Boer				*0.7*	*0.7*	*0.8*	*0.8*
	J.J.M.M. Rutten	*0.8*	*0.8*	*0.8*	*0.8*	*0.8*	*1.0*	*0.8*
Programmers:	*C.L. Blom*	*1.0*	*1.0*	*1.0*	*1.0*	*1.0*	*1.0*	
	F.J. Burger	*1.0*	*1.0*	*0.7*	*0.6*	*0.6*	*0.6*	*0.6*
	C.T.H. Everaars	*1.0*	*1.0*	*1.0*	*1.0*	*1.0*	*1.0*	*1.0*
Total tenured staff		**5.3**	**5.3**	**5.0**	**5.7**	**5.3**	**5.4**	**4.4**
Non-tenured staff		1.4	0.8	1.1	1.0	2.3	2.8	2.9
CWI PhD students		0.3	1.0	2.5	3.8	3.8	3.0	1.8
Total research staff CWI payroll		**7.0**	**7.1**	**8.6**	**10.5**	**11.4**	**11.2**	**9.1**
Seconded PhD students		*0.6*	*0.0*	*0.0*	*0.0*	*0.2*	*1.0*	*1.0*
Other seconded staff		*1.6*	*2.1*	*2.6*	*1.5*	*1.9*	*0.8*	*0.8*
Total hosted research staff		***9.2***	***9.2***	***11.2***	***12.0***	***13.5***	***13.0***	***10.9***

Table 4.11. Scientific output of SEN3

Output class		1999	2000	2001	2002	2003	2004	Total
Academic	refereed journals and proceedings	13	9	16	24	34	45	141
	other journals and proceedings	0	2	0	3	1	0	6
	book chapters	0	1	2	0	1	2	6
	Total academic	**13**	**12**	**18**	**27**	**36**	**47**	**153**
Monographs		1	0	0	4	0	2	7
PhD dissertations		0	0	0	1	0	1	2
Professional pub./products		1	0	1	16	9	6	33

Table 4.12. Funding percentages of SEN3

SEN3	1999	2000	2001	2002	2003	2004	Average
Direct NWO	86.0%	86.8%	75.5%	75.9%	68.7%	67.8%	76.8%
Other research funds	4.9%	6.1%	18.3%	20.5%	28.9%	29.0%	17.9%
Grants/contracts	0.8%	0.6%	0.3%	0.0%	0.5%	0.0%	0.4%
Other	8.3%	6.5%	5.9%	3.6%	1.9%	3.2%	4.9%
Total	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**

4.3.1 Senior researchers

Prof.dr.ir. F. Arbab, Prof.dr. J.W. de Bakker (till July 2002), Dr. F.S. de Boer (as of 2001), Prof.dr. J.J.M.M. Rutten.

4.3.2 Research orientation, highlights, and future directions

Mission and research area. Large systems of concurrent, distributed, heterogeneous software components play an increasingly important role in our society. The paradigm shift from objects to components in software engineering is necessitated by such societal demands, and is fueled by internet-driven software development. Using components means understanding how they individually interact with their environment, and specifying how they should engage in mutual, cooperative interactions in order for their composition to behave as a coordinated whole. Coordination models and languages address these key issues in the discipline of Component Based Software Engineering. In this discipline, SEN3 focuses on coordination, interaction, and dynamic composition of components. The activity in this theme is organized within three interrelated focal subthemes, each led by a current senior member of the theme: coordination and component-based architectures (F. Arbab), formal methods for coordination languages (F.S. de Boer), and coalgebraic models of computation (J.J.M.M. Rutten). There is close collaboration among the members of the three subthemes in SEN3, integrating both theory and practice of coordination languages in compositional construction of concurrent distributed systems. The importance of the symbiosis of experimental and theoretical computer science research is illustrated by our work on Reo, which is a distributed channel-based coordination middleware for compositional construction of component connectors (see also below). The successful integration of theory and practice is further illustrated by the following numbers: it is worth mentioning that over the last five years, SEN3 has shown a clear increase of both scientific output (from 15 publications in 1999 to 56 in 2004) and external funding (from 4.9% in 1999 to 29% in 2004), whereas its staff has only grown by a factor of less than 1.5. The societal relevance of our work is underlined by our participation in various projects involving industrial partners. There our methods are used in, amongst others, ICT infrastructures for incident management such as flood or fire (SENTER project CIM), enterprise architectures (Telematica project ArchiMate), and real-time embedded systems (EU project Omega).

Research highlights. Arbab's earlier work on the Manifold coordination language

established the concepts of *exogenous coordination* (from outside) versus *endogenous coordination* (from inside) and *control-oriented* versus *data-oriented* coordination models in the scientific community. The usefulness of these concepts and the Manifold system were demonstrated in real-life applications. In 2002, a spin-off company, Adaptive Planet B.V., was set up to use Manifold as enabling technology. The investigations of SEN3 into the formal semantics of Manifold led Arbab to develop a generalization of its channel-based communication model, and the notion of mobile channels as primitive building blocks for coordination. Consequently, a simpler, yet more expressive, exogenous coordination model, called Reo, resulted. Reo presents a powerful paradigm to construct software by combining black-box components, based on a calculus of (mobile) channel composition. Reo derives its formal simplicity and expressiveness from the coalgebraic underpinnings of its stream calculus semantics, developed by Arbab and Rutten. Applications of Reo encompass component-based software, composition of web services, distributed deployment, coordination in systems biology, compositional verification, and reasoning about quality of service properties.

In his thesis De Boer was one of the first to develop a rigorous mathematical theory of the correctness of object-oriented programs. This work has proven a fruitful source for further research on formal semantics and logics for concurrent programming languages including the popular object-oriented language Java which is currently the language for internet applications. De Boer is also a co-author of the book *Concurrency Verification: Introduction to Compositional and Noncompositional Methods* (Cambridge University Press, 776 pages, 2001). In the context of the bilateral NWO/DFG project Mobi-J (assertional methods for mobile asynchronous channels in Java), De Boer and colleagues have successfully organized three international symposia on formal methods for components and objects (FMCO 2002, 2003, 2004) with proceedings in Lecture Notes in Computer Science and special issues in the sister journals of *Theoretical Computer Science* and *Science of Computer Programming*. De Boer and colleagues have developed semantics and Hoare logics (with corresponding tool support) for the programming language Java. In close collaboration with the University of Kiel, this work resulted in a first sound and complete Hoare logic for multithreaded Java programs. A study of a compositional semantics of Java has led to a first fully abstract semantics which captures the dynamic interaction between an open object-oriented system and its environment.

Rutten and his colleagues in SEN3 have been initiators and major contributors to the development of the field of coalgebra. As a unifying formalism for state-based dynamical systems, it has become a general and useful tool in both computer science and mathematics. Applications include automata and formal languages, programming semantics, probabilistic systems and software engineering, in computer science, and formal power series, analysis, control theory, and combinatorics, in mathematics. A coalgebraic calculus of streams (infinite sequences), which was developed by Rutten in close analogy to classical analysis, has played a central role in much of this development. It was the subject of various invited lectures. Rutten has been the initiator of the, by now well-established, annual workshop series CMCS (Coalgebraic Methods in

Computer Science), and its successor CALCO (Conference on Algebra and Coalgebra), to be held for the first time in 2005.

Future directions. Experimental systems and theoretical work on exogenous coordination, interaction, compositional reasoning, emergent behavior in composed systems, dynamically reconfigurable architectures, and the mathematical foundations of these concepts comprise the strenght and the core competence of SEN3. The practical relevance of these issues in terms of their impact on the future of software will grow as, e.g., composition of web services, mobile computing, and ubiquitous dynamically evolvable applications increase in number, significance, and sophistication.

Autonomy, interaction, collaboration, and reconfiguration to adapt to an evolving environment naturally arise in systems that do not strictly consist of software. The same concepts that comprise the core competence of SEN3, therefore, also play a significant role in, for instance, enterprise architectures, business processes, or even coordination of dynamically evolving agent collaborations in response to emergency incidents. SEN3 has worked on such applications in the context of projects like ArchiMate and Cybernetic Incident Management. More recently, we started applying some of these concepts to model coordination of processes in biological systems, with promising results.

Future plans of SEN3 include (1) maintaining its strength in its areas of core competence; (2) developing middleware, programming support environments, and tools to demonstrate the practical viability of coordination-based compositional models and systems in software engineering; and (3) pursuing goals that extend the applications of coordination, composition, and interaction in new areas. Our two-prong strategy consists of (1) developing software engineering models, tools, and systems for deployment and quality of service concerns, composition of web services, and dynamically reconfigurable distributed component-based software; and (2) leveraging our core competence to expand into new areas. Our preliminary results and contacts indicate that it is promising to pursue the study of coordination networks in biological systems, and the development of formal models of coordination in dynamic hierarchical agent societies that arise, for instance, in cybernetic incident management.

For the next five years, design and development of a programming environment for Reo will comprise a central focus of activity in SEN3. This involves work on visual programming, distributed middleware, models for deployment and quality of service, logics and tool support for computer-aided verification of coordinating connector glue-code. Our work on formal methods for the study of coordination will proceed with the development of logics and tool support for formal reasoning about the properties of connector glue-code. In the next five years, this effort will focus on the development of interface description languages for compositional verification of object-oriented programs and components that interact in dynamically reconfigurable networks. The recent applications of the coalgebraic calculus of streams to the software connector circuits of Reo are part of a broader study on the semantics of circuits in general, including signal flow graphs, weighted automata, and Boolean circuits. We

expect further successful applications, amongst others, on the semantics of recent and future extensions of Reo, on (Boolean) circuit synthesis, and on 2-adic arithmetic.

Knowledge transfer. The senior members of SEN3 currently advise and/or supervise eleven PhD students at CWI, and various Dutch and foreign universities. They also presently supervise the work of three postdoctoral researchers in SEN3. An additional four other postdoctoral researchers who currently hold positions at other international institutes, have worked at CWI with the senior researchers in SEN3 between 1999 and 2003.

Adaptive Planet, B.V. (in the Netherlands) is a spin-off of CWI with the partnership of the software company Adaptive Planet, Belgium, oriented to the mobile device market. Adaptive Planet sees Manifold as a first step toward incorporating the powerful exogenous coordination model of Reo into their future software products.

In the past five years, the senior members of SEN3 have organized five conferences or symposia; given sixteen special courses or tutorials, six invited talks at symposia, twelve seminar talks, and eleven invited talks at international conferences and workshops. They have also taught seven regular university courses in Dutch universities. The Amsterdam Coordination Group (ACG) is an (on average biweekly) colloquium in which SEN3 members and invited guests present and discuss ongoing research on coordination models and languages and coalgebra.

4.3.3 Implementation of the 1999 recommendations

- In 2002 SEN3 created a spin-off in close collaboration with Adaptive Planet.
- Although coalgebraic techniques continue to play a role in the control of discrete event systems (MAS2), the Concurrency and Control pilot was not created.

4.3.4 Overview of the results

See Table 4.11 on page 88 for a numerical overview. A list of all publications can be found in the SEN3 sections of *CWI Overview Research Activities 1999–2003* (CD-ROM).

Selection of major publications

1 J.J. DEN HARTOG, E.P. DE VINK, J.W. DE BAKKER (1999). Full abstractness of a metric semantics for action refinement. *Fundamenta Informaticae* **40**, 335–382.

2 J.W. DE BAKKER, F.C. VAN BREUGEL (2000). From Banach to Milner: Metric semantics for second order communication and concurrency. G.D. PLOTKIN ET AL (eds.). *Proof, Language, and Interaction, Essays in Honour of Robin Milner*, MIT Press, 99–132.

3 M.M. BONSANGUE, F. ARBAB, J.W. DE BAKKER, J.J.M.M. RUTTEN, A. SCUTELLS, G. ZAVATTARO (2000). A transition system semantics for the control-driven coordination language manifold. *Theoretical Computer Science*. **240** (1), 3–47.

4 J.J.M.M. RUTTEN (2000). Universal coalgebra: a theory of systems. *Theoretical Computer Science* **249** (1) (Fundamental Study), 3–80.

5 J.I. DEN HARTOG, E.P. DE VINK, J.W. DE BAKKER (2001). Metric semantics and full abstractness for action refinement and probabilistic choice. *Proceedings MFCSIT 2000*, ENTCS **40**.

6 F.S. DE BOER (2002). A Hoare logic for dynamic networks of asynchronously communicating deterministic processes. *Theoretical Computer Science* **274**, 3–41.

7 E. ABRAHAM-MUMM, F.S. DE BOER, W.-P. DE ROEVER, M. STEFFEN (2003). A tool-supported proof system for multithreaded Java. *Lecture Notes in Computer Science Tutorial Series* **2852**, Springer-Verlag, 1–32.

8 F. ARBAB (2003). Abstract behavior types: a foundation model for components and their composition. *Lecture Notes in Computer Science Tutorial Series* **2852**, Springer-Verlag, 33–70.

9 J.J.M.M. RUTTEN (2003). Behavioural differential equations: a coinductive calculus of streams, automata, and power series. *Theoretical Computer Science Volume* **308** (1–3) (Fundamental Study), 1–53.

10 F. ARBAB (2004). Reo: A channel-based coordination model for component composition. *Mathematical Structures in Computer Science* **14** (3), 329–366.

11 F.S. DE BOER, M. GABBRIELLI, M.C. MEO (2004). Proving correctness of timed concurrent constraint pograms. *ACM Transactions on Computational Logic (TOCL)* **5** (4), 706–731.

12 J.J.M.M. RUTTEN (2004). On streams and coinduction. Mathematical techniques for analysing concurrent and probabilistic systems. *CRM Monograph Series* **23**, American Mathematical Society, 1–92.

PhD theses

- W. de Vries (external) (Thesis advisor: J.J.-Ch. Meyer, Co-advisor: F.S. de Boer, University: UU, Date: November 11, 2002, Title: *Agent Interaction: Abstract Approaches to Modelling, Programming and Verifying Multi-Agent Systems*)
- J.I. den Hartog (Thesis advisor: J.W. de Bakker, University: VU, Date: October 17, 2002, Title: *Probabilistic Extensions of Semantical Models*)
- F. Bartels (Thesis advisors: J.J.M.M. Rutten, J.C.M. Baeten, University: VU, Date: June 3, 2004, Title: *On Generalised Coinduction and Probabilistic Specification Formats*)
- **Future thesis:** E. Abraham-Mumm (Thesis advisors: W.-P. de Roever, J.N. Kok, Co-advisor: F.S. de Boer, University: UL, Date: January 20, 2005, Title: *An Assertional Proof System for Multithreaded Java - Theory and Tool Support*)

Table 4.13. Some major externally funded projects of SEN3

Acronym	Full name	Dates		k€	Source
Omega	Correct development of real-time embedded systems in UML	2002	2005	350	EU
CIM	Cybernetic incident management	2003	2005	425	SENTER
C-Quattro	Developing a compositional calculus of component connectors	2004	2008	440	NWO

4.3.5 Context

SEN3 has ongoing active collaborations with national and international research groups at UL (J.N. Kok, M.M. Bonsangue), RU (B. Jacobs), UvA (Y. Venema), VU (Klop, Grabmayer), UU (J.J. Meyer), University Tehran (M. Sirjani), University Waterloo (F. Mavaddat), University Bonn (C. Baier), CAU Kiel (W.-P. de Roever), and University Cyprus (G.A. Papadopoulos). Most of the research in SEN3 is carried out in the context of externally funded projects.

4.3.6 Scientific reputation

Awards

- M.M. Bonsangue received a five-year fellowship from KNAW while he was a member of SEN3.
- J.W. de Bakker was appointed Ridder in de Orde van de Nederlandse Leeuw upon his retirement.

Memberships of committees and other professional activities

For a more extensive survey, please see the SEN3 section of the *CWI Overview Research Activities 1999–2003* (CD-ROM).

F. Arbab	full professor at UL, adjunct full professor at the University of Waterloo, Canada, four editorships, thirty memberships of boards, steering committees, advisory groups, reviewer and evaluator for EU projects
J.W. de Bakker	full professor at VU, member of KNAW and of Academia Europaea, four editorships, five memberships of boards, steering committees, advisory groups
F.S. de Boer	associate professor at UL, three editorships, fifteen memberships of boards, steering committees, advisory groups
J.J.M.M. Rutten	full professor at VU, eight editorships, twenty-six memberships of boards, steering committees, advisory groups

4.4 Theme SEN4 – Evolutionary Systems and Applied Algorithmics

Research in	Techniques: Computational intelligence, adaptive algorithms Problem domains: competitive and economic games in multiagent systems; optimization and classification
Started in	September 1997 as new pilot theme; September 1999 as full-fledged theme
Theme leader	Prof.dr.ir. J.A. La Poutré (1999–present)
CR classification	I.2, I.5, I.6, J.4, F.2, G.1, 91A

Table 4.14. Staff of SEN4, 1999–2005 (in FTE/year, *prognosis)

SEN4		1999	2000	2001	2002	2003	2004	2005*
Leader:	*J.A. La Poutré*	*0.2*	*0.2*	*0.20*	*0.2*	*0.2*	*0.20*	*0.2*
Researchers:	*S.M. Bohte*						*0.67*	*1.0*
	J.A. La Poutré	*0.8*	*0.8*	*0.65*	*0.6*	*0.6*	*0.60*	*0.6*
Programmers:	*H. Noot*							*0.4*
Total tenured staff		**1.0**	**1.0**	**0.9**	**0.8**	**0.8**	**1.5**	**2.2**
Non-tenured staff		2.6	1.6	4.6	4.0	4.8	4.7	4.3
CWI PhD students		1.7	4.2	5.0	3.1	2.4	3.0	2.5
Total research staff CWI payroll		**5.3**	**6.8**	**10.5**	**7.9**	**8.0**	**9.2**	**9.0**
Seconded PhD students		*0.8*	*0.8*	*0.7*	*0.0*	*0.0*	*0.0*	*0.0*
Other seconded staff		*0.8*	*0.8*	*0.1*	*0.1*	*0.7*	*0.4*	*0.4*
Total hosted research staff		***6.9***	***8.4***	***11.3***	***8.0***	***8.7***	***9.6***	***9.4***

Table 4.15. Scientific output of SEN4

Output class		1999	2000	2001	2002	2003	2004	Total
Academic	refereed journals and proceedings	14	18	12	16	20	35	115
	other journals and proceedings	0	1	0	1	0	2	4
	book chapters	1	0	0	0	1	0	2
	Total academic	**15**	**19**	**12**	**17**	**21**	**37**	**121**
Monographs		0	1	0	0	0	0	1
PhD dissertations		1	0	1	1	1	2	6
Professional publications/products		1	14	7	7	5	6	40

4.4.1 Senior researchers

Dr. S.M. Bohte (as of May 1, 2004), Prof.dr.ir. J.A. La Poutré

4.4.2 Research orientation, highlights, and future directions

Mission and research areas. SEN4 performs fundamental and applicable research into intelligent and adaptive systems. The theme focuses on adaptive computational tech-

Table 4.16. Funding percentages of SEN4

SEN4	1999	2000	2001	2002	2003	2004	Average
Direct NWO	76.8%	66.8%	76.4%	72.6%	60.5%	64.6%	69.6%
Other research funds	18.4%	28.3%	23.6%	26.2%	39.5%	35.4%	28.6%
Grants/contracts	1.2%	2.2%	0.0%	1.2%	0.0%	0.0%	0.8%
Other	3.6%	2.7%	0.0%	0.0%	0.0%	0.0%	1.0%
Total	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**

niques, like evolutionary systems, adaptive algorithms, and neural networks. Its problem and application domains concern competitive games in multiagent systems and economics, as well as fundamental optimization and classification problems. For the multiagent domain, techniques are typically designed, implemented, and applied in order to solve the novel problems in this domain, while the optimization and classification areas serve as more conventional areas for which the techniques are developed.

The research with respect to multiagent systems addresses the following. The concepts of software agents in computer science as well as (human) agents in economics and social sciences yield important areas of research. Interactions between such agents can be modeled as, e.g., competitive or economic games. In order to perform well in the complex settings of multiagent systems, adaptive behavior of agents is essential, based on their own information and capabilities ("bounded rationality") and reactive on their dynamic environment. An important aspect of adaptivity for an agent is the skill of learning.

In order to allow learning in agent systems, adaptive techniques are necessary. In SEN4, especially adaptive computational techniques are investigated, focusing on the following: adaptive strategies for competitive and economic games in multiagent systems, like for negotiations, auctions (game theory), and dynamic pricing; Design and simulation of market mechanisms for e-commerce; Simulation of markets in the fields of ACE and CAS (agent-based computational economics; complex adaptive systems). These three fields can be seen as different levels of abstraction, from microscopic behavior (the learning software of an agent) to macroscopic behavior (behavior of economic markets with adaptive agents). These form a growing area of research, important for the design and implementation of software agents as well as for economics.

Fundamental research on the adaptive computational techniques is also performed in the more conventional problem domains of optimization and classification. Here, the emphasis is on the mere development of these techniques, which in addition are facilitating other research activities, like for agent systems. For example, special attention is given to a novel type of neural networks, consisting of spiking neurons; and various techniques are developed for improving and analyzing the performance of evolutionary algorithms and adaptive discrete algorithms, like for (dynamic, on-line, or constraint) optimization problems and automated programming, as well as novel types of optimization problems arising from agent system research.

Research highlights. After SEN4 had become a full-fledged theme in September 1999,

it has further expanded in the following years, towards its current status.

In the ASTA project (Autonomous Systems of Trade Agents in E-Commerce), a novel agent system was designed for market-based recommendation concerning the allocation of consumer attention space. Several auction mechanisms were designed and evaluated, and effective techniques were developed for agents to bid. In addition, the results were patented in a joint patent by KPN (Royal Dutch Telecom) and CWI. Also, original negotiation mechanisms and adaptive solutions were developed for the sales and distribution of information goods. This concerned the design of novel negotiation mechanisms as well as various effective computational techniques, based on evolutionary techniques, adaptive algorithms, and aggregate knowledge. For one-to-many negotiation, an important decomposition of negotiation strategies into substrategies was designed. Based on this decomposition, effective and efficient adaptive solutions were developed that can synergetically work in parallel. This work also yielded a prototype software system for the sales and distribution of financial information goods (in cooperation with TNO and ING).

In the DEAL project (Distributed Engine for Advanced Logistics), agent systems were developed for the distributed allocation of cargo to trucks, especially based on auctions (for spot markets). Significant fundamental results were obtained with adaptive solutions on auctions with decommitment options and complex negotiations using aggregate knowledge. Also, pioneering results were obtained on repeated auctions with complementarities, and on novel optimization problems on dynamic routing, anticipating on future transport orders, by means of their spatial distribution and by using dynamic evolutionary algorithms.

The main focus of the research on neural networks has been on a novel type of artificial neural networks that are built from spiking neurons, that more closely mimic real biological neurons' behavior. It had been shown (by W. Maass) that theoretically, such spiking neurons have more computational power. In the research, learning rules were derived that enable that such spiking neural networks to be applied to real tasks similar to traditional neural networks. Following up on this work, it was worked out how particular features of spiking neurons can be used to solve important issues fundamental to the prominent called "binding" problem, and it was also shown how a learning rule aimed at coding stability for a spiking neuron indeed reproduces the learning curves of real neurons.

In the research on agent-based computational economics, various results on (economic) agents playing negotiation games or economic games (like the Cournot game, and several network formation problems) were obtained. In addition, first but important steps were made in the investigation of more robust simulation techniques and methods for the area of economic games.

Fundamental research was performed on adaptive, on-line algorithms. The techniques were advanced especially for various on-line scheduling problems. An important step was taken for the minimization of the total completion time on-line on a single machine, using restarts. This was one of the very first and original results where an algorithm that uses restarts was proved to be better than without restarts.

Finally, specific additional application problems were explored and very efficient and effective solutions were developed, especially for non-parametric unsupervised classification of remote sensing data (for CRREL (Cold-Region Research Laboratory, Hanover, USA), and also for exploratory data-analysis of high-dimensional data (for the Ministry of Traffic).

Future directions. The general research strategy and directions in the theme remain; most activities will be continued, but some changes are taking place.

The research on competitive games in multiagent systems will be extended and will have a substantial additional effort and focus on the design of adaptive techniques for repeated competitive games. This aims to be a fundamental answer to the important change of paradigm of ICT in society that is currently taking place: Many independent non-cooperating parties, that are connected by distributed networks, interact continuously in a dynamic and ad-hoc way; the terms for these interactions are set via negotiations and auctions. These negotiations and auctions thus occur in a repeated fashion (being sequential, simultaneous, or even unstructured), as repeated competitive games.

In addition, the current application areas for multiagent systems (logistics and e-commerce), may be extended to communication networks (possibly in cooperation with PNA2), and in addition, further attention will be given to planning in the health care sector. This particularly addresses patient planning.

Research on spiking neural networks will be centered around the Veni/multiagent project "Scalable Reinforcement Learning in Asychronous Spiking Neural Networks", which aims to develop credit assignment strategies for neural networks based on ideas derived from multiagent systems, with particular attention to economic mechanism design.

Finally, the research on fundamental on-line algorithms for scheduling problems comes to an end. It is anticipated that research on fundamental algorithms will be done in the area of mechanism design and game theory (like algorithmic or evolutionary game theory), in relation to the ongoing research on competitive and economic games in multiagent systems.

