CWI-evaluation
Progress Report 1993–1998

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Summary

CWI is a reputable scientific institute in the area of mathematics and computer science that gains much recognition in the scientific world, the industrial world, as well as the governmental world. CWI has further developed into a dynamic, extrovert research institute.

CWI has a strong research programme with fundamental and application driven characteristics and readily participates in new scientific developments and in new national and international research projects. The research is both fundamental and focused on problems from society; scientific collaboration, interaction with society and knowledge transfer have expanded significantly.

CWI has taken great care of the dynamics, vitality and innovation of its research programme. Several successful projects have been terminated and transferred to universities (biomathematics, cryptography, computer algebra, dynamical systems laboratory), and several new projects have been initiated (mathematics of finance, evolutionary computing, environmental mathematics, quantum computing, digital libraries, signals and images), in some cases by introducing a new organizational concept in the form of pilot themes.

CWI has effectively performed an extensive restructuring operation, based on both external recommendations and internal opinions, which resulted in a new set-up of the scientific groups, to obtain a thematic and flexible research organization. CWI has a distinguished national position that is complementary to national university departments in mathematics and computer science.

CWI introduced a decentralized accounting system that puts several responsibilities on a lower level of the organization and that stimulates a balanced spread of the efforts of acquiring externally financed projects over the various research groups.

CWI's output includes a large number of PhD theses, publications, contracts, patents, licences, WWW and ftp hits, spin-offs, and secondment of staff members. CWI's staff has been very successful in acquiring projects funded by third parties and CWI has served the universities by providing high quality theses and professionally educated PhD's and postdocs.

CWI has been a main partner in establishing the Telematics Institute (TI) and has become involved in a number of basic TI research projects. CWI participated in developing projects for the HPCN and the ICES-KIS programmes Brainport and Gigaport. All these activities are often carried out in cooperation with partners from universities and industry.

CWI has been successful in stimulating the creation of spin-off companies in the field of information technology for exploitation of CWI's pioneering research results; a number of these young companies are flourishing.

CWI has strengthened its role in international cooperation, in particular by strong participation in ERCIM and by establishing bilateral cooperative projects with ERCIM partner GMD (Germany).

CWI has signed cooperation agreements with almost all national graduate schools in mathematics and computer science in order to continue its close cooperation with universities and related institutes such as EURANDOM. Many joint research projects have been performed and exchange of staff between CWI and universities has resulted in new scientific cooperation. Traditionally, a significant number of CWI staff members also have positions as a university professor.

CWI's financial position evolved from critical to sound, and CWI has control of a substantial buffer fund for anticipating fluctuations in project funding. A somewhat growing research capacity was realized, with stable (though in some years slightly decreasing) basic NWO subsidy.

CWI has initiated new elements for Human Resource Management that support flexibility and mobility of staff. In particular, pilot themes have a guaranteed protected initial period for exploring new research topics, and these themes may evolve into definite research themes capable of acquiring external funding. CWI participated in the HRM project of the Ministry of OC&W. A considerable effort has been put in scouting, training and development of employees.

1 Introduction

CWI (Centre for Mathematics and Computer Science) is the research institute of the Foundation Mathematical Centre (SMC), which was founded on 11th February 1946. SMC is funded mainly by the Netherlands Organization for Scientific Research (NWO). CWI's mission is twofold:

- to perform frontier research on strategically selected topics in mathematics and computer science;
- to transfer new knowledge in these fields to society.

Various societal and technical problems related to the environment, traffic, multi-media, image processing, infrastructure, communication, data security, etc. require a thorough knowledge of mathematics and/or computer science. The eminent importance of mathematics and computer science for society and research in other disciplines is evident. In the more than fifty years of its existence, the foundation SMC has, with its research institute CWI, played an important role in the development of the two disciplines, both nationally and internationally.