Knowledge transfer and consultancy. Knowledge transfer takes place in various forms, besides the dissemination via scientific publications.

J.A. La Poutré is currently associated with TUE and is involved in teaching regular courses. In addition, he and other members of the theme give seminars and courses in the national research schools IPA and SIKS; they are regularly active on events for a broader audience; and they also contribute to other media for a broader audience (newspapers, magazines, ICT guides).

Substantial knowledge transfer to business partners has taken place in projects like ASTA, DEAL, and CIM. In these and other projects, various companies participate, like ING Bank, KPN, Vos Logistics, Post Kogeko Transport, Philips Research, Group4Falck, and Almende. In particular, the research project ASTA has led to a joint patent with KPN, in both the USA and the EU. Also, cooperation with TNO occurred via the ASTA

project, and, knowledge transfer has taken place in other, smaller projects for Rijkswaterstaat (Ministry of Traffic) and the CRREL (USA).

4.4.3 Implementation of the 1999 recommendations

- In 2000, SEN4 became a full-fledged theme with the slightly modified name Evolutionary Systems and Applied Algorithmics.
- In 2004 S. Bohte joined the tenured staff.

4.4.4 Overview of the results

For a more extensive survey, please see the SEN4 section of the *CWI Overview Research Activities 1999–2003* (CD-ROM).

A selection of major publications

1 W.B. LANGDON (1999). Scaling of program tree fitness spaces. *Evolutionary Computation* **7** (4), 399–428.

2 S.M. BOHTE, J.N. KOK, J.A. LA POUTRÉ (2002). Unsupervised classification in a layered RBF network of spiking neurons. *IEEE Transactions on Neural Networks* **13**, 426–435.

3 E.H. GERDING, D.D.B. VAN BRAGT, J.A. LA POUTRÉ (2003). Multi-issue negotiation processes by evolutionary simulation: validation and social extensions. *Computational Economics* **22**, 39–63.

4 B.G.W. CRAENEN, A.E. EIBEN, J.I. VAN HEMERT (2003). Comparing evolutionary algorithms on binary constraint satisfaction problems. *IEEE Transactions on Evolutionary Computation* **7** (5), 424–444.

5 S.S. SEIDEN, R. VAN STEE, L. EPSTEIN (2003). New bounds for variable-sized online bin packing. *SIAM Journal on Computing* **32** (2), 455–469.

6 S.M. BOHTE, E.H. GERDING, J.A. LA POUTRÉ (2004). Market-based recommendation: agents that compete for consumer attention. *ACM Transactions on Internet Technology* **4**, 1–29.

7 K. SOMEFUN, E.H. GERDING, S.M. BOHTE, J.A. LA POUTRÉ (2004). Automated negotiation and bundling of information goods. *Agent-Mediated Electronic Commerce V (AMEC-V)*. Springer Lecture Notes in Artificial Intelligence (LNAI/LNCS) **3048**, Springer, 1–17.

8 R. VAN STEE (2005). A PTAS for two-dimensional strip packing with rotations. 37th Annual ACM Symposium on Theory of Computing (STOC2005).

9 E.H. GERDING, J.A. LA POUTRÉ (2005/2003). Bilateral bargaining with multiple opportunities: knowing your opponent's bargaining position. *IEEE Transactions on Systems, Man and Cybernatics (SMC), Part C*.

10 S.M. BOHTE, M.C. MOZER (2005). Reducing spike train variability: a computational theory of spike-timing dependent plasticity. *Advances in Neural Information Processing Systems* **17**, The MIT Press.

PhD theses

- C.H.M. van Kemenade (Thesis advisor: J.N. Kok, University: UL, Date: March 18, 1999, Title: *Recombinative Evolutionary Search*)
- R. van Stee (Thesis advisors: J.A. La Poutré, J.N. Kok, University: UL, Date: May 8, 2002, Title: *On-line Scheduling and Bin-Packing*)
- S.M. Bohte (Thesis advisors: J.A. La Poutré, J.N. Kok, University: UL, Date: March 5, 2003, Title: *Spiking Neural Networks*)
- E.H. Gerding (Thesis advisors: J.A. La Poutré, H.M. Amman, University: TUE, Date: July 6, 2004, Title: *Autonomous Agents in Bargaining Games: An Evolutionary Investigation of Fundamentals, Strategies, and Business Applications*)
- F. Alkemade (Thesis advisors: J.A. La Poutré, H.M. Amman, University: TUE, Date: October 7, 2004, Title: *Evolutionary Agent-based Economics*)

Table 4.17. Some major externally funded projects of SEN4

Acronym	Full name	Dates		k€	Source
ASTA	Autonomous systems of trade agents in E-commerce	9/1999	12/2003	1,200	TI
DEAL	Distributed engine for advanced logistics	4/2002	3/2006	1,250	Senter-Novem
EESEM	Evolutionary exploration systems for electronic markets	10/1999	9/2003	110	NWO

4.4.5 Context

SEN4 has several joint projects with other partners, like ASTA, DEAL, CIM, EESEM, and QoSMM. In this way, cooperation exists with many companies, like ING, KPN, Vos Logistics, Post Kogeko Transport, Philips Research, Group4Falck, Almende, TNO, Rijkswaterstaat and CRREL. On the other hand, via these projects as well as personnel exchange, cooperation exists with several universities, like TUE, TUD, VU, UvA, UM, UL, and EUR. Foreign universities with which joint activities or research are done are, amongst others, University College London, INRIA, Freiburg University, SICS, Cornell University, University of Boulder, Napier University (Edinburgh), Free University of Brussels, University of Szeged, Universidad Carlos III de Madrid. Opportunities for cooperations currently occur for Southampton University (UK), University of Essex (UK), and the University of Bielefeld (Germany).

Within CWI, the theme cooperates with PNA1 via the BRICKS projects on logistics networks and supply chain optimization, and with SEN3 in the CIM project. Finally, an opportunity for cooperation exists for communication networks, with PNA2.

4.4.6 Scientific reputation

Awards

- S.M. Bohte was awarded a Veni grant by NWO, for the project *Scalable Reinforcement Learning in Asynchronous Spiking Neural Networks*. Start of the project: May 2004.
- S.M. Bohte and J.I. van Hemert received a TALENT stipend from NWO.
- Several members of the theme received the SKBS Award for the Best System Demonstration, at the Eleventh BNAIC conference (1999) (Belgium-Netherlands Conference on Artificial Intelligence), for "Neural Vision 2.0 – Exploratory Data Analysis with Neural Networks (M.C. van Wezel, J. Sprenger, R. van Stee, J.A. La Poutré, and J.B.M. van Wieringen)".

Memberships of committees and other professional activities

For a more extensive survey, please see the SEN4 section of the *CWI Overview Research Activities 1999–2003* (CD-ROM).

J.A. La Poutré	full professor at TUE, three editorships, fifteen memberships of program committees, two memberships of boards, steering committees, advisory groups

4.5 Pilot Theme SEN5 – Convergent Media Interfaces

Research in	Distributed systems aspects of multimedia object scheduling, transfer and rendering across heterogeneous presentation interfaces
Started in	January 2004
Theme leader	Dr. D.C.A. Bulterman (2004–present)
CR classification	H.4.3 [Information systems applications]: Communications applications - information browsers H.5.1 [Information interfaces and presentations]: Multimedia information systems - Audio, video I.7.2 [Document and text processing]: Document preparation - format and notation, hypertext/hypermedia, languages and systems, multi/mixed media

4.5.1 Senior staff

Dr. D.C.A. Bulterman, Dr. K. Kleanthous.

Table 4.18. Staff of SEN5, 1999–2005 (in FTE/year, *prognosis)

SEN5		1999	2000	2001	2002	2003	2004	2005*
Leader:	*D.C.A. Bulterman*						*0.2*	*0.2*
Researchers:	*D.C.A. Bulterman*						*0.8*	*0.8*
Programmers:	*A.J. Jansen*						*0.8*	*1.0*
	C.L. Blom							*0.8*
	D. Benden							*0.2*
Total tenured staff							**1.8**	**3.0**
Non-tenured staff							0.0	2.0
CWI PhD students							0.0	2.0
Total research staff CWI payroll							**1.8**	**7.0**
Seconded PhD students							*0.0*	*0.0*
Other seconded staff							*0.0*	*0.0*
Total hosted research staff							***1.8***	***7.0***

4.5.2 Research orientation, highlights, and future directions

The continued convergence of digital media production, distribution systems and presentation devices presents a host of new problems related to the creating, sharing, adaptation and rendering of hypermedia/multimedia on a range of dissimilar devices. This pilot theme studies fundamental problems related to media distribution and modeling, media encoding and creation, and platform-agnostic media distribution. The output of this theme consists of research papers describing scheduling models and algorithms, the specification of scheduling languages and (open source) experimental software implementations.

Mission and research area. The research focus of SEN5 is to study end-to-end models for the creation, distribution and rendering of time-sensitive data across a heterogeneous, convergent environment. In this environment, the partitioning of media clients

Table 4.19. Scientific output of SEN5

Output class		1999	2000	2001	2002	2003	2004	Total
Academic	refereed journals and proceedings					4	5	9
	other journals and proceedings					1	1	2
	book chapters					0	0	0
	Total academic					**5**	**6**	**11**
Monographs						0	1	1
PhD dissertations						0	0	0
Professional pub./products						3	5	8

Table 4.20. Funding percentages of SEN5

SEN5	1999	2000	2001	2002	2003	2004	Average
Direct NWO						71.4%	71.4%
Other research funds						7.4%	7.4%
Grants/contracts						21.2%	21.2%
Other						0.0%	0.0%
Total						**100.0%**	**100.0%**

and media servers are becoming increasingly blurred, as are the activities of media consumption and media creation. The research in SEN5 looks at mechanisms for transparently constructing presentations by end users as incremental documents. These documents may be captured (or extended) on devices ranging from tablet PCs, PDAs, telephone handsets, consumer audio-video equipment or home TV remote control devices. We then model the distribution of these incremental collections of audio, video, image and text information as a bundled *multimedia specification document*; the source components are stored on distributed servers, transmitted to clients via a mixed-bandwidth network infrastructure and delivered to client presentation platforms that range from mobile handsets and desktop PC to consumer devices such as next-generation digital televisions.

Although SEN5 is a new pilot theme (started in 2004), the theme has its roots in the CMIF multimedia research performed at CWI in the early 1990s. In 1999, at CWI's urging, the key staff members of the current SEN5 took a four-year leave and started *Oratrix Development* as a CWI technology transfer company. After returning to CWI, they started the current research activities.

SEN5 looks at a variety of related multimedia information application areas as a means of providing a constraining framework for our research. In initial work, we studied the impact of distributed multimedia capture and distribution in the context of medical environments, studying the creation of hypermedia patient dossiers for horses. In subsequent work, this focus has been extended to study the capture, dis-

tribution and presentation of media in a home-area network within the context of an interactive television (iTV) framework, as well as studying the multilevel encoding and customization of information for the disabilities community. Each of these application areas build on the core modeling of the distributed multimedia architecture. In order to provide a basis for experimental results, we have also developed the open-source Ambulant SMIL player which will be a core component of the Ambulant Incremental Authoring environment.

The SEN5 pilot is on a fast-track evaluation path, with a decision expected on its future within 18 months of its start (by mid 2005). The success criteria established for the theme are the critical acceptance of our work by the international community (measured by presentations at internationally-recognized conferences and papers in leading journals), the ability of the theme to generate sufficient research funding to guarantee its long-term existence and the further inbedding of our work on a national level (by establishing concrete ties with one or more Dutch universities). As of the end of 2004, we have succeeded in presenting our work at six international multimedia and hypertext conferences and have had three journal articles accepted for publication. We have also attracted funding for four R&D projects. Finally, we are actively engaged in establishing closer national ties for our group while maintaining a strong international orientation for our work.

Research highlights. During the past six years, the key members of SEN5 have had a substantial impact on the direction of current multimedia research. They were key contributors to the SMIL 2.0 specification and published important articles on media presentation creation and structuring.

Since returning to CWI, SEN5 has focused on building an open experimental base for future research, and on publishing results of initial studies in the area of convergent media interfaces. During the past year, the group has published papers at ACM Multimedia 2004, HyperText 2004, EG Multimedia 2004 and SANE 2004. Papers were also published (or accepted for publication) in *ACM Transactions on Multimedia Computing, Communications and Applications*, *ACM/Springer Multimedia System*, and *IEEE Multimedia*. The group also participated in the ACM Workshop on Web Engineering in Santa Cruz and the JSRPD worksop on media support for persons with disabilities held in Tokyo. In 2003, building on preliminary work, presentations were held at E-Learn '03 in Phoenix and at the ACM DocumentEngineering 2003 in Grenoble. Bulterman was also invited as the only Dutch participant at a special ACM strategic retreat on future research directions in multimedia computing held at Berkeley in October. During the past year, Bulterman published a book on SMIL (written together with INS2's Rutledge), which has become the standard reference work for this multimedia language.

In terms of software output, SEN5 released the Ambulant 1.0 open source SMIL player; this reconfigurable SMIL engine, with implementations for desktop, PDA and mobile devices supporting Windows, Macintosh, or Linux platforms, is the most platform-comprehensive delivery architecture released for the SMIL standard to date. As of November 2004, over 15,000 copies of this software had been downloaded by aca-

demic and advanced research users through Europe, the USA and Asia.

Future directions. We have viewed 2004 (and some preliminary work done in 2003) as an investment in building a new systems-oriented multimedia research group. In the future, SEN5 expects to build on this base by expanding the project group in three areas: *distributed network infrastructures*, *distributed delivery platforms*, and *distributed content creation and modeling*.

The work on distributed network infrastructures, which is centered around our BRICKS PDC-3 BSIK project, will investigate end-to-end models that can be integrated into a new generation of distributed scheduling algorithms. We expect to attract one new PhD student and one new postdoc to this project in 2005. We also expect to work together with SEN3 in formulating new formal models based on the component technology developed in that theme.

The work on distributed delivery platforms, which is centered around our Ambulant-II project, will investigate new delivery platforms based on the SMIL 2.1 Mobile profiles and the SMIL 3.0 advanced multimedia specification language. We expect that this work will result both in a set of open source reference implementations and an open, experimental test bed for verifying the scheduling and distribution algorithms developed by us and a network of partners in Europe, the USA and Brazil.

The work on distributed content creation and modeling, which is centered around our ITEA Passepartout project, will investigate user interfaces for creating and sharing content in the content of decentralized home, medical and transportation applications. We have attracted a postdoc for this project from our partners at INRIA in France, who will start in early 2005. We also expect to attract a second postdoc at the end of 2005 or early 2006.

All of these diverse projects are currently embedded within a single SEN5 pilot. We expect that after conversion of SEN5 to a full-fledged theme, each of these areas will develop into semi-independent subthemes, with expanded research staffs.

Knowledge transfer. The members of SEN5 have been active in the past in the transfer of knowledge in several forms. We were key participants in the SMIL 1 and SMIL 2 standardization efforts and we founded and grew the Oratrix technology spin-off company. More recently, we are active participants in the current W3C SMIL 2.1/3.0 standardization committees and in the W3C Timed Text working groups. We have also been active in meeting the needs of the disabilities communities; our work is already widely used within the deaf, blind and visually impared community. Together with the DAISY consortium, we are planning a new version of the AMIS player (for the visually impaired) based on the Ambulant 1.0 player core. We are also working with the Japanese NCRD to study support for an earthquake emergency warning system for deaf and blind users across Japan.

4.5.3 Overview of the results

See Table 4.19 on page 103 for a numerical overview.

Selection of major publications

1 D.C.A. BULTERMAN (2003). Using SMIL to encode interactive, peer-level multimedia annotations. *ACM DocumentEngineering*, Grenoble, France, November 2003.

2 D.C.A. BULTERMAN, L. RUTLEDGE (2004). *SMIL 2.0: Interactive Multimedia for Web and Mobile Devices*. Springer-Verlag, Heidelberg.

3 D.C.A. BULTERMAN (2004). Is it time for a moratorium on metadata (Invited Paper). *IEEE Multimedia*, October-December, 10–17.

4 D.C.A. BULTERMAN, J. JANSEN, K. KLEANTHOUS, K. BLOM, D. BENDEN (2004). AMBULANT: A fast, multi-platform open source SMIL 2.0 player. *ACM Multimedia*, New York, October, 492–495.

5 D.C.A. BULTERMAN (2004). A linking and interaction evaluation test set for SMIL. *ACM HyperText*, Santa Clara CA, August 2004, 107–109.

6 D.C.A. BULTERMAN, J. JANSEN, K. KLEANTHOUS, K. BLOM, D. BENDEN (2004). *AMBULANT 1.0 open SMIL player*, http://www.ambulantPlayer.org/

7 D.C.A. BULTERMAN, J. JANSEN (2004). *Four functional demonstrators for Ambulant and SMIL*, http://www.ambulantPlayer.org/Demos/

8 D.C.A. BULTERMAN, A.M. BOS (2004). *Paard: a medical multimedia test suite*, http://www.ambulantPlayer.org/Demos/Paard

Table 4.21. Some major externally funded projects of SEN5

Acronym	Full name	Dates		k€	Source
TOPIA-II	Mobile medical multimedia	1/2003	12/2003	85	TI
Ambulant-I/II	Reference implementations for SMIL 2.0 / 2.1 / 3.0	4/2003	9/2006	275	NLnet
BRICKS PDC3	Distributed multimedia environments	1/2003	12/2008	610	BSIK

4.5.4 Scientific reputation

The staff of SEN5 have had a long history of contributions to the research in networked multimedia. The group has been active on the forefront of specification languages and document models since 1991 and has made seminal contributions to the W3C SMIL standards, versions of which have been implemented on over 700,000,000 devices and systems worldwide.

We have also made fundamental contributions to the dissemination of knowledge within our community by serving on the editorial boards of all of the major journals, conferences and professional societies within academic multimedia.

Memberships of committees and other professional activities

D.C.A. Bulterman	editor of three journals, member of six program committees, member of two standards committees
A.J. Jansen	board member of NLUUG, member of one standards committee
C.L. Blom	member of one standards committee

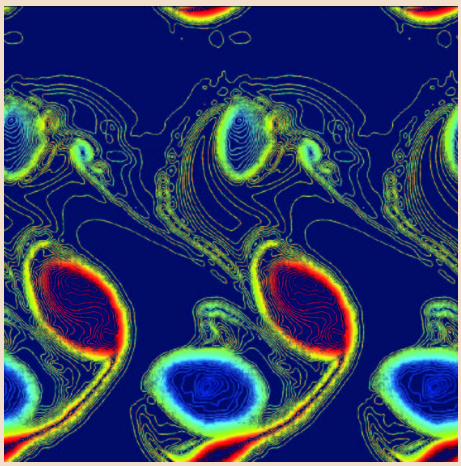
Veni, Vidi, Vici

Stimulating innovative, challenging research by young, excellent scientists is the intention of NWO's Vernieuwingsimpuls subsidy program. The scheme consists of three types of grants, Veni, Vidi, and Vici, aimed at increasingly experienced researchers. It includes an extensive assessment in which thirty percent of the proposals are selected for funding.

Since the establishment of the program in 2000, nine CWI researchers have received a Vernieuwingsimpuls grant. One of them is Sander Bohte. He received a Veni grant, targeted at starting postdocs, for his research on artificial spiking neural networks. Just like classical artificial neural networks, these circuits carry out computations by passing signals through a web of interconnected artificial neurons. Unlike their classical counterparts, however, not only the amplitude of these signals is relevant, but also their timing.

Mathematical methods to determine errors in computations is the subject that earned Pieter Collins a Vidi grant for experienced postdocs. Computers can solve many scientific and engineering problems. However, most computations contain errors of a size which is not always known exactly. In safety- critical systems this is unacceptable. Collins combines the mathematical disciplines of system and control engineering and topology to obtain guaranteed error margins.

Harry Buhrman received a Vici grant for his research on quantum computing. Quantum computers operate with bits that can be 0 and 1 at the same time. For certain computations, for example the factoring of numbers, this principle makes them much faster than classical computers. Buhrman designs novel algorithms that can benefit from the characteristics of quantum computers. He also investigates the limitations of quantum computing.



CWI researcher Jason Frank was awarded a Veni grant for his research on geometric integration. This method can among other things be used for numerical simulation of atmospheric flows.

Judy Brewer, W3C's chair of the Web Accessibility Initiative, at the "Drempels Weg" event in 2001, surrounded by Minister Roger van Boxtel, Deputy Minister Margot Vliegenthart, and CWI Director Gerard van Oortmerssen

In May 2000, the WWW9 conference was organized in Amsterdam. During this event, Tim Berners-Lee, inventor of the Web and Director of W3C, and his W3C Team visited CWI.

Interactive WWW

To grow to its full potential, the World Wide Web has to become more interactive. To achieve this goal, over 350 organizations – companies, governments and research institutes – collaborate in the World Wide Web Consortium (W3C). Since 1994, W3C designs global web standards or "W3C Recommendations". Thanks to this worldwide effort, societies can profit from broadly shared agreements on Web technology. As the starting point of the European Internet, CWI has also been very active in both W3C research and organization.

CWI research constitutes the base of several international W3C Recommendations, such as the Synchronized Multimedia Integration Language (SMIL), XHTML and XForms. SMIL – based upon CWI's CMIF language – allows authors to create synchronized multimedia presentations on the Web. It will also play a vital role in the new generation of internet-aware phones. CWI researcher Steven Pemberton is the international Chair of both the XHTML and XForms Working Groups. XHTML forms the bridge between HTML, which defines web mark-up, and XML, which structures data. XForms makes it easier to reuse web forms, make them device independent and better accessible.

To promote international involvement in Web development, a number of countries have established W3C Offices. Since 1998, CWI hosts the W3C Office in the Netherlands. This was expanded to the W3C Benelux Office in 2002. CWI researcher Ivan Herman was appointed Head of Offices worldwide. Several tutorials for web developers and policymakers were organized in cooperation with ISOC.nl, for instance on SMIL, XHTML, SVG, CSS, XML Architecture and the Semantic Web. Two large events were organized in Brussels, with keynote speakers from the EU. In 2001, W3C's Judy Brewer was a keynote speaker at the 'Drempels Weg' event of the Ministery of Health, Welfare and Sports, directed at making websites better accessible for disabled people.

Chapter 5

Research cluster MAS – Modelling, Analysis and Simulation

General

Cluster leader

Prof.dr.ir. C.J. van Duijn (1999–September 2000)
Prof.dr. J.G. Verwer (September 2000–present)

Strategy and policy

MAS is a mathematics cluster whose principal research area is *applied and numerical mathematics*. The emphasis lies on partial differential equations. Major activities include: mathematical analysis and dynamical systems theory, numerical analysis and scientific computing, computational fluid dynamics and systems with long-range electromagnetic interaction. Smaller sized activities include control and system theory, asymptotics and special functions, and computational number theory and discrete tomography

The principal research aim is twofold: to deliver mathematical contributions to the disciplines we are active in, and to contribute to relevant application fields. Applications for MAS research are numerous and can be found in the natural and physical sciences, in engineering, and in industrial and technological fields. Ongoing trends in computer hardware and software (with desktop performance in the gigaflop range) do steadily increase the demand for advanced modeling, analysis and simulation, with applied and computational mathematics at the center of interest. The cluster policy is to hold a strong position in this 'computational science' development. This requires a well-chosen balance between long-lasting discipline oriented research and more short term applied research with an enduring attention to new challenging applications.

Table 5.1. Global staff survey of MAS1–MAS3 (*prognosis)

MAS		1999	2000	2001	2002	2003	2004	2005*
MAS1	CWI research staff	8.2	8.9	10.8	9.1	8.7	10.8	14.0
	Total research staff	*14.0*	*15.3*	*16.5*	*10.1*	*9.7*	*11.5*	*14.4*
MAS2	CWI research staff	7.1	6.7	6.5	9.8	12.1	11.0	12.0
	Total research staff	*12.2*	*9.9*	*9.5*	*12.0*	*14.2*	*12.7*	*12.4*
MAS3	CWI research staff				3.8	4.1	4.7	6.4
	Total research staff				*5.9*	*6.2*	*6.1*	*6.6*

Themes

- **MAS1:** *Non-linear PDEs: Analysis and Scientific Computing*.
- **MAS2:** *Computing and Control*.
- **MAS3:** *Non-linear Dynamics and Complex Systems*.

Developments

The current MAS3 theme started January 2002 as a pilot (a spin-off of MAS1) and was upgraded to a normal theme in December 2004. Earlier, the two senior MAS3 staff members belonged to theme MAS1, and their achievements during this MAS1 period are mentioned in the MAS3 theme report.

The research on computational number theory and discrete tomography (MAS2) recently moved to a new pilot theme of cluster PNA.

Earlier, a MAS3 pilot on mathematics of finance (1999–2000) was disbanded. This pilot did not reach critical mass due to the departure of senior staff members and will not be discussed further.

Scientific challenges for MAS

The following challenges are currently playing a role at CWI in discussions on future research projects.