After the Second World War, mathematics developed simultaneously with the growth of the technical and economical sciences and with the development of the computer. Both factors led to new application areas in mathematics (e.g., biomathematics and operations research) and to a strong growth of existing areas: mathematical physics, analysis, geometry, etc. Now, and for a number of decades, mathematics and computer science play a key role in societal and technical progress. The computer is used in almost any branch of mathematics. Many of these branches would probably not even exist without the computer. Well-known examples are advanced pattern recognition, modern numerical simulations of physical and chemical processes, cryptography, image processing, combinatorial optimization, queueing theory, logic programming, formula manipulation and so on. On the other hand, specific branches of computer science have been able to develop with the help of mathematics.

At CWI, fruitful use is made of this synergy between mathematics and computer science. In recent years, CWI has reconsidered its mission several times. This has led to a greater emphasis on application-driven and collaborative research.

CWI is pre-eminently suited for innovative and multidisciplinary research projects, which require a large-scale organization. CWI has built up this position because it has at its disposal both highly qualified personnel and an excellent infrastructure with respect to library, computer and network facilities.

2 Organization

2.1 Outline

Until December 31, 1996, CWI was grouped into the following six Scientific Departments:

- Analysis, Algebra and Geometry;
- Operations Research, Statistics and System Theory;
- Numerical Mathematics;
- Software Technology;
- Algorithms and Architecture;
- Interactive Systems.

In accordance with recommendations made by external consultants (commissioned by NWO) as well as by a visiting committee which, in 1995, had examined CWI's mathematics research (see Appendix 1 for the visiting committee's recommendations), in 1996 CWI has been restructured under the code name 'Operation FIT' (Flexible, Interdisciplinary, Thematic). The objectives of this operation were to increase flexibility, and to promote interdisciplinary and thematic cooperation in the organization of CWI's research. Taking up the challenge, CWI prepared a restructuring operation, which resulted in a new, theme-oriented organization of its research, instead of the old discipline-oriented structuring. Now, CWI's research is organized in themes, which are grouped into the four 'Clusters':

- Probability, Networks and Algorithms (PNA);
- Software Engineering (SEN);
- Modelling, Analysis and Simulation (MAS);
- Information Systems (INS).

At this moment, twelve themes exist. In addition, there are also some 'pilot' themes, which have the potential to develop into new research themes. The themes are temporary; based on developments in science and society, CWI's management continuously updates the institute's research agenda. Besides, more attention is given to Human Resource Management and flexibility. All managerial scientific positions became temporary. The theme leaders are appointed for at most five years. The new structure enables the desired further shift to interdisciplinary and application-oriented research in a restricted number of carefully selected themes.

The 1996 restructuring has introduced several caesurae throughout this report.

2.2 Management

The foundation SMC has a Governing Board. Until 1996, this board consisted of 15 members. In 1996, the governing board was transformed into a board with 5 members (see Appendix 2 for the present members), two of which were the chairmen of the former SION and SWON (at present: NWO advisory committee for computer science and mathematics, respectively).

The year 1994 saw a change in CWI's management configuration. Upon resignation of prof. P.C. Baayen as scientific director, dr. G. van Oortmerssen was appointed as general director. This was in line with a more general development towards integral management at CWI.

At present, CWI is managed by a team (the Management Team), consisting of the director (chair), the leaders of the four clusters and the controller. An international Advisory Board (see Appendix 2 for the current membership of this board) advises the general director. Our experiences with the new management structure are positive.

2.3 Clusters and themes

On January 1, 1997, a major restructuring of the research activities of CWI was effectuated. CWI's research is now carried out in theme-oriented research groups, which are – at present – grouped into four clusters. Below we list the clusters, themes and their leaders as of December 1, 1998.