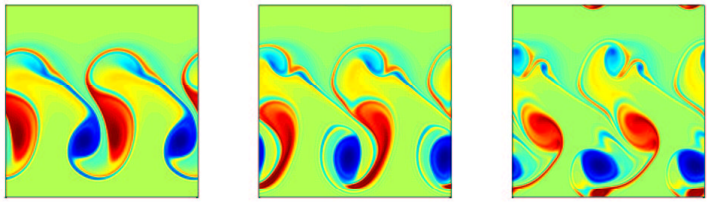


Figure 5.1. From MAS project *Symplectic integration of atmospheric fluid dynamics*: three potential vorticity (PV) snapshots during evolution of the shallow water equations on a rotating plane; these equations are generic for two-dimensional rotating fluids. The PV clearly exhibits several interacting localized structures. Color code indicates the PV magnitude: red is high, blue is low.

Complex models and coherent structures. Complex models in general exhibit an overwhelming richness of interacting scales and mechanisms. Examples include atmospheric lightning, in which a conducting channel with a specific inner structure penetrates into the nonconducting ambient air, and biological morphogenesis, in which individual cells interact with diffusive fields. Complex models will be more often than not "hybrid", which means that different mathematical descriptions – for instance a global PDE part and a probabilistic part at a micro-scale – have to be coupled into one system. The dynamics is often governed by remarkably low-dimensional coherent structures and their complex, often chaotic, interactions. These structures, such as the head of the above-mentioned ionization channel or regions of synchronized spiking neurons in the brain, are essential to the behavior of the system, but are seldom

stable in the classical sense, i.e., for all time. A coherent structure appears, exists for some (relatively long) time, and eventually disappears. This process of emergence, slow evolution, and branching or annihilation is remarkably subtle. It is often related to the complex/hybrid nature of the model, but the slow and/or localized dynamics can also be induced by other intrinsic dynamical properties. This poses fundamental challenges to the analysis, requiring studies in model reduction, non-linear dynamics, pattern formation, and adaptive numerical computing.

Geometric numerical integration. Geometric numerical integration is concerned with methods that exactly conserve physical quantities over long time simulations, e.g., conservation of total energy and angular momentum in celestial mechanics or molecular dynamics applications. For ordinary differential equations the field is now well developed. In recent years the focus of this field has begun to shift to partial differential equations. Challenges include the development of space-time symplectic methods for inviscid fluid dynamics with applications in numerical weather prediction, oceanography and climate, and the analysis and evaluation of these methods in the context of ensemble simulations. A related challenge is the development of new high-order, adaptive, energy conserving methods for Hamiltonian wave equations. The aim is to improve stability and minimize dispersive errors while avoiding spurious reflections and damping. Applications are broad, e.g., in optics, acoustics, and water waves.

Mathematics for system biology. Understanding the functioning of a cell at the molecular level in terms of its huge biochemical reaction network is rapidly becoming a major research topic now that the genome for several organisms is known. System biology is the name of this research program to distinguish it from the reductionist approach, which was dominating in biology until recently. Mathematics can contribute effectively to system biology by developing concepts, theory, and algorithms for the study of dynamic systems. For example, by analyzing large networks of positive systems of differential equations. Control and system theory is effective for this because the networks have tight feedback loops to stabilize and to focus their behavior. A major challenge is to handle networks of very large size by hierarchical decompositions and methods of system reduction. Another mathematical challenge is concerned with the spatial distribution of biochemical compounds, which leads to many new problems of evolutions and patterns for models described by diffusion-reaction partial differential equations. For example, models with singular source terms determined by Dirac delta function expressions require new approximation paradigms. The mathematics needed for system biology includes dynamical system theory, numerical analysis and scientific computing, control and system theory, polynomial and constructive algebra, and graph theory.

Computational electromagnetics. Electromagnetic engineering is rapidly developing (mobile telecommunication, magnetic resonance imaging, electromechanics, magnetohydrodynamic power generation, tokamak reactors). Computational techniques for this field, however, are mathematically less far developed compared to, for example, the field of fluid dynamics. Many techniques in electromagnetic engineering are

time-consuming "trial-and-error" methods that are counterintuitive and thus hamper the generation of new knowledge. The challenge is to properly combine the computational expediency of analytical and even empirical engineering models with the accuracy of sophisticated numerical treatment of the full Maxwell equations.

5.1 Theme MAS1 – Non-linear PDEs - Analysis and Scientific Computing

Research in	Applied and numerical analysis
Started in	January 1997
Theme leader	Prof.dr. J.G. Verwer (1997–2002)
	Dr. M.A. Peletier (2003–August 2004)
	Prof.dr. A. Doelman (September 2004–present)
MSC classification	65-xx [Numerical analysis, partial differential equations]
	35-xx [Analysis, partial differential equations]
	34-xx [Dynamical systems, ordinary differential equations]
	33-xx [Special functions]
	41-xx [Approximations and expansions]

5.1.1 Senior researchers

Drs. J.G. Blom, Prof.dr. A. Doelman (as of September 2004), Prof.dr. C.J. van Duijn (moved to TUE September 2000), Prof.dr. U.M. Ebert (moved to MAS3 December 2001), Dr.ir. J.E. Frank (as of September 2002), Prof.dr. P.J. van der Houwen (retired August 2000), Dr. W.H. Hundsdorfer (moved to MAS3 December 2001), Drs. J. Kok (until 2002), Dr. M.A. Peletier (moved to TUE September 2004), Dr. B.P. Sommeijer, Dr. N.M. Temme (until May 2005), Prof.dr. J.G. Verwer.

Table 5.2. Staff of MAS1, 1999–2005 (in FTE/year, *prognosis)

MAS1		1999	2000	2001	2002	2003	2004	2005*
Leader:	*J.G. Verwer*	*0.20*	*0.20*	*0.2*	*0.2*			
	M.A. Peletier					*0.2*	*0.12*	
	A. Doelman						*0.07*	*0.20*
Researchers:	*J.G. Blom*	*1.00*	*1.00*	*1.0*	*1.0*	*1.0*	*1.00*	*1.00*
	A. Doelman						*0.20*	*0.60*
	C.J. van Duijn	*0.60*	*0.40*					
	U.M. Ebert	*1.00*	*1.00*	*1.00*				
	J.E. Frank				*1.0*	*1.0*	*1.00*	*1.00*
	P.J. van der Houwen	*0.50*	*0.33*					
	W.H. Hundsdorfer	*1.00*	*1.00*	*1.00*				
	J. Kok	*0.63*	*0.30*	*0.2*				
	M.A. Peletier	*0.80*	*1.00*	*1.0*	*0.8*	*0.6*	*0.47*	
	B.P. Sommeijer	*0.80*	*1.00*	*1.0*	*1.0*	*1.0*	*1.00*	*0.90*
	N.M. Temme	*0.40*	*0.43*	*0.8*	*0.8*	*1.0*	*1.00*	*0.42*
	J.G. Verwer	*0.80*	*0.73*	*0.7*	*0.6*	*0.6*	*0.60*	*0.60*
Programmers:	*W.M. Lioen*	*0.50*						
Total tenured staff		**8.2**	**7.4**	**6.9**	**5.4**	**5.4**	**5.5**	**4.7**
Non-tenured staff		0.0	1.4	1.7	0.9	0.3	0.8	3.0
CWI PhD students		1.0	1.1	3.2	2.8	3.0	4.5	6.3
Total research staff CWI payroll		**9.2**	**9.9**	**11.8**	**9.1**	**8.7**	**10.8**	**14.0**
Seconded PhD students		*2.5*	*2.5*	*2.3*	*0.1*	*0.0*	*0.0*	*0.0*
Other seconded staff		*3.3*	*3.9*	*3.4*	*0.9*	*1.0*	*0.7*	*0.4*
Total hosted research staff		***15.0***	***16.3***	***17.5***	***10.1***	***9.7***	***11.5***	***14.4***

Table 5.3. Scientific output of MAS1

Output class		1999	2000	2001	2002	2003	2004	Total
Academic	refereed journals and proceedings	25	48	27	20	16	31	167
	other journals and proceedings	1	0	0	0	0	0	1
	book chapters	2	2	1	0	0	0	5
	Total academic	**28**	**50**	**28**	**20**	**16**	**31**	**173**
	Monographs	0	0	0	1	1	0	2
	PhD dissertations	0	0	0	2	2	0	4
	Professional publications/products	2	0	2	2	4	0	10

Table 5.4. Funding percentages of MAS1

MAS1	1999	2000	2001	2002	2003	2004	Average
Direct NWO	70.3%	70.8%	69.5%	80.8%	84.1%	72.9%	74.7%
Other research funds	14.1%	12.6%	17.9%	17.0%	12.2%	22.9%	16.1%
Grants/contracts	2.1%	3.1%	1.6%	1.0%	3.3%	3.8%	2.5%
Other	13.5%	13.5%	11.0%	1.2%	0.4%	0.4%	6.7%
Total	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**

5.1.2 Research orientation, highlights, and future directions

Mission and research area. Within the MAS scope of applied and numerical mathematics, theme MAS1 focuses on (i) mathematical analysis of non-linear PDEs and dynamical systems theory, (ii) numerical analysis in these areas with a strong focus on evolutionary advection-diffusion-reaction equations and wave equations from continuum mechanics, and (iii) asymptotics and special functions.

The research ranges from fundamental to practical with a considerable part being application driven. Typically, MAS1 applications come from the natural sciences. Until 2000, the focus was on porous media flows and environmental applications (atmospheric air, surface and ground water pollution). Since 2000, attention has gradually shifted towards life science applications (biology and medicine), for which mathematical modeling and scientific computing rapidly become more and more important. More recently MAS1 has also become active in climate dynamics and mathematical modeling in oceanography.

Research highlights. Only some highlights of senior staff members employed or seconded in 2005 are given.

Numerical time integration for air pollution models. In 2002, Verwer, Hundsdorfer and Blom published a comprehensive paper on this subject in *Surveys on Mathematics for Industry* **10**, 107–174. With this they ended a very successful cooperation with atmospheric researchers and a period of challenging numerical research into novel and ef-

ficient methods for large-scale, highly stiff advection-diffusion-reaction systems from atmospheric air pollution modeling (four PhDs).

Numerical solution of time-dependent advection-diffusion-reaction equations (with MAS3). See the report on MAS3 on page 130 for more details.

The Silicon Cell. In 1999 Blom and Peletier joined the Silicon Cell Initiative Amsterdam (*SiC*), the aim of which is to calculate cell functioning based on experimental data. *SiC* is formed by groups from cell biology, physics and mathematics. Blom and Peletier contribute with numerical methods and mathematical analysis and have invested considerably in modeling and mathematical problem definition. This has led to three joint papers with cell biologists, to an NWO Innovative Research Vidi grant for Peletier (see also Section 5.1.6) and, in 2003, to three numerical PhD projects granted by NWO. These three projects started in 2004 and focus on (i) multi-adaptive methods for reaction-diffusion PDEs with strongly varying spatial/temporal scales and space-dependent chemical schemes, (ii) methods that allow the integration of particle-based models with these multi-adaptive methods within a single simulation, and (iii) on hybrid continuum-discrete models where discrete, moving and deformable objects exchange species with the surrounding environment modeled as a continuum.

Phytoplankton dynamics. Phytoplankton, the generic name of micro-organisms living in lakes, seas and oceans, are at the basis of the aquatic food web. They play a key role in the marine ecosystem as well as in the reduction of carbon dioxide in the atmosphere. The dynamics (blooming) is studied experimentally and by means of mathematical and numerical modeling. In this field Sommeijer has an active collaboration with biologists from the UvA. Along with a PhD student, he works on models that take the form of an integro-PDE of advection-diffusion-reaction type and contain light intensity, competition, nutrient supply and transport. The numerical simulations have yielded surprising new results which have been published in *Bull. Math. Biology*, *The American Naturalist*, *J. Sea Research*, *Ecology*, *J. Comput. Appl. Math.*

Symplectic integration of atmospheric fluid dynamics. In 2000, Frank began a long-running collaboration with S. Reich of Imperial College of London (currently Potsdam University) to develop a new numerical approach to atmospheric simulations on climatic time-scales that is suitable for statistical ensemble simulations. The Hamiltonian Particle-Mesh (HPM) method was originally developed for planar shallow water flow, and has been subsequently generalized to two-layer flows, spherical geometry, and 2D vertical slice models. This very progressive project has resulted in a steady output of articles and a growing interest from the meteorological community. In 2002, Frank was awarded an NWO Innovational Research Incentive Veni grant (see also Section 5.1.6). Besides the above-mentioned work on atmospheric fluid dynamics, this grant supports more fundamental research in adaptive numerical methods for wave equations with local conservation properties. Additionally, in 2004, a proposal for PhD research on this topic was the top-ranked proposal in the NWO-ALW Climate Variability program.

Pulse interactions in reaction-diffusion equations. Reaction-diffusion equations are perhaps mathematically the simplest non-linear partial differential equations that exhibit complex patterns, such as pulses, spirals, stripes, defects and 'spatio-temporal chaos'.

Moreover, reaction-diffusion equations serve as relevant, often simplified, models for various biological and chemical processes. Together with various PhD students, Doelman studies the existence, stability and interactions of localized solutions such as pulses or fronts. Most recently, this research focuses on bifurcations of pulses that are induced by mutual interactions, of which the pulse self-replication mechanism is the most well-known and well-studied example.

Special functions and asymptotics. Temme is one of the few, highly acknowledged international experts in this field. He is one of the editors and chapter contributors of the international DLMF (Digital Library of Mathematical Functions) project directed at updating the widely used, classical *Handbook of Mathematical Functions* (Abramowitz and Stegun, eds.). This tremendous project is coordinated by the National Institute of Standards and Technology, see http://dlmf.nist.gov/.

Future directions. August 2004 M.A. Peletier left CWI to take up a full professorship at TUE. A. Doelman came to CWI to become the new MAS1 theme leader. This means that the focus in the PDE analysis research has changed from variational methods to dynamical systems theory. Furthermore, N.M. Temme will retire from CWI in May 2005, consequently his long-standing, successful line of research will be stopped in favor of PDE research for which new staff will be recruited. In the near future three main research lines will exist.

Non-linear dynamics of natural systems (Doelman, Hulshof (UL), vacancies for PhD students and postdocs). In recent years, important new insights into the behavior of PDEs and FDEs (Functional DEs) have been obtained by interpreting these systems as infinite-dimensional (semi-)dynamical systems. At present, there is a strong and stimulating interaction between the theory of (low-dimensional) dynamical systems, and that of PDEs and FDEs, in which an important role is played by intermediate high dimensional systems such as network and lattice equations. These developments are in a crucial way driven by challenges posed to the field by the life and earth sciences. At the same time, the mathematical approach yields insights into fundamental mechanisms in the natural sciences. This fast-developing field is in the focus of international attention. The MAS1 team is one of the major players in a far-reaching initiative of various teams at Dutch mathematical institutes that aims at building a national research cluster in this field (see also Section 5.1.5). MAS1 aims to create two new permanent positions at CWI that will be working in this field.

Numerical methods for life science problems (Blom, Sommeijer, five PhDs, one Postdoc, Verwer as PhD thesis advisor). The research within the Silicon Cell Initiative will be continued and further extended when sufficient progress will have been made with the three recently started PhD projects (see Section 5.1.2). The same holds for the cooperation with the aqueous biologists on plankton modeling and with respect to possible newly emerging research questions from aqueous biology (see Section 5.1.2).

Geometric integration in wave phenomena (Frank, PhD vacancy, Verwer as PhD thesis advisor). The research on symplectic integration of atmospheric fluids will be extended on a number of fronts. A PhD student will work on 3D nonhydrostatic models as well

as a qualitative comparison of the HPM method with other modern techniques. A paramount question to be addressed is the measure of the statistical accuracy of a numerical method in the context of ensemble simulations. Funding will also be sought for fundamental PhD research on adaptive methods for non-linear wave equations. A new class of generalized box schemes will be investigated in terms of local conservation properties, wave propagation signature, and adaptivity based on local refinement, local order control, and moving meshes. The main challenge here is to retain mathematical/physical structures under adaptive temporal and spatial discretization.

Knowledge transfer. Policy is (i) that theme members give (university master) courses and (summer) schools in the Netherlands and abroad, (ii) that theme members are active in submitting research proposals to NWO, (iii) that theme members take part in contract research projects, and (iv) that theme members take part in EU research training network programs. MAS1 has been and will remain active in each of these aspects of knowledge transfer. Examples are (a) local and/or national courses taught by Doelman, Hulshof and Verwer, the organization of several "Stieltjesweeks" at the Lorentz Center in Leiden, a summer school on numerical analysis in Italy (2004) funded by the EU, the MRI/Stieltjes Master Class 2005–2006 "Finite and Infinite Dimensional Dynamical Systems"; (b) the successes in NWO programs like Open Competition, Innovational Research Incentives (Veni and Vidi), Computational Science, Computational Life Science, STW/Applied Mathematics; (c) the participation in the three consecutive ICES-KIS programs for environmental and life science projects; (d) the involvement in the RTN project "Fronts and Singularities" with Hulshof as the national coordinator.

5.1.3 Implementation of the 1999 recommendations

- As of 2000, the research of MAS1 was directed to non-linear PDEs, which was illustrated in its current title.
- In 2003 the project group PDE@CWI consisting of top experts in the field of PDEs, was founded.
- J.E. Frank joined the tenured staff in 2002.

5.1.4 Overview of the results

See Table 5.3 on page 114 for a numerical overview. A list of all publications can be found in the MAS1 sections of *CWI Overview Research Activities 1999–2003* (CD-ROM).

Selection of major publications

1 C.J. COTTER, J.E. FRANK, S. REICH (2004). Hamiltonian particle-mesh method for two-layer shallow water equations subject to the rigid-lid approximation. *SIAM J. Appl. Dyn. Syst.***3**, 69–83.

2 A. DOELMAN, D. IRON, Y. NISHIURA (2004). Destabilization of fronts in a class of bi-stable systems. *SIAM J. Math. An.* **35** (6), 1420–1450.

3 J.L. LÓPEZ, N.M. TEMME (2004). Multi-point Taylor expansions of analytic functions. *Trans. Amer. Math. Soc.* **356**, 4323–4342.

4 J.G. VERWER, B.P. SOMMEIJER (2004). An implicit-explicit Runge-Kutta-Chebyshev scheme for diffusion-reaction equations. *SIAM J. Scientific Computing* **25**, 1824–1835.

5 C. FRANCKE, P.W. POSTMA. H.V. WESTERHOFF, J.G. BLOM, M.A. PELETIER (2003). Why the phosphotransferase system of *Escherichia Coli* escapes the diffusion limitation of signal transduction, transport and metabolism that confronts mammalian cells. *Biophys. J.* **85**, 612–622.

6 W.H. HUNDSDORFER, J.G. VERWER (2003). *Numerical solution of time-dependent advection-diffusion-reaction equations*. Springer Series in Computational Mathematics 33, Springer-Verlag.

7 A. DOELMAN, R.A. GARDNER, T.J. KAPER (2002). A stability index analysis of 1-D patterns of the Gray-Scott model. *Mem. Amer. Math. Soc.* **155**, no. 737.

8 J. HUISMAN, B.P. SOMMEIJER (2002). Population dynamics of sinking phytoplankton in light-limited environments: simulation techniques and critical parameters. *J. Sea Research* **48**, 83–96.

9 J.E. FRANK, C. VUIK (2001). On the construction of deflation-based preconditioners. *SIAM J. Sci. Comput.* **23**, 442–462.

10 M.A. PELETIER (2001). Sequential buckling: a variational analysis. *SIAM J. Math. An.* **32**, 1142–1168.

PhD theses

- D. Lanser (Thesis advisor: J.G. Verwer, Co-advisor: J.G. Blom, University: UvA, Date: March 7, 2002, Title: *Numerical Methods for Atmospheric Flow and Transport Problems*)
- B. Lastdrager (with MAS2) (Thesis advisor: J.G. Verwer, Co-advisor: B. Koren, University: UvA, Date: September 18, 2002, Title: *Numerical Time Integration on Sparse Grids*)
- I.A. Guerra Benavente (Thesis advisors: C.J. van Duijn, J. Hulshof, Co-advisor: M.A. Peletier, University: TUE, Date: January 15, 2003, Title: *Stabilization and Blow-up for Some Multi-dimensional Non-linear PDEs*)
- C. Cuesta (Thesis advisor: J. Hulshof, Co-advisor: C.J. van Duijn, University: VU, Date: March 6, 2003, Title: *Pseudo-parabolic Equations with Driving Convection Term*)
- Future PhD theses: R. Planqué (March 2005, *Constraints in Applied Mathematics: Rods, Membranes, and Cuckoos*), H. van der Ploeg (April 2005, *Pattern Formation in Reaction-diffusion Equations*)

5.1.5 Context

University connections. Senior staff members maintain a wide diversity of national and international academic research relations. In addition, Doelman and Verwer have 0.2 FTE appointments as full professor at UvA, Hulshof (VU) has a 0.2 FTE secondment at CWI, and Diekmann (UU), Westerhoff (VU) and L.A. Peletier (UL) served or serve as advisors.

Table 5.5. Some major externally funded projects of MAS1

Acronym	Full name	Dates		k€	Source
Veni-Frank	Geometric numerical methods for continuum mechanics	2002	present	200	NWO
Vidi-Peletier	Mathematical analysis of partially localized structures	2003	2004	600	NWO
CLS-Blom	Three PhD projects in the field of computational life sciences	2004	present	360	NWO

The national ICES-KIS program. Since the start of the MAS1 theme, the numerical analysts have actively participated in master projects funded by the national ICES-KIS program. For ICES-KIS1 this involved participation in a HPCN (High Performance Computing and Networking) project in cooperation with national labs (RIVM, KNMI, Delft Hydraulics, RIKZ) on environmental projects (lasting until about 2000). Within the framework of ICES-KIS2 (1998–2002) cooperation with biologists working at the Amsterdam Science Park has been established (WTCW project). This cooperation has been very successful and led to new cooperations with groups from neuro, cell and aqueous biology and to participation in ICES-KIS3 (2004–2009) (BRICKS project).

PDE@CWI. An important event was the creation of the subtheme "PDE@CWI" on September 1, 2002, with one day-per-week secondments of A. Doelman (UvA), C.J. van Duijn (TUE), J. Hulshof (VU) and L.A. Peletier (UL). The goal of PDE@CWI was to strengthen cooperations and to generate more research activity in non-linear PDE analysis at CWI and in the Netherlands, as well as to prepare for participation in the national cluster plans for mathematics. The subtheme has been especially successful in initiating new research projects, such as on the stability of free boundaries and pulse interactions (for both projects PhD research received funding through the NWO Open Competition). Moreover, the PDE@CWI subtheme has been essential to the success of the new FOM/NWO Program 'Dynamics of Patterns' (Section 5.1.6). At the end of 2004, the impact of the subtheme can be assessed as very positive. Doelman (from 0.2 FTE to 0.8 FTE employed and theme leader) is one of the authors (with H.W. Broer, RUG, and S.M. Verduyn Lunel, UL) of a well-received national cluster plan "Non-linear Dynamics of Natural Systems", for which CWI will be one of the nodes (RUG acts as hub, UL is the other node). At the time of writing this document no final decision (by NWO) about submitted cluster plans has been made. However, NWO has ranked this cluster proposal as the first proposal to be funded. It is expected that the cluster will be initiated early 2005. As a consequence, CWI's mathematical PDE analysis will be embedded even more strongly in the Dutch research community, with joint projects, joint workshops and increased eaching participation in master courses.

5.1.6 Scientific reputation

Awards

- In 2002, Frank received a three-year NWO Innovational Research Incentive Veni grant for his research project "Geometric numerical methods for continuum mechanics". Challenging issues here are long time integration and preservation of mathematical/physical structures after discretization. This is, for example, of utmost importance in climate dynamics studies.
- In 2003, Peletier received a five year NWO Innovational Research Incentive Vidi grant for his research project "Mathematical analysis of partially localized structures". Here the focus is on variational methods for the study of aggregation of molecules and membrane formation in living cells, a highly challenging research question in mathematical cell biology.
- In the period 2001–2003, Blom, Peletier, Sommeijer and Verwer received a total of six NWO grants for PhD research in new numerical life science projects directed at applications from neuro, cell and aqueous biology.
- Together with Van Saarloos (physics, Leiden), Doelman initiated and received funding for the FOM/NWO program "Dynamics of Patterns". This national program involves eight or nine PhD and/or postdoc projects and started running in November 2004.
- The national cluster plan "Non-linear Dynamics of Natural Systems", developed by Doelman in collaboration with H. Broer (Groningen) and S. Verduyn Lunel (Leiden), obtained the top-ranking within NWO's national cluster competition. Two new permanent positions will be created in the context of this cluster.

Memberships of committees and other professional activities

For U.M. Ebert and W.H. Hundsdorfer, see Section 5.3. For a more extensive survey, please see the MAS1 section of the *CWI Overview Research Activities 1999–2003* (CD-ROM).