Cluster - Theme	**Cluster leader** Theme leader
Probability, Networks and Algorithms (PNA)	**A. Schrijver**
- Networks and Logic – Optimization and Programming (PNA1)	A.H.M. Gerards
- Traffic and Communication – Performance and Control (PNA2)	J.H. van Schuppen
- Stochastics (PNA3)	M.S. Keane
- Signals and Images (PNA4; pilot)	H.J.A.M. Heijmans
Software Engineering (SEN)	**J.W. de Bakker**
- Interactive Software Development and Renovation (SEN1)	P. Klint
- Specification and Analysis of Embedded Systems (SEN2)	J.F. Groote
- Coordination Languages (SEN3)	J.J.M.M. Rutten
- Evolutionary Computation and Applied Algorithmics (SEN4; pilot)	J.A. La Poutré
Modelling, Analysis and Simulation (MAS)	**C.J. van Duijn**
- Environmental Modelling and Porous Media Research (MAS1)	J.G. Verwer
- Industrial Processes (MAS2)	P.W. Hemker
- Mathematics of Finance (MAS3; pilot)	J.M. Schumacher
Information Systems (INS)	**M.L. Kersten**
- Data Mining and Knowledge Discovery (INS1)	A.P.J.M. Siebes
- Multimedia and Human-Computer Interaction (INS2)	D.C.A. Bulterman
- Interactive Information Engineering (INS3)	P.J.W. ten Hagen
- Quantum Computing and Advanced Systems Research (INS4)	P.M.B. Vitányi

In the new structure, which – so far – has met the expectations, CWI is more dynamic and more directed towards the outer world and interdisciplinary collaboration finds a more natural place in the research

plans. CWI is better prepared now to handle dynamic and interdisciplinary research demands. A periodic series of meetings is held to control the budget and research programmes of all themes. Twice a year, CWI's director and controller discuss with the leader of the theme and the corresponding cluster leader: in December about the theme's next year's financial and scientific plans, in the middle of the year about the progress in realizing these plans.

In the four following sections, details are given on the policies and results of the four clusters. In Appendix 3, brief research reports over the period 1993–1998 are given for all themes. (For detailed accounts of all research activities over this period, we refer to the 'Annual Reports' 1993–1998 and – particularly – to the 'Overviews of Research Activities' 1993–1998, as well as to the book 'Images of SMC Research'.)

2.3.1 Probability, Networks and Algorithms

The cluster PNA focuses on discrete and probabilistic modelling, optimization and control (with control theory, discrete mathematics, logic, operations research, and stochastics as prime tools), and on their applications in technology and management, in particular (but not exclusively) in information technology and operations management.

The first and foremost research objective of PNA is to make fundamental and applied contributions to problems and techniques in these areas. Testing and implementing the new techniques for practical use and developing algorithms also belong to the objectives, as exemplified by participation in several externally funded application-oriented projects and a considerable number of consultancies.

As for consultancies, it is PNA's policy not to compete with other parties in the service sector, but rather to supplement them by developing innovative scientific techniques and implementing and testing them in practice. Results of PNA's research are being used in transportation (Dutch Rail, State Highways), information technology (IBM, Hewlett Packard, Philips, Microsoft), communication (KPN Research, AT&T, Bell Communications Research), public health (hospitals), environment (RIVM), seismology (Shell, KNMI), and finance (PriceWaterhouseCoopers).

Much of PNA-research is on the borderline of mathematics and computer science. Examples are computational logic, computer-intensive methods in stochastics, computational complexity, fractal image coding and compression, wavelet transforms for signal analysis, morphological image processing, control of discrete-event systems and hybrid systems, performance and control of computer-communication networks, and the design of digital and VLSI-circuits.

PNA aims to maintain strong ties with academia and other research institutions. Six members hold a university professorship, while three others have other kinds of university associations. Members of PNA play an active role in several Dutch research schools, in graduate networks, and in research institutes like EURANDOM and the Telematics Institute. They present graduate courses and are involved in the organization of international conferences.

PNA receives financial support from NWO (SWON, SION, STW), ERCIM, NATO, INTAS, and international programs with Indonesia and Hungary, for several research positions for PhD students and postdocs. In addition, the European Commission supports PNA through the Training and Mobility of Researchers (TMR) Program in the projects 'System Identification' (with CWI as coordinator) and 'Discrete Optimization Network'.