A. Doelman	full professor at UvA, editor of one journal, member of five program committees, member of three advisory committees
M.A. Peletier	associate professor at TUE, since August 2004 full professor, (co)-organizer of one conference, editor of one journal, board member of KWG
B.P. Sommeijer	editor of two journals, (co-)organizer of several conferences. Lecturer at UvA
N.M. Temme	editor of seven journals, member of one governing board, organizer CWI scientific meetings, CWI co-ordinator for the Dutch research schools in mathematics and computer science
J.G. Verwer	full professor of Numerical Analysis at UvA, editor of three journals, (co-)organizer of several conferences, member of two advisory committees, thesis advisor, co-advisor, and committee member several PhD theses

5.2 Theme MAS2 – Computing and Control

Research in	Computational fluid dynamics, computational electromagnetics (as of April 2003), numerical mathematics (discontinuous Galerkin methods, multigrid methods, singular-perturbation methods), parallel computing, computational number theory (as of September 2004 moved to PNA5), control and system theory (as of January 2002 moved from PNA2)
Started in	January 1997
Theme leader	Prof.dr. P.W. Hemker (1997–2001) Prof.dr.ir. B. Koren (2002–present)
MSC classification	11-xx [Number theory] 35-xx [Partial differential equations] 39-xx [Difference and functional equations] 41-xx [Approximations and expansions] 65-xx [Numerical analysis] 68W10 [Parallel algorithms] 76-xx [Fluid mechanics] 78-xx [Electromagnetic theory] 93-xx [Systems theory and control] 94A12 [Signal theory]

5.2.1 Senior researchers

Prof.dr. P.W. Hemker, Prof.dr.ir. B. Koren, Dr.ir. H.J.J. te Riele (until September 1, 2004), Prof.dr.ir. J.H. van Schuppen (as of January 1, 2002). 122 for more details.

5.2.2 Research orientation, highlights, and future directions

Mission and research area. The theme Computing and Control is concerned with the numerical and system-theoretical analysis of complex applications in science and engineering, as well as with their simulation and control. Numerical simulation enables the investigation of phenomena that are too dangerous, too expensive, too difficult, or simply impossible to be studied by real experiments. Control and system theory is a major factor in the effective functioning of technological systems as well as in the modeling of biological systems. Because there is no end in sight yet for the growth of computing power and algorithmic improvements in numerical mathematics and system theory, the potential benefits of computing and control are enormous. The challenge is the simulation, control, design and optimization of ever more realistic problems.

The current research is directed towards applications of fluid dynamics, electromagnetics, and control and system theory. Advanced numerical techniques for complex fluid-flow problems are developed for ship hydrodynamics, and for aircraft and spacecraft aerodynamics. In April 2003, numerical research started for the Maxwell equations: computational electromagnetics. Control and system theory is currently primarily motivated by network problems from engineering and biology (traffic net-

Table 5.6. Staff of MAS2, 1999–2005 (in FTE/year, *prognosis)

MAS2		1999	2000	2001	2002	2003	2004	2005*
Leader:	*P.W. Hemker*	*0.20*	*0.20*	*0.2*				
	B. Koren				*0.2*	*0.2*	*0.20*	*0.2*
Researchers:	*P.W. Hemker*	*0.80*	*0.60*	*0.6*	*0.8*	*0.8*	*0.80*	*0.8*
	P.J. van der Houwen	*0.50*	*0.33*					
	J. Kok	*0.15*	*0.20*	*0.2*				
	B. Koren	*0.60*	*1.00*	*1.0*	*0.6*	*0.6*	*0.60*	*0.6*
	H.J.J. te Riele	*0.70*	*1.00*	*1.0*	*1.0*	*1.0*	*0.67*	
	J.H. van Schuppen				*0.8*	*0.8*	*0.80*	*0.8*
	B.P. Sommeijer	*0.20*						
Programmers:	*W.M. Lioen*	*0.50*						
	M. Nool	*0.60*	*0.60*	*0.6*	*0.6*	*0.6*	*0.60*	*0.6*
	D.T. Winter	*0.20*						
Total tenured staff		**4.5**	**3.9**	**3.6**	**4.0**	**4.0**	**3.7**	**3.0**
Non-tenured staff		0.8	0.0	0.2	2.0	2.5	2.0	2.0
CWI PhD students		1.8	2.0	1.7	3.8	5.6	5.3	7.0
Total research staff CWI payroll		**7.1**	**5.9**	**5.5**	**9.8**	**12.1**	**11.0**	**12.0**
Seconded PhD students		*3.3*	*1.7*	*1.5*	*0.9*	*0.8*	*0.7*	*0.0*
Other seconded staff		*1.8*	*1.5*	*1.5*	*1.3*	*1.3*	*1.0*	*0.4*
Total hosted research staff		***12.2***	***9.1***	***8.5***	***12.0***	***14.2***	***12.7***	***12.4***

works, wireless communication networks, and biochemical reaction networks).

Until September 2004, a long-standing and successful research activity in the theme was computational number theory and data security. As of September 1, 2004, this subtheme has been moved to the newly founded pilot theme Cryptology and Information Security (PNA5).

Research highlights. Research on numerical methods for gas dynamics in special relativity, directed towards the simulation of extremely energetic astrophysical phenomena (gamma-ray bursts). This research was supported through the Computational Science Program of NWO.

Long-standing research on and development of a very efficient computational method for Navier-Stokes flows with free-surface gravity waves around sea vessels. The work was fully funded by MARIN. The research was continued through PhD projects funded by STW and BSIK.

Successful research on multigrid-accelerated discontinuous Galerkin methods for elliptic boundary-value problems (pure diffusion as well as convection-diffusion), with embedded boundary techniques. (Completion with several journal papers and thesis of PhD student M. van Raalte.)

Establishment of several world records for factoring large numbers during the study of factoring methods (the difficulty of factoring large numbers is the basis for the security of the widely used RSA crypto system).

Successful parallel implementation of state-of-the-art numerical software, in MAS2 itself (by scientific programmer Nool), and in cooperation (by Koren) with theme SEN3 (Coordination Languages, group of Arbab).

Table 5.7. Scientific output of MAS2

Output class		1999	2000	2001	2002	2003	2004	Total
Academic	refereed journals and proceedings	13	16	14	19	26	22	110
	other journals and proceedings	2	0	0	0	0	0	2
	book chapters	0	4	0	0	0	0	4
	Total academic	**15**	**20**	**14**	**19**	**26**	**22**	**116**
Monographs		1	0	0	0	0	0	1
PhD dissertations		0	1	1	2.5	1	2	7.5
Professional pub./products		3	4	3	2	1	0	13

Table 5.8. Funding percentages of MAS2

MAS2	1999	2000	2001	2002	2003	2004	Average
Direct NWO	78.4%	81.9%	76.0%	76.4%	72.5%	68.6%	75.6%
Other research funds	4.0%	3.1%	14.8%	16.4%	23.1%	23.0%	14.1%
Grants/contracts	5.1%	5.3%	4.3%	0.0%	0.2%	0.0%	2.5%
Other	12.5%	9.7%	4.9%	7.2%	4.2%	8.4%	7.8%
Total	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**

Fruitful continuation of the long-standing research cooperation with the Russian mathematician G.I. Shishkin on numerical methods for singular perturbation problems.

Start of a research project on computational electromagnetics funded through a special program of the Dutch Ministry of Economic Affairs (IOP-EMVT).

In research on control of hybrid systems sufficient conditions were obtained for reachability and controllability of piecewise-affine systems on polytopes, and necessary and sufficient conditions for realizability of switched systems. Financial support for this research came in part from two projects of the European Commission.

Research in control of discrete-event systems has produced results for a coalgebraic framework for control with partial observations, for modular control with partial observations, and for the complexity of decentralized control with communication between controllers. Financial support was provided by a project of NWO and a project of the European Commission.

Research in stochastic realization and stochastic control has produced highlights for stochastic realization in a σ-algebraic framework, for optimal control of stochastic team problems, and for control of stochastic pension fund systems.

Research for realization and control of biochemical reaction networks has started and preliminary results concern the realization of rational positive systems and control of such systems motivated by rational drug design via inhibition of enzymes.

Research in system identification has resulted in a PhD thesis with results in al-

gebraic optimization methods for minimization of polynomial and rational functions with applications to system identification and control. Financial support for the investigation was provided by a project of NWO.

Future directions. Research in computational fluid dynamics will be continued in a multidisciplinary fashion: combined with electromagnetics (magnetohydrodynamics), the thermodynamics of structures (thermal fluid-structure interaction), etc. A step will be made to inverse methods for these multidisciplinary problems.

Research in the area of computational electromagnetics will be further extended with a new IOP-EMVT funded project in cooperation with the Electromagnetics Group at TUE.

Research in computational topology for systems and control will be performed. It will be directed at computation of properties of non-linear and hybrid systems, with an emphasis on formal computability analysis and the development of algorithms. Case studies will come from systems biology and electrical and electronic systems. Financial support will be provided by a Vidi grant of NWO.

Research in realization will be continued for hybrid systems (control of cars and electric power networks), for rational positive systems (biochemical reaction networks), and for stochastic systems (signal processing and mathematical finance).

Research in control of hybrid systems will be directed at sufficient conditions for the existence of controllers for piecewise-affine hybrid systems and at discrete-event control of hybrid systems based on abstractions, with coalgebra and bisimulations.

Research in control of discrete-event systems will be directed at control of modular and of decentralized systems with decomposition methods, hierarchical control, and with communication between controllers.

Research in control of non-linear system will be directed at control of rational positive systems (by biochemical reaction networks such as genetic regulatory networks, signal transduction networks, and metabolic networks). It will also be directed at stochastic control for mathematical finance, in particular at control of pension funds.

Knowledge transfer. All three current scientific staff members are full professors at a Dutch university: Hemker at UvA, Koren at TUD, and Van Schuppen at VU.

Guest courses were given at various other institutes (Thomas Stieltjes Institute for Mathematics, J.M. Burgers Research Center for Fluid Mechanics, Mathematisches Forschungsinstitut Oberwolfach, and various universities in the Netherlands and abroad).

Supervision of 10 to 20 trainees from universities and research institutes in the Netherlands and abroad.

Several source code license agreements were made with companies in the Netherlands, the USA, Germany and France, allowing the use of the Number Field Sieve factorization code developed by, among others, MAS2 PhD students M. Huizing and S. Cavallar. The code has also been made available, on a non-commercial basis, to various cooperating research groups in the USA, Germany, Denmark, Hungary, UK.

The subtheme discontinuous dynamical systems was stopped after J.M. Schumacher

left CWI in 1999 for the UvT.

In 2002 P.W. Hemker stepped down as theme leader after his five-year term and was appointed CWI Fellow. B. Koren (who was appointed full professor in 2002) succeeded Hemker as theme leader.

J.H. van Schuppen switched in 2002 from PNA2 to MAS2 with his project group Control and System Theory.

The theme was renamed Computing and Control.

In August 2004, the project group Computational number theory and data security (H.J.J. te Riele and K.J. Batenburg) left MAS2 to staff the newly created pilot theme PNA5 (Cryptology and Information Security).

In 2000, the subtheme Initial Value Problems was concluded, after its principal researcher retired.

5.2.3 Overview of the results

See Table 5.7 on page 123 for a numerical overview. A list of all publications can be found in the MAS2 sections of *CWI Overview Research Activities 1999–2003* (CD-ROM).

Selection of major publications

1 J. NOORDMANS, P.W. HEMKER (2000). Application of an adaptive sparse-grid technique to a model singular perturbation problem. *Computing* **65**, 357–378.

2 A. OVERKAMP, J.H. VAN SCHUPPEN (2000). Maximal solutions in decentralized supervisory control. *SIAM Journal on Control and Optimization* **39**, 492–511.

3 J.H. VAN SCHUPPEN (2000). Stochastic realization of σ-algebras. *Proceedings 14th International Symposium MTNS2000*, published on CD-ROM only, University Perpignan, France.

4 P.W. HEMKER, G.I. SHISHKIN, L.P. SHISHKINA (2001). High-order time-accurate parallel schemes for parabolic singularly perturbed problems with convection. *Computing* **66**, 139–161.

5 B. LASTDRAGER, B. KOREN, J.G. VERWER (2001). The sparse-grid combination technique applied to time-dependent advection problems. *Applied Numerical Mathematics* **38**, 377–401.

6 B. KOREN, M.R. LEWIS, E.H. VAN BRUMMELEN, B. VAN LEER (2002). Riemann-problem and level-set approaches for homentropic two-fluid flow computations. *Journal of Computational Physics* **181**, 654–674.

7 H.J.J. TE RIELE, H. WILLIAMS (2003). New computations concerning the Cohen-Lenstra heuristics. *Experimental Mathematics* **12**, 99–113.

8 P.W. HEMKER, W. HOFFMANN, M.H. VAN RAALTE (2004). Two-level Fourier analysis of a multigrid approach for discontinuous Galerkin discretization. *SIAM Journal on Scientific Computing* **25**, 1018–1041.

9 L.C.G.J.M. HABETS, J.H. VAN SCHUPPEN (2004). A control problem for affine dynamical systems on a full-dimensional polytope. *Automatica* **40**, 21–35.

10 P. MOREE, H.J.J. TE RIELE (2004). The hexagonal versus the square lattice, *Mathematics of Computation* **73**, 451–473.

PhD theses

- J.E. Frank (Thesis advisors: P. Wesseling, P.J. van der Houwen, Co-advisor: A. Segal, University: TUD, Date: April 17, 2000, Title: *Efficient Algorithms for the Numerical Solution of Differential Equations*)
- M. Genseberger (Thesis advisor: H.A. van der Vorst, Co-advisors: H.J.J. te Riele, G.L.G. Sleijpen, University: UU, Date: September 10, 2001, Title: *Domain Decomposition in the Jacobi-Davidson Method for Eigenproblems*)
- E.H. van Brummelen (Thesis advisor: P.W. Hemker, Co-advisors: B. Koren, H.C. Raven, University: UvA, Date: February 8, 2002, Title: *Numerical Methods for Steady Viscous Free-surface Flows*)
- S.H. Cavallar (Thesis advisor: R. Tijdeman, Co-advisors: H.J.J. te Riele, P.L. Montgomery, University: UL, Date: June 5, 2002, Title: *On the Number Field Sieve Integer Factorisation Algorithm*)
- B. Lastdrager (joint with MAS1). See the report on MAS1.
- D. Jibetean (Thesis advisors: J.H. van Schuppen, B. Hanzon, University: VU, Date: June 11, 2003, Title: *Algebraic Optimization with Applications to System Theory*)
- M.R. Lewis (Thesis advisor: B. Koren, University: TUD, Date: June 8, 2004, Title: *Numerical Methods for Water Flows with Free-surface Gravity Waves*)
- M.H. van Raalte (Thesis advisor: P.W. Hemker, Co-advisor: W. Hoffmann, University: UvA, Date: December 6, 2004, Title: *Multigrid Analysis and Embedded Boundary Conditions for Discontinuous Galerkin Methods*)

Table 5.9. Some major externally funded projects of MAS2

Acronym	Full name	Dates		k€	Source
BRICKS	Development of a state-of-the-art surface-capturing method for two-fluid flows	2004	2008	415	BSIK
IOP-EMVT	Space-mapping and related techniques for inverse problems in magnetic shape design, with applications to an electromagnetic actuator	2003	2007	630	SENTER
CC	Control and computation	2002	2004	400	EU

5.2.4 Context

The research of the current senior staff (Hemker, Koren, Van Schuppen) and co-workers is mainly directed towards engineering problems arising in high-tech, classical manufacturing industries (ship and aircraft building, the manufacturing of electrical devices, etc.). Many contacts exist with these industries and related specialized research institutes (such as MARIN and the Philips Research Laboratories Eindhoven). The MAS2 staff has an open mind though for non-industrial research: either purely academic

(e.g., astrophysics) or from relevant other application areas (Van Schuppen, e.g., plays an active role in mathematics for life sciences). Many contacts exist with industries and academia in and outside the Netherlands.

5.2.5 Scientific reputation

Awards

- End 2001, Hemker was appointed CWI Fellow.
- During the *Seventh ICFD Conference on Numerical Methods for Fluid Dynamics*, March 26–29, 2001, University Oxford, MAS2 PhD student Van Brummelen was awarded the *Bill Morton Prize* for his paper "Adjoint Shape Optimization for Steady Free-Surface Flows".
- In 2003, MAS2 PhD student Wackers was awarded the prize of best graduate of that year (out of more than 100 candidates), at the Faculty of Aerospace Engineering, TUD, for his MSc work carried out as a trainee at CWI.
- In 2004, Collins received a five-year NWO Innovational Research Incentive Vidi grant for his research project "Computational Topology for Systems and Control".

Memberships of committees and other professional activities

For a more extensive survey, please see the MAS2 section of the *CWI Overview Research Activities 1999–2003* (CD-ROM).

P.W. Hemker	full professor at UvA, Member Koninklijke Hollandsche Maatschappij der Wetenschappen, editor of one journal, four memberships of boards, steering committees, advisory groups
B. Koren	full professor at TUD, coordinator of one collaboration project, two memberships of boards, steering committees, advisory groups
H.J.J. te Riele	three memberships of boards, steering committees, advisory groups
J.H. van Schuppen	full professor at VU, editor of four journals, three memberships of boards, steering committees, advisory groups, coordinator of three collaboration projects, four memberships of boards, steering committees, advisory groups

5.3 Theme MAS3 – Non-linear Dynamics and Complex Systems

Research in	Applied non-linear dynamics and numerical analysis
Started in	January 2002 as a pilot. It becomes a full theme in 2005
Theme leader	Prof.dr. U.M. Ebert (2002–present)
MSC classification	35-xx [Analysis, partial differential equations]
	65-xx [Numerical analysis, partial differential equations]

5.3.1 Senior researchers

Prof.dr. U.M. Ebert, Dr. W.H. Hundsdorfer.

Table 5.10. Staff of MAS3, 1999–2005 (in FTE/year, *prognosis)

MAS3	1999	2000	2001	2002	2003	2004	2005*
Leader: U.M. Ebert				*0.2*	*0.2*	*0.2*	*0.2*
Researchers: U.M. Ebert				*0.6*	*0.6*	*0.6*	*0.6*
W.H. Hundsdorfer				*1.0*	*1.0*	*1.0*	*1.0*
Total tenured staff				**1.8**	**1.8**	**1.8**	**1.8**
Non-tenured staff				0.0	0.0	0.0	1.0
CWI PhD students				2.0	2.2	2.9	3.6
Total research staff CWI payroll				**3.8**	**4.0**	**4.7**	**6.4**
Seconded PhD students				*1.0*	*1.1*	*1.0*	0.2
Other seconded staff				*0.7*	*0.3*	*0.2*	0.0
Total hosted research staff				***5.5***	***5.4***	***5.9***	**6.6**

Table 5.11. Scientific output of MAS3

Output class		1999	2000	2001	2002	2003	2004	Total
Academic	refereed journals and proceedings			7.5	19	12	10	49
	other journals and proceedings			0	2	1	0	3
	book chapters			0	0	0	0	0
	Total academic			**7.5**	**21**	**13**	**10**	**52**
	Monographs			0	0	0.5	0.0	0.5
	PhD dissertations			0	0	0	1	1
	Professional publications/products			1	5	4	4	14

Ebert joined CWI and MAS1 in September 1998. Together with Hundsdorfer, also MAS1, she started the new pilot theme MAS3 in 2002. For the sake of clarity, the content of their work and that of Ebert's first collaborators during the MAS1 period, postdoc M. Arrayás (September 1999–August 2001), postdoc Rocco (September 2001–February 2003), PhD student Šijačić (May 2000–December 2004) and frequent long-term guest P. Rodin is fully included in the present section and not discussed under MAS1.

Table 5.12. Funding percentages of MAS3

MAS3	1999	2000	2001	2002	2003	2004	Average
Direct NWO				83.2%	83.5%	72.8%	79.8%
Other research funds				6.5%	5.9%	19.6%	10.7%
Grants/contracts				0.0%	0.0%	0.0%	0.0%
Other				10.3%	10.6%	7.6%	9.5%
Total				**100.0%**	**100.0%**	**100.0%**	**100.0%**

5.3.2 Research orientation, highlights, and future directions

Mission and research area. We investigate non-linear dynamics and pattern formation in spatially extended systems. Patterns can be understood as coherent structures, i.e., as generic solutions of (sets of) non-linear PDEs. Research is concerned with fundamental questions such as the analysis and numerical solution of pulled fronts, as well as with numerical methods for convection-diffusion equations with emphasis on monotone numerical schemes and grid refinements in space and time. Also stochastic problems with a chemical or biological motivation have been analyzed.

For applications, the theme focuses increasingly on patterns in electric discharges, in particular, on the formation of spark channels. This is a rather unexplored field relevant for various technological processes as well as for geophysical lightning-related phenomena. The phenomena are described by reaction-advection-diffusion equations for the charged particle species that are coupled in a threefold way to the Poisson equation of electrostatics and give rise to three distinct length scales already on the level of a single channel.

Research highlights.

Universal algebraic temporal convergence of pulled fronts. The Mathematics Classification Index does distinguish parabolic or higher order equations, since these are traditional concepts of linear PDE theory. However, it does not allow to distinguish between pushed or pulled traveling fronts as fundamentally different solutions of non-linear PDEs or lattice equations. Pulled fronts are pulled along by their leading edge that penetrates a linearly unstable state. Unlike pushed or bistable fronts that are well covered by textbooks, pulled fronts converge algebraically slowly in time to their asymptotic speed, perturbation theory about such a front can not be evaluated by Fredholm analysis, numerical grid refinement techniques fail and the response to noise differs. These properties were analyzed by Ebert, Van Saarloos and collaborators in a series of eight papers between 1998 and 2004, including a very well cited 100-page research paper in *Physica D* in 2000. A present PhD project (Montijn) supervised by Hundsdorfer and Ebert addresses the numerical aspects in the context of pulled ionization fronts.

Spontaeous branching of spark channels as a Laplacian instability. A simple continuum PDE description of a discharge creates not only single spark channels, but also allows one to understand the spontaneous branching of the channel. This discovery (Arrayás, Ebert, Hundsdorfer, Rocco) is based on numerical solutions and supported by the un-

derstanding that the system is susceptible to a Laplacian instability. It had a wide resonance in the public media. This first observation branched out to several studies: the development of a numerical code with adaptive grid refinement for preciser numerical studies of the phenomenon (Montijn, Wackers, Hundsdorfer, Ebert), analytical studies of the lateral stability of planar ionization fronts (Arrayás, Ebert) and model reductions to moving boundaries and their solutions with conformal mapping methods (Meulenbroek, Rocco, Ebert). The search for an appropriate regularization mechanism of the moving boundary problem and its inclusion into the conformal mapping solutions is an interesting question not only for spark formation, but also for certain hydrodynamic problems (viscous fingering), and we (Meulenbroek, Ebert) recently have identified a new regularization mechanism and a new class of regularized and exactly solvable solutions. A controlled experiment is presently being set up at TUE (Briels, Van Veldhuizen, Ebert), on which the theoretical predictions can be tested very accurately with nanosecond resolution.

Other patterns and waves in electric discharges. A thin gas discharge layer sandwiched with a linear conductor within a stationary voltage exhibits a variety of spatial, temporal and spatio-temporal patterns. They were analyzed in the PhD thesis of Šijačić (2004) through construction of heteroclinic orbits, eigenvalue calculations in linear perturbation theory, and 2D time-dependent computations (together with ERCIM-fellow Rafatov). Rodin investigated ionization fronts in fast high power semiconductor switches for applications in three papers with Ebert, Hundsdorfer and Grekhov.

Chemical and biological problems, stochastics. The extensive past research of Ebert on problems of polymer and DNA diffusion was completed by three extensive papers in 1999, 2002 and 2003 with Schäfer and Baumgärtner on quantitative predictions for polymer "reptation", the snake-like motion of a linear chain through an array of obstacles. This problem became exactly solvable through our mapping onto an ensemble of random walkers moving on a random walk chain, and it was validated against extensive Monte Carlo simulations. Arrayás published four papers on Brownian ratchets in 2000 and 2001, i.e., on how directed motion in living cells can emerge from a stochastic process. Ebert and Arrayás also contributed to the analytical understanding of phytoplankton populations in two papers. The further development of the project under supervision of Sommeijer is described under MAS1.

Numerical solution of time-dependent advection-diffusion-reaction equations. In 2003 Hundsdorfer and Verwer published a successful textbook/research monograph on this topic in the Springer Series in Computational Mathematics. The book contains an in-depth presentation of spatial and temporal discretization for advection-diffusion-reaction equations. The last two chapters, on splitting methods and stabilized explicit time integrations, are derived from the authors' research in the last decade. Reviews have been published by the American Mathematical Society, electronically at MathSciNet, and by the Society for Industrial and Applied Mathematics in *SIAM Review* **46** (2004), 581–583.

Monotonicity properties of multistep methods. In 2001 Hundsdorfer started collaboration with S.J. Ruuth of the Simon Frasier University, Canada, to investigate monotonicity and boundedness properties of linear multistep methods, in particular TVD/TVB

properties for non-linear hyperbolic partial differential equations. At that point multistep methods were thought to be inferior to one-step (Runge-Kutta) methods. This research has changed that perception, and it has led to a number of publications and invitations to present keynote lectures at important numerical analysis conferences (e.g., at the 20th Biennial Conference on Numerical Analysis, Dundee, 2003, and the forthcoming conference SCICADE05).