Among the research accomplishments are:

- A proof of the homomorphism theorem for noncommutative Bernoulli schemes with strictly different entropies (a problem posed in 1975 by A. Connes).
- A sharp bound for the number of factors in a regular bipartite graph (solving a problem of Erdös and Rényi (1968)), and a fast algorithm finding them, yielding a tight bound for the 3D dimer problem in statistical physics.
- A new, more robust method for the density of randomly moving, coalescing particles on the d-dimensional grid, extending the simplest model of Bramson and Griffeath.
- A forbidden-minor characterization of the representability of matroids over GF(4).
- A proof that there are no more than $2m$ equidistant points in m-space under the l_1 metric, for $m \leq 4$.
- A characterization of the existence, and sufficient conditions for minimality, of realizations of positive linear systems based on a partial classification of primes in the positive matrices.
- A new programming language combining the advantages of logic and imperative programming.
- The system CADANS, finding and optimizing the timetable for Dutch Rail.

- Models of heavy-tailed communication traffic, and analytic expressions for several performance characteristics of such models.
- An extension of the theory of Hellinger integrals and Hellinger processes, developed by Liptser et al. for binary experiments, to abstract parametric families of statistical experiments.
- The result that the elementary symmetric polynomial can be successfully bootstrapped, under certain mild conditions.
- The development of a new transform, the wavelet X-ray transform, (uniting the continuous wavelet and the Radon transform), which has been used successfully for the filtering of unwanted geometrical features from seismic (geological) data.
- The construction of an axiomatic framework for multiresolution image analysis and synthesis, enabling the construction of nonlinear (morphological) wavelets, with potential applications in image compression, image fusion, texture analysis, and image and video indexing and retrieval.
- The development of a random set model (extending the well-known Boolean model of a binary image), taking into account internal correlation, and of likelihood-based estimation techniques for it, utilizing modern Markov chain Monte Carlo methods.

2.3.2 Software Engineering

Cluster SEN performs research on a number of themes in the broad area of software engineering. Precursors of the cluster were most groups of the former department of Software Technology, and two teams from the former department of Interactive Systems. The members of SEN bring together expertise in areas such as software architecture, distributed and embedded systems, scientific visualization, evolutionary computing and theoretical foundations. Over the years considered in the present evaluation, the general focus in the work of SEN has shown a marked transition from fundamental studies to research with a clear strategic motivation.

As to the involvement of SEN in strategic and industrial collaborations, the period under review exhibits a substantial shift in emphasis: whereas in the early nineties most of our externally funded work took place in EU projects (ESPRIT, SCIENCE, HCM, ...), more recently we have completed several large scale contracts with Dutch government and industry (Ministry of Public Works, HPCN, banks, software industry, Philips, Dutch Railways, and others). The level of NWO project funding, esp. through (the former) SION, has remained at approximately the same (high) level. In the area of university interaction, we mention

- four SEN members are part-time (full) professor at some university
- SEN maintains close ties with IPA (the Dutch Research School on Programming Research and Algorithms)
- in the years 1993–1998, 20 PhD theses were awarded to (former) SEN members

The work of theme **SEN1** on Software Development and Renovation builds on a long tradition of the group concerning programming environments and algebraic specification, in particular based on the ASF+SDF (Meta)Environment. Triggered by industrial needs, the functionality, performance and flexibility of the system have been enhanced considerably. The software renovation effort has led to a flexible tool set capable of analyzing real-life COBOL legacy systems using cluster and concept analysis, automatic type inference, and program visualization. In the area of software optimization, SEN1 developed PIM, a toolkit for compilers (jointly with IBM TJ Watson Research). Furthermore, the system Sophus, a novel programming style for numerical applications incorporating the idea of 'coordinate-free numerics', was developed. In the area of domain specific languages, the language RISLA for describing financial products was designed, formalized and implemented. RISLA is a commercial success, and a long term research cooperation with CAP Gemini was established. In the area of interactive visualization environments, techniques were studied which allow a more precise representation of complex data. The results were used in the visualization of turbulent flow. A novel specification method was studied to allow interactive manipulation of geometric objects.