Multirate methods for partial differential equations. In 2003 Hundsdorfer initiated research on this new and promising topic. Multirating for PDEs requires novel discretization schemes that can perform different temporal step sizes over the spatial grid so as to efficiently capture large gradients (e.g., in moving fronts). A PhD proposal was the top-ranked proposal within the NWO general mathematics program. For this, Hundsdorfer received the Peterich prize in 2003. The research on this topic has started in 2004 and focuses on theoretical questions regarding consistency, stability and convergence.

Future directions. In the near future, research will focus mainly on a deeper understanding of spark formation in a close cooperation of modeling, analysis, large computations and controlled experiments. (Ebert also participates in planning the experiments at TUE.) The growth of a branched pattern of ionized channels with its multiple scales offers many challenges for the respective fundamental methods and opens up a wide field of applications in fundamental gas discharge physics, industrial applications of high power electro-engineering, and in geophysical lightning-related phenomena, in particular, in the recently discovered "upwards lightning" above thunderclouds.

The propagation of single discharge channels can be understood in terms of a PDE approximation, traveling ionization waves, and a subsequent moving boundary approximation. The three distinct length scales already of a single channel require adaptive grid refinement for computations of long channels. While computations can be validated on analytical results such as the ionization front velocity, the computations in turn inspire new model reductions where the complete channel head and the channel body are understood as coherent structures. If an appropriate characterization of these structures can be found (we do have working hypotheses), they form the building blocks of a large scale reduced model. Such a model is required to describe the breakup of a large discharge into many channels – brute force numerics starting from the microscopic description is out of the question here, but comes into play again after the model reduction. On small length scales, on the other hand, the continuous PDE approximation breaks down in the leading edge of the ionization front at the moment of channel splitting. This process has to be modeled in a hybrid way, i.e., in continuum PDE approximation in a large part of space and with a Monte Carlo process in a small spatial region. Again, numerical research will be accompanied by analytical investigations.

Along with the application-oriented numerical research, fundamental properties of numerical discretization methods for partial differential equations will continue to

be investigated. The emphasis will be on splitting methods and combined implicit-explicit methods for time-dependent equations, since the solution of such evolution equations in large-scale computations is still extremely demanding in terms of computing times and memory requirements.

Knowledge transfer. MAS3 participates in knowledge transfer in a similar way as MAS1, for details see the sections on Context and Scientific reputation.

Particular emphasis is presently put on a very broad cooperation on the subject of spark formation that combines basic research on modeling and analysis (Ebert), numerical analysis (Hundsdorfer) and controlled experiments (Briels, Van Veldhuizen, and Kroesen at the physics department of TUE). The newly developed understanding is shared with researchers in applied high power electro-engineering and in lightning related geophysical discharges. Ebert also replies to the substantial interest of the general public in lightning related phenomena through talks, articles and interviews.

5.3.3 Overview of the results

See Table 5.11 on page 128 for a numerical overview. A list of all publications can be found in the MAS3 sections of *CWI Overview Research Activities 1999–2003* (CD-ROM).

Selection of major publications

1 U. EBERT, W. VAN SAARLOOS (2000). Front propagation into unstable states: universal algebraic convergence towards uniformly translating pulled fronts. *Physica D* **146**, 1–99. [A closely related article appeared in *Eur. J. Appl. Math.* **13**, 53–66 (2002).]

2 U. EBERT, M. ARRAYÁS, N. TEMME, B. SOMMEIJER, J. HUISMAN (2001). Critical conditions for phytoplankton blooms. *Bull. Math. Biol.* **63**, 1095–1124.

3 W. HUNDSDORFER (2001). Partially implicit BDF2 blends for convection dominated flows. *SIAM J. Numer. Anal.* **38**, 1763–1783.

4 M. ARRAYÁS, U. EBERT, W. HUNDSDORFER (2002). Spontaneous branching of anode-directed streamers between planar electrodes. *Physical Review Letters* **88**, 174502-1–174502-4.

5 L. SCHÄFER, U. EBERT, A. BAUMGÄRTNER (2002). The coherent scattering function in the reptation model: Analysis beyond asymptotic limits. *Phys. Rev. E* **65**, 061505-1-061505-30.

6 W. HUNDSDORFER, J.G. VERWER (2003). *Numerical solution of time-dependent advection-diffusion-reaction equations*. Springer series in computational mathematics **33**, Springer-Verlag.

7 W. HUNDSDORFER, S.J. RUUTH, R.J. SPITERI (2003). Monotonicity-preserving linear multistep methods. *SIAM J. Numer. Anal.* **41**, 605–623.

8 M. ARRAYÁS, U. EBERT (2004). Stability of negative ionization fronts: regularization by electric screening? *Phys. Rev. E* **69**, 036214-1-036214-10.

9 B. MEULENBROEK, A. ROCCO, U. EBERT (2004). Streamer branching rationalized by conformal mapping techniques. *Physical Review E* **69**, 067402-1–067402-4.

PhD theses

- D. Šijačić (Thesis advisor: U.M. Ebert, Co-advisor: W.H. Hundsdorfer, University: TUE, Date: December 2, 2004, Title: *Spatio-temporal Pattern Formation in a Semiconductor-gas-discharge System*)

Table 5.13. Some major externally funded projects of MAS3

Acronym	Full name	Dates		k€	Source
STREAMERS	Electric fracture: growth and branching of ionized channels	2005	2009	180	STW NWO
MRPDE	Multirate methods for partial differential equations	2/2002	1/2008	160	NWO
NUMLED	Numerical methods for leading edge dominated dynamics	11/2001	10/2005	160	FOM NWO

5.3.4 Context

In September 1998, Ebert moved from a postdoc position at the physics department of UL to a position as researcher in theme MAS1 at CWI. This move was made possible through a personal two-year grant (till August 2000) of NWO's interdisciplinary priority program on "Non-linear Systems". Ebert's research soon found further funding through the Open Competition 1999 of the physics funding agency FOM and through the EU-TMR-network "Patterns, Noise and Chaos".

Using the opportunities of collaboration with CWI colleagues from numerical analysis within MAS1 and, in particular, with W. Hundsdorfer, a joint project on analysis and simulations of ionization fronts started that found funding through the FOM/-NWO-program on "Computational Science" in 2001.

In 2002, Ebert was appointed part-time professor of physics at TUE; and Hundsdorfer and Ebert split off the theme MAS1 and formed the staff for the new pilot theme MAS3 that meanwhile has become a full theme.

In 2003, Hundsdorfer got funding in NWO's Open Competition Mathematics for a project on adaptive time stepping in numerical PDE analysis. He continues his fundamental research in numerical mathematics and at the same time supervises the applied numerical work within the theme. MAS3 is also participating in the numerical BRICKS project funded by BSIK (2004–2009) with a project on hybrid computations for ionization fronts.

Coordinating the internationally unique experimental possibilities at TUE with the analytical and numerical studies of ionization fronts and spark formation at CWI, in 2004 Ebert was successful in getting a Dutch-Russian (NWO-RFBR) joint project and a large STW project (STW supports technologically relevant research). She also participates in the national mathematical cluster proposal "Non-linear Dynamics of Natural Systems" (see MAS1).

5.3.5 Scientific reputation

Awards

- The publication *Spontaneous branching of anode-directed streamers* (see page 129) found broad resonance in the international media, including Nature. The paper gives the first quantitative prediction for the spontaneous splitting of a discharge channel as one encounters in sparks and lightning.
- In 2004 Ebert received FOM's Minerva Prize for this publication and related work. The Minerva Prize is awarded bi-annually for the best publication of a woman on a subject in physics.
- In 2003 Hundsdorfer received the Peterich Prize for the best proposal in NWO's Open Competition Mathematics.

Memberships of committees and other professional activities

For a more extensive survey, please see the MAS3 section of the *CWI Overview Research Activities 1999–2003* (CD-ROM).

U.M. Ebert	full professor at TUE, member of two steering committees and several PhD committees, coordinator of a collaboration project, (co-)organizer of two upcoming conferences
W.H. Hundsdorfer	lecturer at UL, member of several PhD committees, organizer of CWI's scientific meetings with S.M. Bohte

Chapter 6

Research cluster INS – Information Systems

General

Cluster leader

Prof.dr. M.L. Kersten (1999–present)

Strategy and policy

The research activities in this cluster are focused on various dimensions of information systems, spanning from real-world inspired applications to theoretical studies on new computing paradigms. The scientific approach taken lies in the core of computer science, where theory development based on mathematics/physics is matched with empirical research validated using mature experimentation platforms. In addition, transfer of knowledge to the community at large has been a major guidance for project initiations.

Table 6.1. Global staff survey of INS0–INS4 (*prognosis)

INS		1999	2000	2001	2002	2003	2004	2005*
INS0	CWI research staff		2.5	5.0	5.2	6.2	2.9	3.4
	Total research staff		*2.5*	*5.0*	*5.2*	*6.2*	*2.9*	*3.4*
INS1	CWI research staff	10.8	13.0	10.2	11.5	12.8	11.9	13.9
	Total research staff	*12.3*	*14.1*	*11.7*	*12.1*	*13.5*	*13.5*	*14.1*
INS2	CWI research staff	5.8	8.0	7.8	7.6	9.9	8.7	8.0
	Total research staff	*5.8*	*8.1*	*10.0*	*7.8*	*10.2*	*9.6*	*8.0*
INS3	CWI research staff	2.5	3.0	3.8	3.8	4.8	6.6	8.8
	Total research staff	*2.5*	*3.0*	*4.0*	*4.0*	*4.9*	*6.7*	*8.9*
INS4	CWI research staff	4.4	2.9	5.2	7.8	7.4	9.4	10.1
	Total research staff	*10.2*	*9.6*	*8.8*	*11.0*	*9.6*	*11.3*	*11.1*

Themes

- **INS1:** *Database Architectures and Information Access.*
- **INS2:** *Multimedia and Human/Computer Interaction.*
- **INS3:** *Visualization and 3D Interfaces.*
- **INS4:** *Quantum Computing and Advanced Systems Research.*

Developments

In line with the recommendations of the previous evaluation committee the research theme on INS3 on Interactive Information Engineering has been phased out. Its leader P. ten Hagen started a CWI spin-off company, Epictoid. The facial animations project (Ruttkay, Noot) was positioned in INS2, with the explicit task to capitalize the research effort and to make it available to Epictoid. This research line ended in Februari 2004 with Ruttkay leaving the institute.

The cluster projects Applied Logic (van Eijck) and Interactive Information Engineering (Hazewinkel), both part of INS0, were terminated. In January 2004, Van Eijck joined SEN1 and Hazewinkel joined PNA. INS0 also contains our W3C activities.

In 2002 the CWI spin-off Oratrix was terminated and the former CWI employees joined the department to start a research theme on Multimedia Delivery Infrastructures. A reorientation on the position of this research line resulted in the pilot theme SEN5.

Scientific challenges for INS

The following challenges are currently playing a role at CWI in discussions on future research projects.

Data management, exploration, and knowledge elicitation. In many scientific fields ever larger data sets are collected, interrelated, and annotated for the purpose of digital archiving and scientific discovery. Exploring this wealth of information requires tools and techniques going far beyond what is available today. For example, living cell initiatives produce data sets to be looked at with a 3D digital microscope, which is as important to the biology researcher today as the first microscope developed in 1590 by the Dutch lens grinders Hans and Zacharias Janssen. The discoveries made in this way are stored on the semantic web using a domain-specific ontology and disseminated through personalized summaries. A sample of the key challenges in the coming period are the following:

Peta-byte datamanagement. The next generation DBMS will be primarily based on collaboration of autonomous, self-organizing sources. In such a setting, data management and query execution is a best-effort approach, which provides end users (which may be applications) with a handle to interrupt or steer the process.

Data lineage. It should be easy to *drill down* from a scientific report to the underlying experimental data, and to replay derivations upon need. This calls for innovation in the way we keep track of time, locality, and authorship of the information and the (semi-)automated steps taken to enrich it.

Multimedia information retrieval. Searching information is shifting from simple keyword lookup towards a multi-step human-computer interaction to retrieve information using partial knowledge and incomplete requests using probabilistic reasoning.

Knowledge elicitation. In a cultural heritage setting, knowledge management forms the basis to interrelate knowledge from different sources while retaining their authenticity. The key challenge in this field is to develop techniques and tools to aid goal-driven personalized elicitation.

Augmented and mixed world realities. A grand challenge of scientific visualization is the analysis of multi-level scale spatial and temporal data in which the levels vary over many orders of magnitude. Augmented and mixed reality environments are envisioned to allow a more integrated presentation of the underlying data.

Computing paradigm shifts. The Von Neumann computation model has proved successful over the last 60 years. However, its limitations are all too apparent and they challenge both engineers and computer scientists to explore new areas. Such explorations cover the spectrum of fundamental research in the area of learning and complexity, but extend into the realms of physics and biology.

Quantum computing is one of the exciting future directions for this field. Since nature is quantum mechanical, it seems natural to incorporate such features into our computing model. The result permits algorithms that are orders of magnitude faster than the classical Von Neumann algorithms.

An unexpected direction that quantum computing has taken in the last couple of years is the following. Purely *classical* theorems can be proved using the quantum computing paradigm. For example, an exponential lower bound can be derived on the size of certain error correcting codes, called locally decodable codes. No classical proof of this lower bound is known to date. We expect that this use of quantum computing will yield unexpected results. These types of result have the added bonus that they do not need a physical, working quantum computer: the quantum computer functions as a formal tool to prove mathematical statements.

6.1 Theme INS1 – Database Architectures and Information Access

Research in	Database management systems architectures and multimedia information retrieval technology
Started in	July 1985 (Database architectures) January 1993–2003 (Data mining and knowledge discovery) December 2004 (Database architectures and information access)
Theme leader	Prof.dr. A.P.J.M. Siebes (1999–2000) Prof.dr. M.L. Kersten (2000–present)
CR classification	H.2 [Database management], H.3 [Information storage and retrieval]

6.1.1 Senior researchers

Prof.dr. A.P.J.M. Siebes (until July 2000), Prof.dr. M.L. Kersten, Dr. N.J. Nes (as of December 2000), Dr.ir. A.P. de Vries (as of December 1999), Dr. P.A. Boncz (as of May 2002), Dr. S. Manegold (as of December 2002), Dr. Z.R. Struzik (until July 2003).

Table 6.2. Staff of INS1, 1999–2005 (in FTE/year, *prognosis)

INS1		1999	2000	2001	2002	2003	2004	2005*
Leader:	*A.P.J.M. Siebes*	*0.20*	*0.13*					
	M.L. Kersten		*0.05*	*0.20*	*0.2*	*0.2*	*0.2*	*0.2*
Researchers:	*P.A. Boncz*				*1.0*	*1.0*	*1.0*	*1.0*
	M.L. Kersten	*0.40*	*0.40*	*0.20*	*0.2*	*0.2*	*0.2*	*0.2*
	S. Manegold					*1.0*	*1.0*	*1.0*
	N. Nes		*0.08*	*1.00*	*1.0*	*1.0*	*1.0*	*1.0*
	A.P.J.M. Siebes	*0.80*	*0.40*					
	A.P. de Vries						*1.0*	*1.0*
Programmers:	*K. van 't Hoff*	*0.25*						
	K.S. Mullender				*1.0*	*1.0*	*1.0*	*1.0*
	W.M. Lioen		*1.00*	*0.92*				
Total tenured staff		**1.7**	**2.1**	**2.3**	**3.4**	**4.4**	**5.4**	**5.4**
Non-tenured staff		2.3	4.3	2.9	2.0	2.6	0.0	1.5
CWI PhD students		6.8	6.6	5.0	6.1	5.8	6.5	7.0
Total research staff CWI payroll		**10.8**	**13.0**	**10.2**	**11.5**	**12.8**	**11.9**	**13.9**
Seconded PhD students		*1.0*	*0.2*	*0.5*				
Other seconded staff		*0.5*	*0.9*	*1.0*	*0.6*	*0.7*	*1.6*	*0.2*
Total hosted research staff		***12.3***	***14.1***	***11.7***	***12.1***	***13.5***	***13.5***	***14.1***

6.1.2 Research orientation, highlights, and future directions

Mission and research area. The scientific mission of the group is to simplify and improve data management and information access in high-demanding application domains. This is realized through the combined expertise in the area of database kernel architectures, multimedia information retrieval, and data-mining algorithms. The scientific approach is based on concurrent progress in the development of models, algorithms, techniques, and their evaluation against mature experimentation software

Table 6.3. Scientific output of INS1

Output class		1999	2000	2001	2002	2003	2004	Total
Academic	refereed journals and proceedings	7	26	16	15	7	11	82
	other journals and proceedings	4	2	0	1	3	1	11
	book chapters	4	0	0	0	3	0	7
	Total academic	**15**	**28**	**16**	**16**	**13**	**12**	**100**
Monographs		0	0	0	0	0	0	0
PhD dissertations		1	3	0	3	1	1	9
Professional pub./products		0	9	5	1	8	4	27

Table 6.4. Funding percentages of INS1

INS1	1999	2000	2001	2002	2003	2004	Average
Direct NWO	60.9%	51.8%	50.5%	58.8%	92.9%	63.8%	63.2%
Other research funds	38.9%	47.0%	45.6%	41.0%	6.4%	36.2%	35.8%
Grants/contracts	0.2%	0.8%	3.9%	0.0%	0.7%	0.0%	0.9%
Other	0.0%	0.4%	0.0%	0.2%	0.0%	0.0%	0.1%
Total	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**

platforms. These platforms are made available to a wider public as open-source initiatives.

In the reporting period the emphasis has been shifted towards multimedia information retrieval with a particular emphasis on content-based image retrieval using probabilistic models. Emerging areas are the development of novel database architectures for information management in sensor-based networks, such as they appear in the Ambient Intelligent vision pursued by Philips, and database solutions that address the problem of "enterprise search", i.e., information seeking in intranets of large coorporations. These steps are fully in line with the challenges identified for the field at large in the Lowell report on database research, 2003.

Research highlights. The group has a long-standing and leading position in the area of developing innovative database technology. It has pioneered development of highly parallel database engines (1986–1992), main-memory database technology for decision support applications (starting 1993), and started a research line on database technology for multimedia (2000) and ambient applications (2003).

Although the focus on simplified, main-memory driven database architectures has already been on our research agenda since the mid-1980s, it has only been since the late-1990s that it is also recognized as a key area for DBMS research in the Asilomar report on database research. The MonetDB system and its scientific papers in the leading conferences and journals are proof of our frontier position. They demonstrate that an approach based on a fully decomposed storage scheme can scale to the requirements of

very large databases, even if they do not fit the primary memory of the machine it runs on. Circumstantial proof is given by our former PhD students, who are working on the DBMS core products at Microsoft, IBM, and Oracle and deployment of the technology in the financial industry, such as ING, ABN AMRO, and OHRA.

During the reporting period the activities on multimedia retrieval has significantly increased. Under the direction of De Vries, our group developed novel techniques for multimedia retrieval based on Gaussian mixture models capturing the content of queries and collection items. Promising results have been obtained this way in, e.g., the TRECVID 2002–2004 search tasks. Furthermore, steps have been taken to transfer the multimedia query processing from a predominantly Matlab environment towards a database kernel. A novel relational array language front-end for MonetDB has been developed to ease this transition.

After a decade of research on database support for data-mining algorithms, this line was phased out with the departure of Siebes. The last postdoc (Struzik) took up a job at Tokyo University to continue his research on wavelet theory in economics. At the end of 2003 the successful spin-off company DataDistilleries was sold to SPSS, but remains an active partner in our projects. The challenges to better support this application domain with database technology, however, have not been reduced. Instead, the data-mining part is taken up by our partners, such as UU (Siebes) and University of Massachusetts Amherst (Schapira), both of which exploit our technology for novel solutions for this field.

Future directions. The research activities for the coming period are natural continuations of the current activities, but with an emphasis on cross-fertilization between application requirements and hardware/software opportunities for effective and efficient information management.

The research on multimedia information retrieval is part of a large national project running until 2008. The key scientific challenges are to develop sound probabilistic methods to improve querying of multimedia objects and XML documents in large databases. The information retrieval focus is complemented with and supported by development of an array-query language, called RAM, with accompanying optimizer and kernel support. The target experimentation platform is the MonetDB product family.

Research on database architectures itself is driven by requirements of diverse application areas. In the domain of Ambient applications we seek solutions for ad-hoc collaboration of information sources, efficient (storage/processing) resource management, and embedded database management systems. The term Organic Databases has been coined and promoted worldwide as our big challenge for this database research, i.e., to develop a database system which can be embedded in a wide collection of hardware appliances and provides an autonomous, self-descriptive, self-organizing, self-repairable, self-aware stable data store-recall functionality. In the area of scientific databases, we seek cooperation with astronomy to better understand, analyse and support peta-byte databases. It is an area not well supported by commercial systems and

poses major scientific and technical challenges at the heart of the relational query processing scheme.

Knowledge transfer. The group has direct links to educational institutes. Kersten holds a part-time professorship chair at UvA, and De Vries holds a part-time associate professorship chair at TUD. Furthermore, our seniors are involved in postdoctoral education in the research school SIKS. The group hosted 16 master students, including students from Poland, Spain, India, and Germany.

Knowledge transfer to industry has long been an integral part of our activities. Boncz has provided consultancy and development services to SPSS/DataDistilleries. Aside from this successful spin-off, we are currently involved in a national program geared to cross-fertilization between research institute and industry. In this context we have close cooperations with, e.g., Philips to develop database technology, and the Netherlands Institute for Sound and Vision (Beeld en Geluid) and NOB to develop information retrieval technology. For Deloitte and Touche we provided consultancy services to develop the European-wide Schengen Information System.

Dissemination of all our scientific reports is supported by our webserver, which extends the opportunities of the CWI repository to monitor take-up. For example, the recent PhD thesis reports were downloaded over 6,000 times in this period (Waas 354, Nes 1,802, Boncz 1,173, Schmidt 848, Manegold 2,179, Windhouwer 318). In the institute-wide monitor of downloads of scientific reports over the period 1996–2001, 50% of the top 25 reports were produced in INS1. The #1 report on data-mining reached an audience of over 16,000 people.

6.1.3 Overview of the results

See Table 6.3 on page 139 for a numerical overview. A list of all publications can be found in the INS1 sections of *CWI Overview Research Activities 1999–2003* (CD-ROM).

Selection of major publications

1 P.A. BONCZ, M.L. KERSTEN (1999). MIL primitives for querying a fragmented world. *The VLDB Journal* **8** (2), 101–119.

2 P. CH. IVANOV, M. G. ROSENBLUM, L. A. NUNES AMARAL, Z. R. STRUZIK, S. HAVLIN, A. L. GOLDBERGER, H. E. STANLEY (1999). Multifractality in human heartbeat dynamics. *Nature* **399**, 461–465.

3 S. MANEGOLD, P.A. BONCZ, M.L. KERSTEN (2000). Optimizing database architecture for the new bottleneck: memory access. *The VLDB Journal***9** (3), 231–246. (Best paper award)

4 A.P. DE VRIES (2001). Content independence in multimedia databases. *Journal of the American Society for Information Science and Technology* **52**, 954-960.

5 S. MANEGOLD, P.A. BONCZ, M.L. KERSTEN (2002). Optimizing main-memory join on modern hardware. *IEEE Transactions on Knowledge and Data Eng.* **14** (4), 709–730.

6 Z.R. STRUZIK, A.P.J.M. SIEBES (2002). Wavelet transform based multifractal formalism in outlier detection and localisation for financial time series. *Physica A: Statistical Mechanics and its Applications* **309** (3-4), 388–402.

7 A.P. DE VRIES, N. MAMOULIS, N.J. NES, M.L. KERSTEN (2002). Efficient k-NN search on vertically decomposed data. *Proceedings of the ACM SIGMOD International Conference on Management of Data*, Madison, WI, USA, 322–333.

8 T. WESTERVELD, A.P. DE VRIES, A. VAN BALLEGOOIJ, F.M.G. DE JONG, D. HIEMSTRA (2003). A probabilistic multimedia retrieval model and its evaluation. *EURASIP Journal on Applied Signal Processing* **2003** (2), 186–198. Special issue on Unstructured Information Management from Multimedia Data Sources.

9 S. MANEGOLD, P.A. BONCZ, N.J. NES, M.L. KERSTEN (2004). Cache-conscious radix-decluster projections. *Proceedings of the International Conference on Very Large Data Bases (VLDB)*, Toronto, August 2004.

10 T. WESTERVELD, A.P. DE VRIES (2004). Multimedia retrieval using multiple examples. *CIVR 2004*, 344–352. (Best paper award).