Within **SEN2** and its predecessors, work has been done on the semantics of specification languages, rewriting technology, real time and verification techniques for distributed systems. Techniques have been developed that are able to verify the kernel of realistic, hybrid protocols (e.g. Philips' Remote Control 6 standard or the Firewire or IEEE 1394 protocol). Moreover, it was shown that systems such as Coq or PVS can be used to check such verifications. During the last two years the focus has shifted towards automatic verification, in an attempt to handle textually large systems. The tools of SEN2 were based

on Linear Process Operators, in order to exploit symbolic information, and to avoid the state space problem. The tools as developed have a performance comparable to state of the art verifiers such as Caesar/Aldebaran or SPIN, though the fruits of the symbolic nature of the approach have still to be reaped. Within the realm of term rewriting, extensions have been studied to term graph rewriting, infinite rewriting and origin tracking (the latter enabling an analysis of the sequential nature of the lambda calculus improving a classical theorem of Berry).

Theme **SEN3** resulted from a merger of the former Computational Models group and the Interaction and Parallelism group. In the former, the long-term project on foundations and applications of (metric) semantics was concluded with the publication of a comprehensive monograph. The study of co-algebraic semantics, including the important proof principle of co-induction, was initiated, and ample evidence for the broad applicability of the methodology was collected. The latter group continued its work on the pure coordination language Manifold, comprising a system running on many platforms. The group successfully aimed at the dissemination of the scientific concepts of Manifold in the academic world, and at applying the language in a number of case studies, such as the parallelization of numerical libraries, and the coordination of software packages used by Delft Hydraulics for High Performance Computing. SEN3 has so far benefitted from the synergy between its fundamental and applied lines of research, by producing a well-founded mathematical model of Manifold that will serve as a basis for the future development of programming environments for coordination, notably tools for debugging and visualization.

For pilot theme **SEN4** on evolutionary algorithms, new insights were established for transmission function models of genetic algorithms, for both finite and infinite populations; and new approaches for penalty functions in constrained numerical optimization were obtained. Also, new results were achieved for air traffic flow management by using evolutionary algorithms. By using neural networks, a software system for visualization and clustering of high dimensional data has been developed. New results are also established for unsupervised classification problems in remote sensing (RS) data. This has recently led to both novel research results and a novel software system, which seems to be able to become an innovative step in RS classification software systems.

2.3.3 Modelling, Analysis and Simulation

The MAS research program was concerned with numerical, computational and qualitative aspects of mathematical models that arise in a wide range of real-life applications. These applications were combined into three themes, each containing a number of characteristic projects.

MAS mainly builds upon the former department of Numerical Mathematics (NW). During the 're-structuring' of 1996, P. van der Houwen stepped down as head of NW and received the honorable status of CWI-Fellow. At the same time the group Modelling and Analysis (AM2) was incorporated. This group has experienced a drastic change in research direction during the period of this evaluation. The first years it was headed by O. Diekmann with successful programs on Dynamical Systems and Population Dynamics. A true highlight was the 5-year existence of the national facility 'Dynamical Systems Laboratory' and the development of the bifurcation package CONTENT by Y. Kuznetsov. During 1995 it shifted towards PDE research with Porous Media as main field of application (with C.J. van Duijn replacing O. Diekmann). Also in 1995, the mathematical software company CAN was created as a spin-off. Another MAS development is the build-up of research in Financial Mathematics, first (1997) as a project within MAS2, later (1998) as the pilot theme MAS3. In the Fall of 1999 this pilot will be evaluated. Based on the outcome, a decision will be made with respect to its future status.

Two years after CWI's transition towards a theme-oriented organization, MAS has grown into a healthy structure. It now has identifiable mathematical disciplines in the projects, which are connected to – and inspired by – the outside world through distinct applications. These projects are dealing with numerical analysis, large scale computing, computational fluid dynamics, and more theoretically oriented analysis for (partial) differential equations. They reflect the philosophy of MAS to contribute to these areas on the one hand and to keep, on the other hand, an open mind for problems and applications which are of high societal relevance. In this respect, knowledge-transfer is a key 'leitmotiv' in the work of MAS. In the international context, MAS is best characterized as a cluster with a SIAM signature. In 1998 C.J. van Duijn received the prestigious 'Max Planck Award for International Cooperation'.