PhD theses

- F . Waas (Thesis advisor: M.L. Kersten, University: UvA, Date: November 3, 2000, Title: *Principles of Probabilistic Query Optimization*)
- J. Karlsson (Thesis advisor: M.L. Kersten, University: UvA, Date: December 14, 2000, Title: *Scalable Distributed Data Structures for Database Management*)
- N.J. Nes (Thesis advisor: M.L. Kersten, University: UvA, Date: December 14, 2000, Title: *Image Database Management System Design Considerations, Algorithms and Architecture*)
- P.A. Boncz (Thesis advisor: M.L. Kersten, University: UvA, Date: May 31, 2002, Title: *Monet: A Next-Generation DBMS Kernel For Query-Intensive Applications*)
- A.R. Schmidt (Thesis advisor: M.L. Kersten, University: UvA, Date: November 7, 2002, Title: *Processing XML in Database Systems*)
- S. Manegold (Thesis advisor: M.L. Kersten, University: UvA, Date: December 17, 2002, Title: *Understanding, Modeling, and Improving Main-Memory Database Performance*)
- M.A. Windhouwer (Thesis advisor: M.L. Kersten, University: UvA, Date: November 6, 2003, Title: *Feature Grammar Systems - Incremental Maintenance of Indexes to Digital Media Warehouses*)
- T.H.W. Westerveld (Thesis advisor: F.M.G. de Jong Co-advisor: A.P. de Vries University: UT Date: November 25, 2004, Title: *Using Generative Probabilistic Models for Multimedia Retrieval*)

6.1.4 Software products

The empirical research lines call for a sound and well-maintained experimentation platform. Substantial resources are dedicated to develop and maintain them. Moreover, we are convinced that research at large benefits if this investment is not isolated to preparing for the next scientific paper alone, but packaged in such a way that other researchers can also use it.

MonetDB (http://monetdb.cwi.nl) is an open source database system designed to provide high performance on complex queries against large , e.g., combining tables

with hundreds of columns and multi-million rows. As such, MonetDB is able to be used in application areas that performance-wise are no-go areas for using traditional database technology in a real-time manner. MonetDB has been successfully applied in high- performance applications for data-mining, OLAP, GIS, XML Query, text and multimedia retrieval.

Xmark (http://www.xml-benchmark.org). A sidetrack of our research on supporting XML in a database kernel brought the Xmark benchmark, a functional and performance benchmark for Xquery. It is supported by a website and has become the de facto standard worldwide to assess the implementation of XML-enriched database systems and native XML implementations.

Acoi (http://monetdb.cwi.nl/acoi). The Acoi database is a Dutch national experimentation platform for multimedia storage, indexing and retrieval. Its novel plug-in architecture provides the means to subsequently index these multimedia objects using feature extraction algorithms published in the literature or developed by the partners in the various affiliated research projects.

The Calibrator (http://monetdb.cwi.nl/Calibrator) is a small C program that is supposed to analyze a computer's (cache-)memory system and extract the following parameters: number of cache levels, for each cache level its size, line size, and access/miss latency, main memory access latency, number of TLB levels, for each TLB level, its capacity (i.e., number of entries), the page-size used, and the TLB miss latency.

Table 6.5. Some major externally funded projects of INS1

Acronym	Full name	Dates		k€	Source
DMW	Digital media warehouse systems	6/1998	5/2002	1,000	TI
MIA	Multimedia information analysis	5/1999	4/2003	4,000	ICES/KIS
MultimediaN	Multimedia Netherlands	1/2004	1/2008	3,950	BSIK

6.1.5 Context

The research conducted in INS1 mostly takes place in the context of externally (nationally) funded projects, mostly as (co-)leader, e.g., Digital Media Warehouses project (Telematica Instituut), WTCW/Multimedia Information Analysis (ICES-KIS), MultimediaN (BSIK), Bricks Organic Databases (BSIK), Bricks Petabyte Datamining (BSIK), Waterland (STW) and Cirquid (NWO). These activities are all long term engagements geared towards joint research and development of software platforms.

In addition, researchers of INS1 have collaborated with researchers from Stanford (USA), Microsoft (Seattle, USA), INRIA (France), University of Hong Kong, Aarhus University (Denmark), University of Massachusetts (Amherst, USA), University of Valencia (Spain), Polytechnic University of Barcelona (Spain), Carnegie Mellon (USA), University of Maryland (USA), University Konstanz (Germany), BEA Systems (San Jose, USA).

Strong software co-development activities are taking place with researchers from University of Konstanz on the Pathfinder project, aimed at providing Xquery support on top of MonetDB, and researchers of the University of Massachusetts, Amherst on their relational data-mining product called Proximity.

6.1.6 Scientific reputation

Awards

The group received two best paper awards mentioned above.

Memberships of committees and other professional activities

For a more extensive survey, please see the INS1 section of the *CWI Overview Research Activities 1999–2003* (CD-ROM).

A.P.J.M. Siebes	full professor at TUE (until August 2000), then UU, member of two program committees, editor of two journals, member of two boards, advisory groups
M.L. Kersten	full professor at UvA, member of about 37 program committees, editor of two journals, reviewer for about seven journals, member of eight boards, steering committees, working groups, reviewer for two project funding organizations
A.P. de Vries	lecturer at TUD, member of eight program committees, organizer of three workshops, co-chair of one international conference (2007), reviewer of one EU project and one project funding organization
P.A. Boncz	organizer of three workshops, member of seven program committees, reviewer for four journals
S. Manegold	member of one program committee, reviewer of three conferences, reviewer for four journals
Z.R. Struzik	member of three program committees, editor of one journal

6.2 Theme INS2 – Multimedia and Human/Computer Interaction

Research in	Hypermedia presentation generation, Semantic Web technologies for media annotation
Started in	January 1997
Theme leader	Prof.dr. L. Hardman (1999–present)
CR classification	H.5.1 [Information systems]: Multimedia information systems I.7.2 [Computing methodologies]: Document and text processing – *Document preparation* H.5.4 [Information systems]: Information interfaces and presentation–*Hypertext/hypermedia* I.2.4 [Computing methodologies]: Artificial intelligence – *Knowledge representation formalisms and methods*

Table 6.6. Staff of INS2, 1999–2005 (in FTE/year, *prognosis)

INS2		1999	2000	2001	2002	2003	2004	2005*
Leader:	*L. Hardman*	*0.20*	*0.2*	*0.2*	*0.2*	*0.2*	*0.2*	*0.2*
Researchers:	*D.C.A. Bulterman*	*0.50*						
	L. Hardman	*0.80*	*0.8*	*0.6*	*0.6*	*0.6*	*0.6*	*0.6*
	L.G.L.T. Meertens	*0.23*						
	J.R. van Ossenbruggen				*1.0*	*1.0*	*1.0*	*1.0*
	S. Pemberton	*1.00*	*1.0*					
	L.W. Rutledge				*1.0*	*1.0*	*1.0*	*1.0*
Programmers:	*H. Noot*			*1.0*	*1.0*	*1.0*	*0.5*	
	A.J. Jansen	*0.50*						
	K.S. Mullender	*0.50*						
Total tenured staff		**3.7**	**2.0**	**1.8**	**3.8**	**3.8**	**3.3**	**2.8**
Non-tenured staff		1.0	2.9	3.3	2.0	2.1	1.4	1.2
CWI PhD students		1.1	3.1	2.7	1.8	4.0	4.0	4.0
Total research staff CWI payroll		**5.8**	**8.0**	**7.8**	**7.6**	**9.9**	**8.7**	**8.0**
Seconded PhD students								
Other seconded staff			*0.1*	*2.2*	*0.2*	*0.3*	*0.9*	
Total hosted research staff		***5.8***	***8.1***	***10.0***	***7.8***	***10.2***	***9.6***	***8.0***

6.2.1 Senior researchers

Prof.dr. L. Hardman, Dr. F.-M. Nack, Dr. J.R. van Ossenbruggen, Dr. L.W. Rutledge.

6.2.2 Research orientation, highlights and future directions

Mission and research area This theme has always tried to facilitate the hypermedia authoring experience, as well as the hypermedia end-user experience. The theme's long expertise in hypermedia and web technology has over the recent years extended to the Semantic Web. Our long-term interest in authoring has likewise extended into the human-guided, semi-automatic generation of web-based hypermedia from media repositories encoded with Semantic Web technology. Explorations into hypermedia discourse have guided our development of this process.

Table 6.7. Scientific output of INS2

Output class		1999	2000	2001	2002	2003	2004	Total
Academic	refereed journals and proceedings	7	8	12	11	14	1	53
	other journals and proceedings	3	3	3	5	2	5	21
	book chapters	0	1	0	0	1	1	3
	Total academic	**10**	**12**	**15**	**16**	**17**	**7**	**77**
Monographs		0	0	0	0	0	0	0
PhD dissertations		0	0	1	0	0	0	1
Professional pub./products		8	8	4	11	6	1	38

Table 6.8. Funding percentages of INS2

INS2	1999	2000	2001	2002	2003	2004	Average
Direct NWO	69.3%	62.7%	75.8%	69.1%	61.9%	65.0%	67.3%
Other research funds	10.2%	29.1%	17.0%	24.7%	30.6%	30.0%	23.6%
Grants/contracts	20.5%	8.2%	0.0%	0.0%	0.2%	0.0%	4.8%
Other	0.0%	0.0%	7.2%	6.2%	7.3%	5.0%	4.3%
Total	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**

The general architecture we assume starts with repositories using Semantic Web technology, for which we explore best practices for application to hypermedia generation. This leads to our investigations on how discourse applies to, and emerges from, semantics, both across all domains and within specific domains and presentation genres. Finally, we develop means of presenting these semantics and the discourse structure around them to the final user. This includes investigating media types, graphic design and user models.

Highlights During the past five years, INS2 has standardized its multimedia authoring research results, acquired a professorship, formed firm international bonds through student exchanges and developed a suite of programs for its next generation of research in Semantic Web media archives and interfaces to them. The theme's primary knowledge transfer is SMIL 2.0, released in August 2001 as the W3C's Recommendation for multimedia on the WWW. INS2 was a founding member of SMIL's working group, and a full member through the whole process. Many of the group's research results in the 1990s now have a place in this standard. A group member is also co-author of a book on SMIL, published by Springer. Our knowledge transfer was also further extended by the theme leader becoming a professor at TUE.

The exchange of researchers has formed tight bonds with the University of California at Berkeley and the University of Queensland in Australia. This includes INS2 arranging one postdoctoral researcher and three doctoral student visits, lasting several months each, to these laboratories. This resulted in the theme's solid connection with,

understanding of and participation in international research on media archiving and presentation generation from archives.

As another part of this transition from authoring multimedia to its archiving and automated re-composition, INS2 has developed a suite of demonstrators called Cuypers. The Cuypers demonstrators use the ARIA digital repository and metadata of the Rijskmuseum Amsterdam to generate adaptive hypermedia presentations. They generate presentations based on user topic requests. They also explore the adaptivity of generated presentations as well as extended authoring paradigms for them.

Redirection of research strategies Five years ago, this theme had just been through a near simultaneous merge and spin-off, signifying a new start for the group. The release of the W3C Recommendation SMIL represented the border between these two periods for the theme, with the group's earlier research captured in this standard and their authorship in a book about it. At that time, INS2 also began the next step in its evolution. Instead of direct human creation of multimedia presentations, the theme began focusing on their automated creation. This moved the human creative process a layer of abstraction further from the details of the timing and layout of the presentation. Specifically, we began exploring the use of Semantic Web technology to represent the underlying information and to describe the media components that are input to the process of generating interactive multimedia presentations. Over the past five years, the group's international reputation has evolved from being international experts on SMIL and multimedia presentations to being experts on the semantic annotation of media and on hypermedia generation.

This period also marked a growth in personnel. We started with the core of three senior staff. Now the group includes an additional postdoc researcher and three PhD students. Furthermore, two other PhD students pursue their dissertations under this theme's leader. We have also hosted the developmental work of six other graduate degree students. This flow-through of many people from diverse talents and backgrounds has added depth and breadth to our research and publications. In this period, the theme has also produced a full professor – the theme leader now has a part-time professorship at TUE.

Finally, as suggested in the previous evaluation, INS2 has tightened its bond with INS1 over the past five years. The personal and social bond is certainly tighter, enhanced in part by the shared location of the INS cluster in the temporary building and the pleasant atmosphere arranged for it. This increased social interaction also carries much professional interchange. Furthermore, authors from both groups have been co-authors on a publication. The two themes have also cooperated in several projects, and will continue doing so in the upcoming MultimediaN projects.

Future directions The topic focus of the group will remain generation of hypermedia presentations from annotated media repositories. Participation and publication in the three most related prestigious international conference series, World Wide Web (WWW), International Semantic Web Conference (ISWC), and ACM Multimedia, will be the main venues for presenting this research and building the theme's reputation.

These conferences will be the focus for upcoming publications. The addition of the newest conference, ISWC, represents our moving focus toward semantics. While conferences such as these are as important, or more so, than journals in this field and closely related fields in computer science, INS2 will nonetheless continue to target its usual journal venues. Specifically, the group will target the now emerging top journal in the field *ACM Transactions on Multimedia Computing, Communications and Applications (ACM TOMCCAP)*.

Cultural heritage has been the main area for examples in applying our research in recent years. This application area will become stronger in the coming years with shared project involvement with the Rijksmuseum Amsterdam and other cultural heritage institutes. The theme is becoming involved in MultimediaN and CATCH, two national prestigious programs in this area.

Currently, five of INS2's PhDs are in or approaching the second half of their thesis work. They should thus expect to publish papers on their thesis work in major venues, included those mentioned above. The coming several years should also be quite productive in other areas related to the final years of thesis work, such as giving presentations, maturing demonstrators and national and international exposure.

For national collaboration, INS2 will continue to expand its close relationship with INS1 as well as its relationships with TI and TUE. TI and CWI's Topia project resulted in the theme leader becoming supervisor of one of TI's PhD students. This project has also resulted in some publications and a demonstrator that continues to develop. Upcoming projects with TI along this topic are currently under development. The theme's professorship at TUE has led to collaboration with researchers at the university. This professorship will also provide contact with potential student project workers at CWI.

Extended student exchanges have resulted in shared publications as well as the invaluable exchange of insight and expertise. We will continue this successfull form of collaboration.

Table 6.9. Some major externally funded projects of INS2

Acronym	Full name	Dates		k€	Source
CHIME	Cultural heritage in an interactive multimedia environment	11/2002	10/2006	365	NWO
RTIPA	Real-time internet platform architectures	10/1999	12/2001	400	ITEA SENTER
I2RP	Intelligent information retrieval and presentation in public historical multimedia databases	1/2002	12/2005	230	NWO

6.2.3 Implementation of the 1999 recommendations

- Several staff appointments (J.R. van Ossenbruggen, L.W. Rutledge, among others) took place.

6.2.4 Overview of the results

See Table 6.7 on page 146 for a numerical overview. A list of all publications can be found in the INS2 sections of *CWI Overview Research Activities 1999–2003* (CD-ROM).

Selection of major publications

1 H.L. HARDMAN, J.R. VAN OSSENBRUGGEN, L.W. RUTLEDGE, K.S. MULLENDER, D.C.A. BULTERMAN (1999). Do you have the time? Composition and linking in time-based hypermedia. *Proceedings of the 10th ACM conference on Hypertext and Hypermedia*, Darmstadt, Germany, 189–196.

2 L.W. RUTLEDGE, J.R. VAN OSSENBRUGGEN, H.L. HARDMAN, D.C.A. BULTERMAN (1999). Anticipating SMIL 2.0: the developing cooperative infrastructure for multimedia on the web. *Proceedings of The Eighth International World Wide Web Conference (WWW8)*, Toronto, Canada, 343–352.

3 L.W. RUTLEDGE, J.R. VAN OSSENBRUGGEN, H.L. HARDMAN, D.C.A. BULTERMAN (1999). Mix'n'match: exchangeable modules of hypermedia style. *Proceedings of ACM Hypertext* **99**, 179–188.

4 L.W. RUTLEDGE, B. BAILEY, H.L. HARDMAN, J. GEURTS, J.R. VAN OSSENBRUGGEN (2000). Generating presentation constraints from rhetorical structure. *Proceedings of the 11th ACM conference on Hypertext and Hypermedia(HT00)*, San Antonio, USA, 19–28.

5 F.-M. NACK, W. PUTZ (2001). Designing annotation before it's needed. *Proceedings ACM Conference on Multimedia 2001 (MM01)*, Ottawa, Canada, 251–260.

6 J.R. VAN OSSENBRUGGEN, J.P.T.M. GEURTS, F. CORNELISSEN, L.W. RUTLEDGE, H.L. HARDMAN (2001). Towards second and third generation web-based multimedia. *The Tenth International World Wide Web Conference (WWW 10)*, Hong Kong, 479–48.

7 J.R. VAN OSSENBRUGGEN, J.P.T.M. GEURTS, H.L. HARDMAN, L.W. RUTLEDGE (2003). Towards a formatting vocabulary for time-based hypermedia. *The 12th International World Wide Web Conference (WWW 2003)*, Budapest, Hungary, 384–393.

8 L.W. RUTLEDGE, M. ALBERINK, R. BRUSSEE, S. POKRAEV, W. VAN DIETEN, M. VEENSTRA (2003). Finding the story – broader applicability of semantics and discourse for hypermedia generation. *Proceedings of the 14th ACM conference on Hypertext and Hypermedia (HT03)*, Nottingham, UK, 67–76.

9 J.P.T.M. GEURTS, S. BOCCONI, J.R. VAN OSSENBRUGGEN, H.L. HARDMAN (2003). Towards ontology-driven discourse: from semantic graphs to multimedia presentations. *Second International Semantic Web Conference (ISWC2003)*, Sanibel Island, Florida, USA, 597–612.

10 J.R. VAN OSSENBRUGGEN, F.-M. NACK, H.L. HARDMAN (2004). That obscure object of desire: multimedia metadata on the web (Part I). *IEEE Multimedia* **11** (4), 38–48.

Master theses. The MSc students J. Werner, J.P.T.M. Geurts, K. Schwarz, A.S.K. Manniesing, K. Czajka, O. Rosell Martinez, V. van Moppes were guided by INS2 members

in getting their MSc degree.

PhD theses

- J.R. van Ossenbruggen (Thesis advisor: J.C. van Vliet, University: VU, Date: April 10, 2001, Title: *Processing Structured Hypermedia: A Matter of Style*)

Software developed. INS2 developed the Cuypers research prototype system to experiment with the generation of web-based presentations as an interface to semi-structured multimedia databases. Cuypers differs from XSL-based transformations in that it explores a set of abstractions, both on the document and on the presentation level, that are geared toward interactive, time-based and media centric presentations, rather than presentations that are based on text-flow.

Cuypers has evolved to experiment with RDF-encoded knowledge from the Semantic Web. Specifically, the system has an interface to the Sesame RDF storage and querying engine. This demonstrator uses both the Rijksmuseum and Open Archive Initiative repositories for sample data.

TI and INS2 developed a demonstrator for the Topia project. This demonstrator generates timed multimedia presentations based on the Rijksmuseum repository. It combines the use of RDF-based semantic processing with efficient XSLT-based syntactic transformations.

6.2.5 Scientific reputation

Memberships of committees and other professional activities

For a more extensive survey, please see the INS2 section of the *CWI Overview Research Activities 1999–2003* (CD-ROM).

L. Hardman	full professor at TUE, guidance of seven PhD students and two MSc students, (co-)organizer of two conferences
F.-M. Nack	(co-)organizer of one conference, guidance of four MSc students
J.R. van Ossenbruggen	guidance of two MSc students
L.W. Rutledge	(co-)organizer of one conference

6.3 Theme INS3 – Visualization and 3D Interfaces

Research in	Scientific visualization, virtual environments
Started in	January 2001
Theme leader	Prof.dr.ir. R. van Liere (2001–present)
CR classification	I.3.6 [Computer graphics]: Methodology and techniques I.3.7 [Computer graphics]: Three-dimensional graphics and realism Virtual reality H.5.2 [Information interfaces and representation]: User interfaces evaluation/methodology, input devices and strategies

Until 2001, the research of this theme was carried out in the theme SEN1. For reasons of clarity, the entire evaluation period is covered in this section.

6.3.1 Senior researchers

Prof.dr.ir. R. van Liere, Dr.ir. W.C. de Leeuw.

Table 6.10. Staff of INS3, 1999–2005 (in FTE/year, *prognosis)

INS3		1999	2000	2001	2002	2003	2004	2005*
Leader:	*R. van Liere*			*0.2*	*0.2*	*0.2*	*0.2*	*0.2*
Researchers:	*W.C. de Leeuw*		*1.0*	*1.0*	*1.0*	*1.0*	*1.0*	*1.0*
	R. van Liere	*1.0*	*1.0*	*0.8*	*0.6*	*0.6*	*0.6*	*0.6*
Total tenured staff		**1.0**	**2.0**	**2.0**	**1.8**	**1.8**	**1.8**	**1.8**
Non-tenured staff		1.0	0.0	0.6	1.0	1.0	1.0	1.0
CWI PhD students		0.5	1.0	1.2	1.0	2.0	3.8	6.0
Total research staff CWI payroll		**2.5**	**3.0**	**3.8**	**3.8**	**4.8**	**6.6**	**8.8**
Seconded PhD students		*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
Other seconded staff		*0.0*	*0.0*	*0.2*	*0.2*	*0.1*	*0.1*	*0.1*
Total hosted research staff		***2.5***	***3.0***	***4.0***	***4.0***	***4.9***	***6.7***	***8.9***

Table 6.11. Scientific output of INS3

Output class		1999	2000	2001	2002	2003	2004	Total
Academic	refereed journals and proceedings	5	10	3	3	7	7	35
	other journals and proceedings	0	0	0	0	0	0	0
	book chapters	0	2	0	1	0	0	3
Total academic		**5**	**12**	**3**	**4**	**7**	**7**	**38**
Monographs		0	0	0	0	0	0	0
PhD dissertations		0	0	2	0	0	0	2
Professional pub./products		0	0	2	5	4	3	14

Table 6.12. Funding percentages of INS3

INS3	1999	2000	2001	2002	2003	2004	Average
Direct NWO			75.3%	76.4%	84.2%	65.0%	75.3%
Other research funds			20.9%	18.4%	15.8%	35.0%	22.5%
Grants/contracts			3.8%	0.0%	0.0%	0.0%	0.9%
Other			0.0%	5.2%	0.0%	0.0%	1.3%
Total			**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**

6.3.2 Research orientation, highlights, and future directions

Mission and research area. Research in visualization and 3D user interfaces has a multi-disciplinary character, intersecting various disciplines in computer science (in particular computer graphics and user interfaces) and mathematics (in particular numerical mathematics and statistics), and also has connections with research in perception and industrial design. The scientific mission of INS3 is to research those methodologies and techniques involved in designing and engineering interactive visualization systems. An important aspect is the application and evaluation of these systems in real world scientific visualization applications.

The research activities of INS3 are organized in two tracks:

Data visualization. The data visualization track has focused on projects in the application area of the Dutch *living cell* initiative. The research focus is on interactive analysis and visualization of time dependent data sets.

3D user interfaces. The 3D user interfaces track is concerned with applying virtual reality technology to scientific visualization in cost effective desktop virtual environments. The research focus is on the design and evaluation of two-handed 3D tangible interfaces.

Research highlights. The research of INS3 started in 1997 headed by Ten Hagen under the name Interactive Information Engineering. At the end of 2000, Ten Hagen retired from CWI and INS3 was restructured. A new pilot, headed by Van Liere with the name Visualization and 3D Interfaces, was initiated in 2001. After a period of two years the research pilot was promoted to a full-fledged theme.

INS3 highlights since 2002:

Personal Space Station (PSS). The 3D user interface track has put a substantial effort in the engineering of the PSS, a novel design of a desktop virtual reality environment. The PSS will be instrumental for future research in the evaluation of effective 3D interaction techniques.

Several affiliated universities and research institutes are using the PSS for their research and applications. These include TUE, UvA, TUD, Academic Hospital Maastricht, and SARA, the national computing and networking services.

Cell Organization Visualization. During the past years, the data visualization track has been working closely with cell biologists from the Swammerdam Institute for Life Sciences at UvA. Many novel time dependent visualization techniques have been de-

veloped for the analysis of cellular structures acquired from laser scanning confocal microscopy. This has resulted in a joint publication in *Chromosome Research*, in which the affiliated biologists claim that the developed techniques are one of the few ways "to obtain detailed insight into chromatin movement in the living cell". In addition, these activities have led to the spin-off company Podiceps, which will further develop and market the developed technology.

Future directions. In the near future, INS3 plans to organize the research activities along the two tracks outlined above. The research activities of the data visualization track will continue to focus on methods for the extraction of quantitative information and interactive exploration of time dependent data sets. The need for such techniques in the life sciences will increase as acquisition devices, such as laser scanning confocal microscopes and mass-spectrometers, continue to improve. The research activities of the user interface track will continue to focus on 3D interaction for scientific visualization in near-field virtual environments. The emphasis of these activities will shift slightly from virtual reality system design to evaluation of effective interfaces. The approach will be to develop a practical model for bi-manual interaction which can be used for user performance modeling during 3D interactive tasks.

The strategy to realize these plans is to seek partners and funding of multi-disciplinary projects. Partners from two disciplines have being sought.

Life sciences. INS3 will continue to strengthen the collaboration with partners from the life sciences. Strong relations currently exist with the computational sciences group at UvA and with research groups from SILS, AMOLF. Funding for these collaborations is secured until 2009 from the national BSIK project Virtual Laboratory for e-Science. INS3 leads the visualization activities in this project. Additional funding is currently being sought with a multi-disciplinary project at STW.

Human factors. Collaborations with the user centered system group at TUE and the perception group at TNO Human Factors in Soesterberg will be sought. Funding for these collaborations is partially secured until 2009 from the national BSIK project BRICKS. Additional funding is being sought from the VIEW program, an NWO funded stimulus program for scientific visualization.

6.3.3 Overview of the results

See Table 6.11 on page 151 for a numerical overview.

Selection of major publications

1 W.C. DE LEEUW, R. VAN LIERE (2001). Multi-level topology for flow visualization. *Computers and Graphics* **24** (3), 325–331.

2 R. VAN LIERE, W.C. DE LEEUW (2003). Graphsplatting: visualizing graphs as continous fields. *IEEE Transactions on Visualization and Computer Graphics* **9** (2), 206–212.

3 R. VAN LIERE, J.D. MULDER (2003). Optical tracking using projective invariant marker pattern properties. *Proceedings IEEE Virtual Reality 2003*, Los Angeles, USA, 191–199.

4 E.M. MANDERS, A.E. VISSER, A. KOPPEN, W.C. DE LEEUW, R. VAN LIERE, G.J.

BRAKENHOFF, R. VAN DRIEL (2003). Four-dimensional imaging of chromatin dynamics during the assembly of the interphase nucleus. *Chromosome Research* **11** (5), 537–347.

5 W.C. DE LEEUW, R. VAN LIERE (2003). BM3D: Motion estimation in time dependent volume data. *Proceedings of IEEE Visualization 2002*, Boston, 427–434.

6 R. VAN LIERE, A. VAN RHIJN (2004). An experimental comparison of three optical trackers for model based pose determination in virtual reality, *Proceedings Eurographics Symposium on Virtual Environments*, Grenoble.

7 J.D. MULDER, B.R. BOSCHKER (2004). A modular system for collaborative desktop VR/AR with a shared workspace. *Proceedings of the IEEE Virtual Reality Conference 2004*, 75–82.

PhD theses

- S.C. Marshall (Thesis advisor: Prof.dr. M. Delest, Co-advisor: Dr. I. Herman, University: Université de Bordeaux, Date: June 8, 2001, Title: *Graph Visualization of Complex Information*)
- R. van Liere. See the theme report of SEN1.

Software. The experimental research tracks call for a mature experimentation platform. Substantial resources have been spent to develop and maintain software. We believe that these efforts benefit research.

argos is an analysis and visualization software system of time dependent time sets from confocal microscopes. *argos* is used on a daily basis by biologists from SILS. In addition, the spin-off company Podiceps will use the software in its product family.

Portable Virtual Reality (PVR) is a software system that implements the basis layer of virtual environments. It includes viewing and optical tracking functionality. PVR is used to drive the PSS environment. It is used on a daily basis by seven national universities and research institutes.

Table 6.13. Some major externally funded projects of INS3

Acronym	Full name	Dates		k€	Source
BioVR	Analysing biological structures with virtual reality techniques	1998	2001	600	NWO SLW
WTCW Vis	WTCW visualisation prism project	2001	2003	720	ICES / KIS2
VLeVis	Virtual laboratory for e-sciences visualisation	2004	2008	1,000	BSIK

6.3.4 Scientific reputation

INS3 has built up a leading national reputation in the area of researching innovative virtual reality technology. In recognition, Van Liere has recently been appointed as the

first full professor in the area of virtual reality in the Netherlands. Van Liere is also involved in national advisory and steering committees for virtual reality research. Finally, INS3 heads the visualization activities in the national BSIK project. The VL-e project brings visualization groups from TUD, VU and CWI together to research visualization methods in a GRID environment.

Memberships of committees and other professional activities

For a more extensive survey, please see the INS3 section of the *CWI Overview Research Activities 1999–2003* (CD-ROM).

R. van Liere	full professor at TUE, member of three PhD committees, coordinator of two collaboration projects, member of four program committees, (co-)organizer of three conferences

6.4 Theme INS4 – Quantum Computing and Advanced Systems Research

Research in	Quantum information processing, computational learning, genomics
Started in	1997
Theme leader	Prof.dr. H.M. Buhrman (2003–present) Prof.dr.ir. P.M.B. Vitányi (1999–2002)
CR classification	E.4, F.1, F.2, H.3, I.2, I.5 D.3.2 [Language classifications]

Table 6.14. Staff of INS4, 1999–2005 (in FTE/year, *prognosis)

INS4		1999	2000	2001	2002	2003	2004	2005*
Leader:	*P.M.B. Vitányi*	*0.20*	*0.2*	*0.2*	*0.20*			
	H.M. Buhrman					*0.2*	*0.2*	*0.2*
Researchers:	*A.E. Brouwer*	*0.10*						
	H.M. Buhrman	*0.92*	*1.0*	*0.8*	*0.80*	*0.6*	*0.6*	*0.6*
	J.T. Tromp				*0.92*	*1.0*	*1.0*	*1.0*
	P.M.B. Vitányi	*0.60*	*0.6*	*0.6*	*0.60*	*0.8*	*0.8*	*0.8*
Total tenured staff		**1.8**	**1.8**	**1.6**	**2.5**	**2.6**	**2.6**	**2.6**
Non-tenured staff		1.6	1.0	2.0	2.7	2.0	2.0	1.5
CWI PhD students		1.0	0.1	1.6	2.6	2.8	4.8	6.0
Total research staff CWI payroll		**4.4**	**2.9**	**5.2**	**7.8**	**7.4**	**9.4**	**10.1**
Seconded PhD students		*3.7*	*3.0*	*2.6*	*2.2*	*1.8*	*1.0*	*1.0*
Other seconded staff		*2.1*	*3.7*	*1.0*	*1.0*	*0.4*	*0.9*	*0.0*
Total hosted research staff		***10.2***	***9.6***	***8.8***	***11.0***	***9.6***	***11.3***	***11.1***

Table 6.15. Scientific output of INS4

Output class		1999	2000	2001	2002	2003	2004	Total
Academic	refereed journals and proceedings	31	37	24	26	26	23	167
	other journals and proceedings	0	0	0	0	0	8	8
	book chapters	0	0	2	3	0	4	9
	Total academic	**31**	**37**	**26**	**29**	**26**	**35**	**184**
Monographs		0	0	0	0	0	0	0
PhD dissertations		1	0	1	1	0	1	4
Professional pub./products		2	15	6	3	9	8	43

6.4.1 Senior researchers

Prof.dr. H.M. Buhrman, Prof.dr.ir. P.M.B. Vitányi, Prof.dr. A.E. Brouwer, Dr. J.T. Tromp.

Table 6.16. Funding percentages of INS4

INS4	1999	2000	2001	2002	2003	2004	Average
Direct NWO	85.4%	69.5%	66.0%	68.4%	64.6%	61.7%	69.2%
Other research funds	14.6%	20.9%	26.9%	26.5%	24.9%	31.7%	24.3%
Grants/contracts	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Other	0.0%	9.6%	7.1%	5.1%	10.5%	6.6%	6.5%
Total	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**

6.4.2 Research orientation, highlights, and future directions

Mission and research area. There is great progress and opportunity in non-classical computational technologies and algorithmics by exploiting novel computational aspects of physical phenomena. Key issues are feasibility of technology and efficiency of algorithms, and theoretical basics. Novel technologies comprise coherent quantum mechanical and reversible low-energy computing.

Quantum information processing is the intersection of quantum mechanics and computer science. It tries to improve on classical computers and classical complexity bounds by making use of quantum mechanical phenomena. After Peter Shor's 1994 discovery of efficient quantum algorithms for factoring and the discrete log (threatening current "classical" cryptography), the field has grown explosively.

The work program in quantum algorithmics includes the design and analysis of new algorithms and communication protocols. We plan to test such algorithms collaborating with experimental groups in the USA and recently also in the EU (viz., the RESQ project). In machine learning we continue our work on algorithmic minimal sufficient statistics and minimal description length learning (MDL). Applications of algorithmic information theory (also known as Kolmogorov complexity) in mathematics and algorithms are investigated and consolidated. A new research strain started in theoretical analysis and applications of computational genomics, in particular in sequencing, analyzing and clustering genomic material.
INS 4 has three subthemes.

INS4.1 studies algorithms and systems based on quantum mechanical principles. This work is exploratory research dealing with quantum algorithmics, quantum communication complexity, quantum information theory. Together with similar groups in Europe and the USA, CWI's work is aimed at making the realization of practical quantum computation possible.

INS4.2 addresses a range of issues related to machine learning and statistical inference, both theoretically and practically. It studies the relation between data compression and generalization properties and prediction, for example in the sense of the "minimum description length" paradigm – basically a formal version of Occam's Razor.

INS4.3 develops principles and algorithms for distributed and parallel systems as well as single-processor architectures. Moreover, it identifies limitations and possibilities of future systems by exploiting fundamental mathematical techniques of complex-

ity theory. A major part of the work is on computational genomics, complexity theory, derandomization and Kolmogorov complexity.

Research highlights.

Quantum computing. A large part of INS4's efforts have been put into research of quantum computing and quantum information. This challenging and new area can roughly be split into two subareas. The first area is the development of a physical implementation of a quantum computer: constructing qubits and demonstrate that computational operations can be applied to these qubits. The second area is more computer science oriented and deals with the question: what can we do more efficiently with a quantum computer. It is this second area that has received the most attention from our group. Interestingly there are only very few groups worldwide that contribute to this second area, although it is key to the development of quantum computing as a whole.

One of the most important problems is the development of new quantum algorithms. Together with the groups in Calgary and Waterloo (Canada) we have developed a lower bound technique, the polynomial method (*JACM* 2001), to show the limitations of quantum computers. Such a technique, very common in classical computing, is very important in the development of actual algorithms. Our group was the first to lay the foundations for such research and the polynomial method is currently at the core of research in quantum computing and information theory. This has led to the development of new algorithms for problems like element uniqueness (INS4 and Institute for Advanced Study, Princeton), and search and counting problems.

An important and widely used and applied area developed by CWI is the area of communication complexity or distributed quantum computing. We were the first to demonstrate that communication problems can sometimes be solved more efficiently when qubits are used instead of classical bits. We showed that a natural problem, the equality problem, can be solved exponentially more efficient with qubits than with classical bits in certain settings. This paper, Quantum Fingerprinting (*PRL* 2001) has been used successfully as building block in new quantum cryptographic protocols, and received a lot of attention in the press worldwide.

Surprisingly the study of quantum computing and information has led to results in classical computing. This application of quantum computing is very unexpected and does not have the drawback that it depends on a physical implementation. INS4 was the first to show that such a result is possible. We proved a lower bound on *classical* error correcting codes, by demonstrating that the corresponding quantum problem needs exponential large codes. The proof of this fact is essentially quantum mechanical.

Another unexpected application was that of quantum communication complexity towards developing experiments that test the foundations of quantum mechanics itself. Our results have been received very positively in the physics community and were published in *PRL*, the most prestigious physics journal.

Computational complexity. Central question in this area is the P versus NP problem, considered one of the main open problems in all of modern mathematics today. See the

website of the Clay foundation, which awards $1,000,000 for anyone who solves this problem. We developed a program to tackle this problem and related problems and successfully showed that this program, which can be seen as an extension of Post's program from the 1930s, can be used to separate complexity classes.

Kolmogorov complexity. Development of the "Incompressibility method", based on Kolmogorov complexity. This is a general method like the "Probabilistic method" or "Counting method", to be used for applications in mathematics and computer science and elsewhere. One out of the many applications given by us was to resolve a 40-year open problem concerning the average-case running time of Shellsort, and an average-case variant of Heilbronn's problem in computational geometry.

Development of a feature (parameter) free method for clustering and classification in machine learning and prediction, based on the universal "similarity metric" based on the earlier "information distance", both proposed by us.

Resolution of the problems surrounding Kolmogorov's 1974 famous proposal of a non-probabilistic statistics expressed in his "structure function." These results have given new directions for statistical inference, such as minimum description length (MDL) methods based on rate-distortion theory as developed using the structure function.

New wait-free distributed algorithms for asynchronous interprocess communication, asynchronous concurrent timestamping, anonymous naming, and synchronization primitives, and lower bounds for compact routing storage requirements in computer networks.

Definition and development for Kolmogorov complexity in quantum information theory.

Advances in the theory of cognitive processes in psychology.

Computational learning theory. This subtheme deals to a large extent with learning from data and reasoning under uncertainty. In the course of the last five years, the subgroup coordinated by Grünwald has established itself as an authority in information-theoretic approaches to machine learning and statistics, most notably the *minimum description length principle*.

The subtheme bridges computer science, information theory, and statistical approaches to learning. There exist at least three distinct research traditions in learning from data: *machine learning*, as developed in computer science; *statistical learning*, as developed by statisticians; and *information-theoretic learning*. Our group is one of the very few groups with experience in all three fields. During the last five years, we have worked both in computer science and statistics departments. Our work was published in journals on information theory (*IEEE Transactions on Information Theory*), computer science (e.g., *Machine Learning Journal*) and statistics (e.g., *Annals of Statistics*).

Future directions.

Quantum computing. The most important question in this area is the development of new quantum algorithms. Problems that are of intermediate complexity like factoring are the most promising candidates for a polynomial time quantum algorithm.

Graph isomorphism and related problems are at the center of our interest. We also will develop the application of quantum proofs to classical statements. Currently we have found a connection between quantum communication complexity and classical fault tolerant computation. We expect that many more relations will be found in the near future.

Another area of interest is the application of quantum computing techniques to physics and foundations of quantum mechanics. We have successfully demonstrated that results from quantum communication complexity can be used to develop robust experiments that test the laws of quantum mechanics itself. We will continue along these lines.

Complexity theory. We will continue developing our structural program to separate complexity classes. It seems that a breakthrough is imminent, though such claims have incorrectly been made and the area is notoriously difficult. Important point of attention will also be derandomization, resource bounded Kolmogorov complexity, quantum computing and the polynomial hierarchy, circuit lower bounds.

Kolmogorov complexity. Continuation and development of the incompressibility method, compression based clustering and the advancement of structure functions in relation with computational learning.

Computational learning theory. August 2005, Grünwald was awarded a prestigious NWO Vidi grant for the project *Learning when all models are wrong*. The project is about *misspecification*, the realistic situation in which we try to learn a model from data where all models under consideration are "wrong", in the sense that they do not describe reality very well. The ultimate goal of this project is to develop a single, unified theory for learning from data that does not suffer from any of the defects of either of the three existing approaches. Preliminary steps in this direction, based on a small-scale version of Martin-Löf's theory of *algorithmic randomness*, look very promising.

Knowledge transfer.

Contract research and external funding.

Buhrman successfuly coordinated an EU project, in the Future and Emerging Technologies (FET) program. This project QAIP received 800 k€and consisted of seven European and five North American partners.

A follow-up of this project RESQ, 1,600 k €is currently half way and is coordinated together with ULB in Brussels. This proposal combines both groups from CS as well as theoretical physics.

Buhrman received funding from NWO for one PhD student and one postdoc (four years) for the project: "Extending feasible computation: Quantum computing".

Buhrman won a Vici award in 2004 (k €1200 for five years).

Vitányi received funding from NWO for two PhD students and two postdocs (two separate projects).

Teaching.

Buhrman teaches a course in Quantum computing at UvA, where he is full professor for one day per week.

Vitányi teaches a course in Kolmogorov complexity at UvA, where he is a full professor for one day per week.

6.4.3 Overview of the results

See Table 6.15 on page 156 for a numerical overview. A list of all publications can be found in the INS4 sections of *CWI Overview Research Activities 1999–2003* (CD-ROM).

Selection of major publications

1 B. BEALS, H. BUHRMAN, R. CLEVE, M. MOSCA, R. DE WOLF (2001). Quantum lower bounds by polynomials. *J. Assoc. Comp. Mach* **48** (4), 778–797. (Journal version of FOCS paper.)

2 H. BUHRMAN, R. CLEVE, J. WATROUS, R. DE WOLF (2001). Quantum fingerprinting. *Physiscal Review Letters* **87** (16).

3 H. BUHRMAN, P. HOYER, S. MASSAR, H. ROEHRIG (2003). Combinatorics and quantum nonlocality. *Physical Review Letters* **91** (4), 047903.

4 J. KERENIDIS, R. DE WOLF (2003). Exponential lower bound for 2-query locally decodable codes via a quantum argument. *35th Annual ACM Symposium on Theory of Computing (STOC'03)*, 106–115.

5 H. KLAUCK, R. ŠPALEK, R. DE WOLF (2004). Quantum and classical strong direct product theorems and optimal time-space tradeoffs. *45th IEEE Symposium on Foundations of Computer Science (FOCS'04)*.

6 H. BUHRMAN, M. FRANKLIN, J. GARAY, J. HOEPMAN, J. TROMP, P.M.B. VITÁNYI (1999). Mutual search. *Journal of the ACM* **46** (4), 517–536.

7 MING LI, BIN MA, J. TROMP (2002). Patternhunter: faster and more sensitive homology search. *Bioinformatics* **18**, 440–445.

8 N. VERESHCHAGIN, P.M.B. VITÁNYI (2004). Kolmogorov's structure functions and model selection. *IEEE Trans. Inform. Theory*. (Journal version of FOCS paper.)

9 M. LI, X. CHEN, X. LI, B. MA, P.M.B. VITÁNYI (2004). The similarity metric. *IEEE Trans. Inform. Th.* **50** (12), 3250–3264.

10 S. HALDAR, P.M.B. VITÁNYI (2002). Bounded concurrent timestamp systems using vector clocks. *J. Assoc. Comp. Mach.* **49** (1), 101–126.

PhD theses

- B. Terhal (cum laude) (Thesis advisor: P.M.B. Vitányi, University: UvA, Date: November 3, 1999, Title: *Quantum Algorithms and Quantum Entanglement*)
- R.M. de Wolf (cum laude) (Thesis advisors: H.M. Buhrman, P.M.B. Vitányi, University: UvA, Date: September 6, 2001, Title: *Quantum Computing and Communication Complexity*)
- W.K. van Dam (Thesis advisor: P.M.B. Vitányi, University: UvA, Date: October 9, 2002, Title: *On Quantum Computation Theory*)
- H.P. Röhrig (Thesis advisors: H.M. Buhrman, P.M.B. Vitányi, University: UvA, Date: January 27, 2004, Title: *Quantum Query Complexity and Distributed Computing*)

Table 6.17. Some major externally funded projects of INS4

Acronym	Full name	Dates		k€	Source
QAIP	Quantum algorithms and information processing	1/2000	12/2002	605	EU
RESQ	Resources for quantum information	1/2003	6/2006	500	EU
QIP	Quantum information processing	4/2004	3/2009	1,250	NWO Vici

6.4.4 Context

The researchers of INS4 work on several international EU projects, QAIP, RESQ, Neurocolt, Pascal. We have ongoing collaborations with Cambridge, Oxford, Bristol, Paris, Aarhus, Max Planck Institute (Garching), Jerusalem, Weizmann, Technion, MIT, Berkeley, Princeton, Rutgers, University of Chicago, Waterloo, Calgary, Montreal, Moscow University, Stanford, Cornell. Within the Netherlands we collaborate with UvA, TUD, and UU.

6.4.5 Scientific reputation

Awards

- Buhrman received a Vici grant from NWO (1200 k€) for the project "Quantum Computing".
- De Wolf received the Cor Baayen award 2003, for the best thesis among all the ERCIM institutes in Europe. It is the first time that this prize goes to the Netherlands and CWI.
- Grünwald received a Vidi grant (600 k€) for the project "Learning when all the models are wrong"
- Grünwald was awarded the FoLLI Outstanding Dissertation Prize for outstanding PhD theses in the fields of Language, Logic and Computation.
- Terhal, De Wolf, and Grünwald received a TALENT stipend from NWO.
- Buhrman and Vitányi were invited keynote speakers at several international conferences.
- Vitányi was appointed CWI Fellow.
- Vitányi was awarded the Kolmogorov medal and the Medal of the University of Helsinki, Finland, 2003.
- The People's Republic of China's 1999 National 1st Prize for Excellent Books in Science and Technology published in the People's Republic of China. Ming Li and Paul Vitányi, *Description Complexity and Applications*, China Science Press, Beijing, December 1998 (Chinese translation by Cheng Qi).

Memberships of committees and other professional activities

For a more extensive survey, please see the INS4 section of the *CWI Overview Research Activities 1999–2003* (CD-ROM).

H.M. Buhrman	full professor at UvA, member of eight program committees and two steering committees, editor of two journals, organizer of two conferences, keynote speaker at several intenational conferences
P.D. Grünwald	member of three program committees
P.M.B. Vitányi	full professor at UvA, member of 17 program committees, editor of four journals, organizer of one conference, keynote speaker at several intenational conferences

Networked library concept

The CWI Library is active in technological development. CWI took part in the EU funded EULER projects. The result is a portal for everyone who is interested in mathematics and which will remain free for end-users. EULER is a virtual library for mathematics with up-to-date technological solutions. EULER aims at offering a complete system where all types of information can be found, i.e., books, articles, proceedings, reports and Internet resources. Unique is, that EULER uses commercial resources as well as of non-profit resources. Through one of the partners, Fachinformationszentrum Karlsruhe (FIZ), the data of Zentralblatt MATH is available. FIZ, CWI, and the University Libraries of Florence and Gttingen continue their collaboration as founding partners in the EULER Consortium, which is sponsored by the European Mathematical Society.

Another innovative project in which CWI Library takes part is DARE (Digital Academic Repositories). Launched in 2003 as a national project by the Dutch universities and coordinated by SURF, DARE aims at setting up and maintaining an institutional repository at every Dutch academic institution. Emphasizing the importance of scientific knowledge transfer, the Dutch government supports the DARE programme, which will last until 2006, with 2 million euro.

Due to the prominent involvement of CWI through NWO, the repository will be extended to accommodate the participation of other NWO institutes.

All About EULER

Top News

Modernized access point to EULER in test phase

The EULER-TAKEUP project has released a new, enhanced version of the EULER Search Engine in July 2002.

The new EULER Engine comes with a complete redesign of the user interface, inspired by other popular and easy to use general purpose search engines, and a new, speed-optimized retrieval machinery in the background.

Our Search

Simple Search
Modernized access point to EULER

Search Tips
Search basics, Results elements

Advanced Search
Fully control your search

Advanced Search Tips
How to exploit all features

Reference Informati

Data Provider Fact S
Databases, Libraries, Put

EULER Engine Fact
Origin, Features, Descrip

EULER Metadata for
Dublin Core, Extensions,

Advertising with EUL
Publishers' Catalogue Ex

Chapter 7

Support departments

CWI currently maintains six departments to support the work of its researchers and visitors, and to support its position nationally and across Europe. The core tasks of the departments are focused on serving the local CWI population, which consists of tenured researchers, postdocs, PhD students and visitors, all drawn from 23 countries worldwide. Additional tasks include supporting CWI's needs in its commitments to national and international organizations and participating in development projects that enhance CWI's research mission.

The composition and organization of the support departments is routinely studied to best match the needs of the Institute. In 2001, several support departments were restructured and further restructuring is expected in 2005.

During the evaluation period, the following support departments existed at CWI:

Management (DIR): the organizational unit containing the general director and controller, and a small support staff for coordinating international cooperation and W3C activities.

Bureau CWI (BCWI): a unit managing contract support, public relations and interactions with CWI's national constituencies. As part of the 2001 restructuring, most of the BCWI members were migrated to the Communications and Publications department.

Facilities and Housing (FAD): a unit maintaining the physical plant and office infrastructure at the Institute. It also coordinates security and emergency medical support for CWI staff. The printing service, which was a part of the FAD through 2000, was migrated to the Communications and Publications department in 2001.

Communications and Publications (CPD): a unit created in 2001 to support CWI's internal and external communications needs.

Computer Systems and Telematics (CST): the largest support department, charged with developing, deploying, and maintaining research and administrative computing infrastructure.

Library and Information Services (LIB): the unit maintaining an internationally recognized collection of mathematics and computer science reference materials, and charged with developing cost-effective methods of making research information available to a local, national and international constituency.

Financial Services (FD): the unit coordinating financial affairs and contract administration.

Personnel (PD): the unit coordinating human resource activities and policies. It also provides housing facilities and other services for CWI's international students and staff.

The total support staff level has remained constant at about 60 persons, representing between 50 and 53 FTE during the evaluation period. Table 7 provides an

Table 7.1. CWI support staff, 1999–2005 (in FTE/year, *prognosis)

Support Staff	1999	2000	2001	2002	2003	2004	2005*
Management	2.5	3.0	4.0	4.9	4.1	4.0	4.8
Library and Information Services	8.2	8.1	7.2	7.5	8.4	8.0	7.1
Communications and Publications			10.5	10.9	10.7	10.4	9.6
Computer Systems and Telematics	12.2	12.8	14.0	13.7	15.2	14.7	14.2
Facilities	11.3	10.4	5.6	4.9	5.6	5.4	4.0
Financial	6.2	7.1	6.1	6.1	6.1	5.8	7.0
Personnel	3.9	4.0	3.6	3.3	3.4	3.9	4.6
Bureau CWI	6.2	4.6					
Total	**50.5**	**50.0**	**51.0**	**51.3**	**53.5**	**52.2**	**51.3**

overview of staff loading by department.

In the sections below, we consider the activities of each support department during the review period. We also consider the major policy issues facing each department for the coming six-year period.