MAS1 focused on numerical and PDE research, related to Environmental and Porous Media Applications. The numerical research was mainly concerned with 3D systems of nonlinear advection-diffusion-reaction equations modelling pollutant transport and chemistry in the atmosphere and surface water. New advection schemes and integration methods based on operator splitting, implicit-explicit and ap-

proximate matrix factorization techniques have been developed. The PDE research was in the direction of nonlinear evolution equations (parabolic and hyperbolic) and free boundary problems related to flow and transport in porous media. New results were obtained with H.W. Alt (Bonn) on the formation of cusp singularities in elliptic free boundaries, and with J. Bruining (Delft) on uniqueness conditions for 2×2 systems of hyperbolic first-order conservation equations. The research has led to a large number of well received publications, extensive contracts and joint projects with atmospheric and porous media researchers.

The research of **MAS2** mainly involved numerical and computational analysis, resulting from extensive collaboration with industry, such as ship and aircraft building, electronic and chemical industry. Specific areas of interest were computational fluid dynamics (CFD), computational number theory (CNT) and initial value problems (IVP). Within CFD the work concentrated on advanced methods for systems of nonlinear conservation laws, multi and sparse grid solution methods, local grid adaptation and parallel computing. A particular research achievement was the development of a sparse grid algorithm for the three-dimensional equations of gas dynamics and the computation with this algorithm of the flow around an aircraft wing. CNT aimed at improving the factorization method 'Number Field Sieve'. Two numbers of 181 and 186 decimal digits have been factored in 1997 and 1998, respectively, establishing two new world records. The results offer cryptographers a reliable estimate of what is still a safe key size in practical RSA public-key crypto systems. IVP focussed mainly on the code PSIDE and the CWI Test Set.

The pilot theme **MAS3** started in 1998 with financial mathematics. This being a fairly new field at CWI, MAS3 has spent much of its time in establishing critical mass by hiring young researchers and mobilizing CWI staff, in exploring the mathematical problems involved and, last but not least, in developing contacts with potential users such as financial institutes and banks. In particular a program has been developed with the two Amsterdam universities which involves courses on Financial Time Series Analysis and Financial Engineering. Research topics that were identified include: statistics of stochastic processes, Monte Carlo and quasi-Monte Carlo methods for derivative pricing and risk management, and processes with heavy-tailed distributions. New results were obtained by K. Dzhaparidze on the relation between binomial trees and continuous-time processes.

2.3.4 Information Systems

The research activities of cluster INS are focussed on various aspects of multi-media information systems, with subsidiary attention to grand-challenges posed in quantum computing. The cluster is an outgrowth of the former department of Algorithmics and Architecture. It has been extended with a group from the department of Interactive Systems dealing with innovative ways to set standards for graphics processing, and one group from the pure mathematics department heavily involved in digital library issues. Together these groups were challenged to find a new basis for frontier research in the area of digital libraries and information engineering.

An important output of the work in this cluster is the development of prototypes for demonstrating and experimenting with solutions. Many of these prototypes are used by affiliated research groups or find their way through partners in (inter)national consortia. The policy regarding their construction is to develop them up to the point that real applications can be built and exercised.

Exploitation of research prototypes, if warranted, is primarily done outside the institute. Therefore, the themes foster transfer of research results to spin-off companies. Out of the 7 companies started from the institute in this reporting period, 5 were initiated by former members of the INS cluster.

Another important outlet of the knowledge acquired is through active participation in International Standardization committees, such as ANSI and W3C dealing with multi-media information systems and the web.

INS themes participate in many EU projects (MERCURY, KESO, CHAMELEON), large national projects (HPCN-IMPACT, AMIS), telematics top institute (DMW), and projects aimed at knowledge transfer (STW-FASE, Elsevier). Such participations are considered a valuable asset in driving frontier and innovative research.