7.1 Library & Information Services (LIB)

The Library & Information Services department (LIB) supports the advancement of scientific knowledge by providing scientists (mathematicians, computer scientists and others) with relevant scientific information. While the direct target group for LIB services is CWI's own scientists, the library's comprehensive collection is also used by the international research community.

Overview of activities. The role of the traditional library has shifted dramatically within the evaluation period. The traditional role of serving as a direct repository of books, journals and other printed publications has been supplemented with tasks that consist of offering e-publications, negotiating licences, qualifying information available on the Internet, deploying user-friendly interfaces to scientific information, analyzing search engines, and providing active personal alerting services. The library's long-term role is to provide and guarantee access to information within the global network. This is especially important for mathematics: according to the 2004 QANU report on research assessment of mathematics, the small-team nature of mathematics research and the extensive scope of the mathematics literature makes a comprehensive library more essential for mathematics than perhaps any other scientific discipline. CWI hosts such a library.

The LIB department does not work in isolation. National cooperation has been largely realized within LOBBI, a Dutch consortium of mathematics and computer science libraries. In 2000, as part of LOBBI, LIB negotiated a number of consortium licences which have been acknowledged as national licences for the Netherlands. In addition to its activities of reducing the cost of periodicals via favorable licensing terms, LIB has been active in a number of development projects related to the retrieval of electronic research information. Examples are EULER (1998-2000), EULER-TAKEUP (2001-2002), and the VOGIN Information Retrieval Tools (IRT) projects. LIB also par-

ticipates in the DARE (Digital Academic Repositories) project (2003-2006) via NWO. In 2004, a beta version of the Open Access Initiative (OAI) compliant NWO-CWI institutional repository was launched. (The repository will also include the scientific output of other NWO institutes.) At a more local level, CWI Image Database project allows images of persons and objects that in any way are related to CWI and its history to be archived.

Issues for the coming period. One of the most critical issues facing libraries in the digital age is the guarantee of perpetual access to licensed content. LIB is an active participant in LOCKSS, an open source, peer-to-peer software system that functions as a persistent access preservation system. In addition to LOCKSS, LIB is also active in other open access initiatives, such as SPARC and the OAI.

LIB also will continue to take part in projects that have an international scope and contribute to the World Digital Mathematical Library (WDML) initiative, which aims to digitize the contents of the total mathematical literature, including those previously only available in print.

Given the housing problems at CWI, LIB is actively engaged in developing alternatives for the storage of and access to journals and books. While further electronic storage of journals and - to a lesser extent - books is an option, the library continues to house a substantial number of periodicals for which no electronic version is available or for which perpetual access is not adequately guaranteed. As other libraries close, such as the Royal Academy's NIWI, LIB will need additional space to house a more complete collection of historical literature. One option is to apply compact or mobile shelving for a large part of the journal volumes. Licences for archival collections are also available, such as JSTOR, Project Euclid, and options offered by major publishers. However, these require additional funding for annual access fees.

LIB will continue to pursue cost-effective methods and favorable licensing terms to stretch the available library budget. Nonetheless, to maintain access to information at its present level, it is important that a structural growth in LIB's funding is allowed.

7.2 Communications and Publications (CPD)

Together with the general director and the management team, CPD plays an important role in developing and implementing an active communications strategy for CWI. This strategy includes internal and external communications, corporate and science communications. In its work, CPD delivers both content and, where needed, products or activities.

Overview of activities. CPD was formed in 2001. It united the production arm of the Institute's printing services and CWI's organizational information units. The purpose of forming CPD was to focus on the activities required to increase CWI's visibility nationally and internationally, and to serve as a single shop for the Institute's electronic and print publication users. CPD was also formed to serve as a more visible interface to the Institute for external groups.

CPD recognizes that effective communication is not a one-way activity. CPD staff

works within the Institute to alert researchers to important dissemination outlets that extend beyond their normal scientific channels. And, on the other hand, CPD monitors signals and trends in society. CPD collaborates with the CWI library in projects aiming at distributing new scientific reports and making old CWI reports accessible within and outside the Institute, and with CST in digital communication projects.

Issues for the coming period. CPD has several priorities for the next six years. One is the optimization of the communication and publication staff. Another is the need to improve CWI's science communication, including strengthening contacts with the print, broadcast and electronic media, and improving the science communication skills of the scientific staff. A third is to increase the interactions among CWI's various target communities, including scientists, entrepreneurs, government and other funding agencies, university and high school students, and CWI alumni. A final priority is to more effectively present the Institute's activities via its various Web outlets.

7.3 Computer Systems and Telematics (CST)

The Computer Systems and Telematics department (CST) is responsible for the deployment and maintenance of CWI's computer infrastructure. This infrastructure consists of a research component, where the emphasis is on open research systems and broad interconnectivity with the outside research community, and an internal business community, where the emphasis is on stable production systems to be used by the support departments.

Overview of activities. During the review period, CST has refocused its activities to support and deploy stable computing environments rather than to develop new technologies. This process has not been easy. Several changes of departmental management have taken place which, together with close interactions with a management team task force, have brought stability to the department. In the current support model, a clear distinction was made between first-line support and second-line support. Each scientific cluster was assigned a dedicated first-line support employee and a more pro-active, customer-driven support approach was initiated. A quality survey carried out in 2004 indicated that these changes were successful.

On the technical front, CST continues to migrate to commodity hardware and open source software as the basis for its research environment. It has also implemented an out-sourcing program for services such as archival backups (using the facilities at SARA) and non-interrupting power supplies (using the facilities at NIKHEF).

Issues for the coming period. At of the end of 2004, CWI's computing infrastructure was better integrated and more stable than at any point in its history. Both high-speed wired and ubiquitous wireless networks are in place, a pro-active support and equipment maintenance policy exist, and researchers have local and external access to nearly all of their electronic information resources. At the same time, however, several significant problems need to be addressed to increase reliability and to better integrate business and administrative processes for the research staff.

A primary concern of CST is Internet security. CWI, with its open network, is rela-

tively vulnerable to attacks. In 2004 a large number of Linux workstations were compromised. In 2005 CST will start a pilot with tokens and one-time passwords for more secure remote access.

Another important area is the integration of productivity applications across the Institute. Looking at CWI's application landscape, elementary functions such as a standard e-mail environment, a standard calendaring application, a document archive, web publishing tools and a content management system for all the Internet and Intranet websites are lacking. As a consequence, each department and cluster has developed local solutions. This is not an optimal situation and requires coordinated attention.

A third area of activity is the support for flexible workspaces. Many employees have a desktop at CWI, a laptop, and a private home desktop computer. CST needs to investigate how modern scientists work (or would like to work) and provide a multi-layered access and support model.

7.4 Facilities (FAD)

The Facilities Support department (FAD) provides support for various aspects of the physical plant at CWI. FAD manages the two CWI buildings, provides physical workspaces (except for computing equipment) and coordinates the implementation of workplace health policies.

Overview of activities. The main operational responsibility of FAD is providing a functioning workspace for CWI's researchers and support staff. This involves the provision of everything from desks to toilet paper. At the beginning of this evaluation period, FAD also supported printing activities, as well as graphic design and editorial support to the CWI community. These activities were transferred to CPD in 2001.

The primary long-term activity of FAD is the coordination of office space available within the Institute. Although CWI hosts a total staff of approximately 220 FTE, the actual number of persons in full-time or part-time residence is significantly higher. As a result, CWI has a critical need for desk space.

In 2000, a new temporary building was installed to replace an older temporary office structure outside the main building. One requirement for the placement of the new temporary structure, which is currently used to house most of the INS cluster, was that a permanent solution be found within a ten year period. Together with CWI's Management, FAD has explored many options to increase space, including new construction, relocation or building extension. Since CWI does not have a separate housing budget, this work was coordinated with NWO, our parent organization. The work was also coordinated with the Amsterdam Science Park.

Issues for the coming period. In addition to responsibilities concerning the day-to-day maintenance of CWI's facilities, the solution of the housing problem is the major issue for FAD in the coming period. The most realistic options to be pursued are the extension of the current building by 4,000m^2 or to expand CWI's space by acquiring office space that is to be vacated by our neighbors.

7.5 Financial Service (FD)

The Financial Service department (FD) provides accounting, bookkeeping and administrative support for CWI. These tasks include the management of income and expense streams for the Institute and the maintenance of research administration information for our various funding agencies - all of whom have different reporting and budgetary requirements. FD also provides accounting services for some of the national and international projects in which it participates (including BRICKS, MultimediaN and VL-e BSIK projects), for related organizations like the Amsterdam Science Park (the organization that manages the facilities at the campus where CWI is located), and for CWI Incubator (CWI's holding and technology transfer company).

Overview of activities. The primary day-to-day responsibility of FD is the management of the Institute's accounting and bookkeeping activities. This consists of systematically collecting, recording, processing and providing financial data in accordance with the legal guidelines stated by NWO and other funding agencies. FD provides financial information and advice to the general management, the research clusters and themes, CWI's support departments and related organizations outside CWI. FD also performs a control function on internal business processes and provides the Institute's interface with the tax office and our accountants.

During the evaluation period, FD also provided financial services for some of CWI spin-off companies, providing them with a sound basis for managing their financial, bookkeeping an taxation affairs.

Issues for the coming period. During the coming period, two levels of transitions will be undertaken by FD. The first is an expanded use of electronic information services, both for information collection and information processing. The goal of this operation is to reduce processing overhead and to increase the flow of management information to members of the research and support staff. Examples are electronic time sheets for CWI's research staff, automatic web-based budgetary management information directly derived from the accounting core, and electronic authorization of invoices.

The second level of changes involves FD staff. In 2004, several employees left the department after many years in service. In November 2004, recruiting began for new employees with new skills. FD sees this as an opportunity to re-focus its staff and to tune the internal distribution of tasks.

In the long-term, project management and control will be an important development issue. Given the changing funding environment for our research projects, strategic project and resource planning is necessary. As was discussed in Chapter 2, the trend toward matching funding requires a pro-active management stance to ensure that CWI is financially able to participate in work that is aligned with its research mission. FD will also support research projects by monitoring the definition of consortia agreements and the coordination of clear IPR agreements that protect CWI's long-term interests.

7.6 Personnel (PD)

The Personnel Department (PD) counsels and supports management and employees in the field of personnel and organization related activities. PD has a responsibility to ensure compliance with national employment policies and to support research themes in acquiring new staff members. In this latter regard, PD has primary responsibility to establish consistent terms of employment, develop and apply primary and secondary employment benefit policy and, where necessary, obtain visa and work permits for the international workforce at the Institute.

Overview of activities. The focus of PD during the evaluation period was specially aimed at creating global HR policies and policies for terms of employment and occupational health. The Institute implemented a pro-active HRM policy that increased the effectiveness of CWI's research staff and limited the burden of unproductive staff members. The Institute also engaged in a stricter management of personnel resources, which resulted in the legally forced termination of four staff contracts during the evaluation period.

In addition to broad policy initiatives, PD focused on improved provision of personnel services to staff members. This included a shift to the digital distribution of forms and information, and an increased use of English in personnel-related publications. It also formulated stricter codes of conduct against harassment, for network use, and for protection of personal data. It also coordinated the development of a mandated smoking policy in 2004.

PD also invested energy in raising the awareness of effective HR policies among mid-level research management. New theme leaders are provided with an HR-related management course. The number of sabbatical leaves is increasing, and participation in mobility programs is encouraged.

Issues for the coming period. PD expects that in the coming period, the importance of our interactions at a European level will increase. PD currently supplies the chair of ERCIM's HR taskforce and is well-positioned to interact with our partners in formulating and implementing new HR policies.

The continued well-being of CWI's staff is also a PD priority. At present, CWI's sickness rate is below 2%, partly thanks to an effective occupational health policy. In order to manage the threats of RSI (CANS) and workplace stress, an effective information policy, coupled with programs like CWI sponsored yoga and chair massage, form a cornerstone of PD activity. PD also developed a four-yearly Institute-wide periodic occupational health check (PAGO), which is due again in 2005.

7.7 Summary

The organization of CWI's support staff is relatively lean and largely efficient. Throughout the coming period, further fine-tuning of the support organization is expected. While a limited growth is anticipated, it is expected that the total loading of the support staff will remain at approximately 25% of the FTE total of the Institute for the next six years.

Appendix

A Acronyms

ACI	Adviescommissie Informatica (committee to advise the NWO council board for physical sciences on computer science issues)
ACM	Association for Computing Machinery
ACTS	Advanced Communications, Technologies and Services
ACW	Adviescommissie Wiskunde (committee to advise the NWO council board for physical sciences on mathematical issues)
ADSL	Asymmetric Digital Subscriber Line
ALW	Aard- en levensWetenschappen, Earth and Life Sciences
AMBULANT	CWI project (www.cwi.nl/projects/Ambulant)
AMOLF	FOM-instituut voor Atomische en MOLeculaire Fysica, Institute for Atomic and MOLecular Physics
ASCI	Advanced School for Computing and Imaging, a Dutch research school
ASF + SDF	Algebraic Specification Formalism + Syntax Definition Formalism
AWT	Adviesraad voor het Wetenschaps- en Technologiebeleid, Advisory Council for Science and Technology Policy
BCWI	Bureau of CWI
BDD	Binary Decision Diagram
BRICKS	Basic Research in Informatics for Creating the Knowledge Society
BRITE	EU research and development programme in the fields of basic technological research and the applications of new technologies
BSIK	Besluit Subsidies Investeringen in de Kennisinfrastructuur (Dutch government program to invest in the knowledge infrastructure)
BTS	Bedrijfsgerichte Technologische Samenwerkingsprojecten, Company oriented Technological Cooperation
CAU	Christian-Albrechts-Universität zu Kiel
CMIF	Language for SMIL
CPD	Communication and Publication Department, a CWI support department
CPU	Central Processing Unit
CRREL	Cold-Region Research Laboratory
CS	Computer Science

CSIRO	Commonwealth Scientific and Industrial Research Organisation
CSS	Cascading Style Sheets
CST	Computer Systems and Telematics, a CWI support department
CWI	Centrum voor Wiskunde en Informatica
CWI-Inc	CWI Incubator BV
DAISY	Consortium to aid people with print disabilities (www.daisy.org)
DARE	Digital Academic REpositories
DBMS	Database Management System
DFG	Deutsche Forschungsgemeinschaft (German research council)
DIR	DIRectie, Management
EIDMA	Euler Institute for Discrete Mathematics and its Applications, a Dutch research school
EMS	European Mathematical Society
EMVT	Elektromagnetische Vermogenstechniek (electromagnetic power technique)
ERCIM	European Research Consortium for Informatics and Mathematics
ERCOM	European Research Centres on Mathematics, a committee of the EMS
ESPRIT	EU information technologies programme
EU	European Union
EULER	EUropean Libraries and Electronic Resources in mathematical sciences
EULER-TAKEUP	Follow-up project to the above
EUR	Erasmus Universiteit Rotterdam
EURANDOM	European Unit for Research and Analysis of Non-Deterministic Operational Models
EUREKA	pan-European network for market-oriented, industrial R&D
EUROPHLUKES	CWI project (www.europhlukes.net)
EW	Exacte Wetenschappen, Physical Sciences
EZ	Ministerie van Economische Zaken (Department of Economic Affairs)
FAD	FAcility Department, a CWI support department
FD	Financial Department, a CWI support department
FIZ	Fachinformationszentrum (Karlsruhe based producer and marketer of scientific and technical information services)
FOM	Fundamenteel Onderzoek der Materie, Foundation for Fundamental Research on Matter
FP	Framework Programme
FTE	Full time equivalent
FWA	Financiële Wiskunde Amsterdam (Financial Mathematics Amsterdam)

GB-E	Gebiedsbestuur Exacte Wetenschappen, Council Board for Physical Sciences
GIS	Geographical Information System
GKS	Graphical Kernel System
GMD	Gesellschaft für Mathematik und Datenverarbeitung, founding member of ERCIM
GSM	Global System for Mobile communications
HPM	Hamiltonian Particle-Mesh
HR(M)	Human Resource (Management)
HTML	Hypertext Markup Language
HvA	Hogeschool van Amsterdam (Amsterdam based polytechnic)
ICES/KIS	Interdepartementale Commissie voor Economische Structuurversterking/Kennisinfrastructuur (interdepartmental commission for strengthening of economic structure/knowledge infrastructure)
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
ICT	Information and Communication Technology
IEEE	Institute of Electrical and Electronics Engineers
IMPA	Instituto de Matemática Pura e Aplicada (institute for mathematics in Rio, Brasil)
ING	Internationale Nederlanden Groep (bank and insurance company)
INRIA	Institut National de la Recherche en Informatique et en Automatique, founding member of ERCIM
INS	INformation Systems, a CWI research cluster
IOP	Innovatiegericht Onderzoekprogramma, Innovation-driven Research Programme
IP	Internet Protocol
IPA	Instituut voor Programmatuurkunde en Algoritmiek, Institute for Programming Research and Algorithmics, a Dutch research school
IPN	Informaticaonderzoek Platform Nederland (national computer science platform)
IPS	Interacting Particle Systems
IR	Institutional Repository
IRT	Internet-information Retrieval Tools
IS	Innovatiesubsidie Samenwerkingsprojecten, Innovation Subsidy for Collaborative Projects
ISOC.nl	Internet Society Nederland
IST	Information Society Technologies
ITC	International Institute for Geo-information Science and Earth Observation
ITEA	Information Technology for European Advancement
Ideals	CWI project (http://www.cwi.nl/projects/ideals)

JFM	Jahrbuch über der Fortschritte der Mathematik (project library)
JSTOR	The Scholarly Journal Archive
KNAW	Koninklijke Nederlandse Akademie van Wetenschappen, Royal Netherlands Academy of Arts and Sciences
KNMI	Koninklijk Nederlands Meteorologisch Instituut (Dutch meteorological institute)
KPN	Koninklijke PTT Nederland (post and telecommunication company)
KWG	Koninklijk Wiskundig Genootschap (Royal Dutch mathematical society)
LAN	Local Area Network
LIACS	Leiden Institute of Advanced Computer Science
LIB	LIBrary, a CWI support department
LNCS	Lecture Notes in Computer Science
LNMB	Landelijk Netwerk Mathematische Besliskunde, Dutch Network on the Mathematics of Operations Research
LOBBI	Landelijk Overleg Beta-Bibliotheken (consortium of Dutch academic mathematics and computer science libraries)
LOCKSS	Lots Of Copies Keep Stuff Safe
LOFAR	Low Frequency Array
MARIN	Maritiem Research Instituut Nederland, Maritime Research Institute Netherlands
MAS	Modelling, Analysis and Simulation, a CWI research cluster
MC	Mathematisch Centrum
μCRL	micro Common Representation Language
MDL	Minimum Description Length
MIT	Massachusetts Institute of Technology
MRI	Magnetic Resonance Imaging
MRI	Mathematical Research Institute, a Dutch research school
MonetDB	database system developed at CWI (http://monetdb.cwi.nl)
MultimediaN	BSIK project
NATO	North Atlantic Treaty Organisation
NCF	Stichting Nationale Computerfaciliteiten (NWO foundation for computer facilities)
NIKHEF	Nationaal Instituut voor Kernfysica en Hoge Energie Fysica, National Institute for Nuclear Physics and High Energy Physics
NIWI	Nederlands Instituut voor Wetenschappelijke Informatiediensten (Dutch institute for scientific information services)
NLR	Nationaal Lucht- en Ruimtevaartlaboratorium, National Aerospace Laboratory
NLUUG	Unix User Group - the NetherLands

NOAG-i	Nationale Onderzoeksagenda Informatica (NWO's national research agenda in computer science)
NOB	Nederlands Omroepproduktie Bedrijf N.V. (company that provides facilities for broadcasting)
NoE	Network of Excellence
NP	Nondeterministic Polynomial time
NRCD	National Rehabilitation Center for persons with Disabilities
NSF	National Science Foundation
NWO	Nederlandse organisatie voor Wetenschappelijk Onderzoek, Netherlands Organization for Scientific Research
OAI	Open Archives Initiative
OCW	Ministerie van Onderwijs, Cultuur en Wetenschap, Dutch Ministry of Education, Culture and Science
OLAP	On-Line Analytical Processing
OOW	Overleg Onderzoekscholen Wiskunde (consortium of Dutch research schools in mathematics)
OR	Ondernemingsraad, Works Council
OTKA	Országos Tudományos Kutatási Alapprogramok, Hungarian Scientific Research Fund
OZSL	Onderzoekschool Logica, a Dutch research school in logic
PAGO	Periodiek Arbeids Gezondheidskundig Onderzoek (periodic health and safety check)
PC	Personal Computer
PCST	Public Communication on Science and Technology
PD	Personnel Department, a CWI support department
PDA	Personal Digital Assistant
PDE	Partial Differential Equation
PNA	Probability, Networks, and Algorithms, a CWI research cluster
PR	Public Relations
PROGRESS	PROGramme for Research on Embedded Systems & Software, a Dutch research programme
PV	Potential Vorticity
QoS	Quality of Service
R & D	Research and Development
RDBMS	Relational Database Management System
RDF	Resource Description Framework
RESQ	CWI project (http://www.ulb.ac.be/project/RESQ/)
RFBR	Russian Foundation for Basic Research
RIKZ	Rijksinstituut voor Kust en Zee (research institute for sea and shore of the Dutch department of transport and water management)
RIVM	Rijksinstituut voor Volksgezondheid en Milieu, National Institute for Public Health and the Environment

RNLN	Royal Netherlands Navy
RSA	Rivest–Shamir–Adleman (public key encryption method)
RSI (aka CANS)	Repetitive Strain Injury (Complaints of the Arm, Neck and/or Shoulder)
RTIPA	Real-Time Internet Platform Architectures
RTN	Research Training Network
RU	Radboud Universiteit (Katholieke Universiteit van Nijmegen (KUN))
RUG	Rijksuniversiteit Groningen
S-CWI	Stichting (Foundation) CWI
SAC	Symposium on Applied Computing
SAFE-NL	Security: Applications, Formal aspects and Environments in the NetherLands
SARA	Stichting Academisch Rekencentrum Amsterdam (foundation for academic computing in Amsterdam)
SE	Software Engineering
SEN	Software Engineering, a CWI research cluster
SenterNovem	Agency of Dutch Department of Economic Affairs
Sentinels	Dutch research program on security (http://www.sentinels.nl)
SFU	Simon Fraser University
SICS	Swedish Institute of Computer Science
SIKS	School voor Informatie- en Kennissystemen, Dutch Research School for Information and Knowledge Systems
SILS	Swammerdam Institute for Life Sciences, UvA
SLE	Stochastic Löwer Evolution
SMIL	Synchronized Multimedia Integration Language
SPARC	Scholarly Publishing and Academic Resources Coalition
SPSS	US software company
SSL	Secure Sockets Layer
STO	Science and Technology Officers
STW	Stichting Technische Wetenschappen (Dutch technology foundation)
SVG	Scalable Vector Graphics
SWOT	Strengths, Weaknesses, Opportunities, Threats
Stevin	Dutch-Flemish research program for Dutch language and speech
TCP	Transmission Control Protocol
TELEMATICS	An applied research program of the European Commission
TI	Telematica Instituut, Telematics Institute
TLB	Translation Look-aside Buffer
TMR	Training and Mobility of Researchers

TNO	Nederlandse organisatie voor Toegepast-Natuurwetenschappelijk Onderzoek, Netherlands Organisation for Applied Scientific Research
TTCN	Tree and Tabular Combined Notation
TTI	Technological Top Institute
TT-Medal	Test & Testing Methodologies for Advanced Languages
TUD	Technische Universiteit Delft
TUE	Technische Universiteit Eindhoven
TVD/TVB	Total Variation Diminishing/Total Variation Boundedness
UHD	Universitair Hoofddocent (senior lecturer, associate professor)
UL	Universiteit Leiden
ULB	Université Libre de Bruxelles
UM	Universiteit Maastricht
UML	Unified Modelling Language
USA	United States of America
UT	Universiteit Twente
UU	Universiteit Utrecht
UvA	Universiteit van Amsterdam
UvT	Universiteit van Tilburg
VAT	Value Added Tax
Veni, Vidi, Vici	Innovational research incentives schemes for young, established, and senior scientists
VL-e	BSIK project
VOGIN	Nederlandse Vereniging van Gebruikers van Interactieve Informatiesystemen, Dutch Association of On-line Users
VSNU	Vereniging van Universiteiten, Association of Universities in the Netherlands
VUA (aka VU)	Vrije Universiteit Amsterdam
VVS	Vereniging voor Statistiek en Operationele Research, Netherlands Society for Statistics and Operations Research
W3C	World Wide Web Consortium
WBSO	Wet Bevordering Speur- en Ontwikkelingswerk (Dutch law on tax reduction for R & D)
WCW	Wetenschappelijk Centrum Watergraafsmeer (administration and control of NWO part of the Science Park)
WDML	World Digital Mathematical Library
WTCW	Wetenschap & Technologie centrum Watergraafsmeer, Amsterdam Science & Technology Center (for coordinating ICES-KIS grant proposals)
WVOI	Werkgeversvereniging Onderzoekinstellingen (employers' association of Dutch research institutes)
WWW	World Wide Web

XForms	Standard for web forms
XML	Extensible Markup Language
XSL	Extensible Stylesheet Language
XSLT	XSL Transformations

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