The work in **INS1** continues and strengthens the activities of the former database group in the direction of extracting knowledge from large databases and the disclosure of information in multi-media databases. In addition to the publications reported elsewhere, the group has produced a state-of-the-art main-memory database management system Monet and demonstrated its performance capabilities on a wide-range of sizeable application benchmarks. Combined with a novel software architecture for data

mining, it has become the technological base for the spin-off company Data Distilleries.

The work in **INS2** has been centered around multi-media authoring systems, based on innovative research in multi-media standardization techniques for the Web. The underlying software prototype, called Grins, has been based on the scripting language Python, developed at CWI in the period 1987-1994. The Python project is continued with the support of NCSA in the USA and has acquired a leading position in this area (next to Perl). Subsidiary attention has been paid to secure payment protocols and electronic publishing using structured documents. The human-computer interfaces research of the early nineties has led to the spinoff General Design, while the multi-media activities led to the spinoff company Oratrix.

The newly formed theme **INS3** deals with research questions stemming from Interaction and Multimedia, Logic and Computational Linguistics and Concept Building for Digital Libraries. The focus for all the projects involved is to provide information engineering methods and tools to automatically create user friendly access and control environments for large data and information collections based on the analysis of the contents. Eidetica has been the first spin-off company from this theme.

The theme **INS4** continues the former Algorithmics and Complexity Research Group (ACRG). In the last five years of ACRG's existence the major research tracks were machine learning, distributed and parallel algorithmics, and description complexity and computational complexity. Research in quantum communication complexity was initiated with a focus on the communication complexity model based on EPR pairs. It was demonstrated that in this setting one can achieve (exponentially) improved performance over classical methods. The mechanics groups at Innsbruck (Austria) and Caltech (USA) (Cavity QED) will implement our protocols, serving as an experimental verification and touchstone of quantum computing and quantum mechanics. The remaining foci of research activities of this group have received the highest international scientific recognition.

During this reporting period the research group on fundamental cryptographic protocols has been dismantled in 1997. Many of its researchers found a job in the spinoffs Digicash and UniPay, while ongoing European research projects were successfully finished under the umbrella of INS2 and INS4. In 1998, R. Cramer (ETH) received the C. Huygens award for the best PhD thesis in ICT in the preceding three years.

2.3.5 Brief quantitative overview of scientific and financial performance

In the current section, some quantitative information is given about all themes and CWI as a whole.

In Table 1 the research personnel formations of all themes are given as they were at the end of 1998. In Table 2, the quantitative development of CWI's total research staff is displayed. (As opposed to the numbers in Table 1, the numbers in Table 2 include scientific management and ignore secondment of scientific staff elsewhere.)

In Table 3, by means of the total numbers of publications, an impression is given of the scientific output of the themes over the last two years.

As a measure of the performance of the themes with respect to the acquisition of externally funded research, in Table 4 percentages are given of the total costs per theme which were covered by such funding. The total costs of a theme include gross salaries, costs for travel and visitors, share of computer and library facilities, overhead for management and support staff, and material costs. The amounts of external funding are based on the income of each theme in the categories:

- NWO subsidies (obtained in national competition, to be distinguished from NWO's basic or lump-sum financing),
- other national projects (such as the HPCN programme),
- international funds (especially EU),
- contract research for government or industry,
- miscellaneous.

In recent years, the de facto target for external funding (i.e. all income besides NWO's basic subsidy) for CWI as a whole has been set at 30%. The data in Table 4 should be seen from this perspective. Thus, when a theme scores more than 30%, it outperforms CWI's overall target (profit situation). In the same way, a percentage below 30% falls short of the target. In case of profit, a theme is allowed to invest half of it in the theme.

In Tables 5 and 6 we give some more data for CWI as a whole. In Table 5 the scientific output of CWI is given, similarly as in Table 3, but now over the entire report period. In Table 6 some quantitative

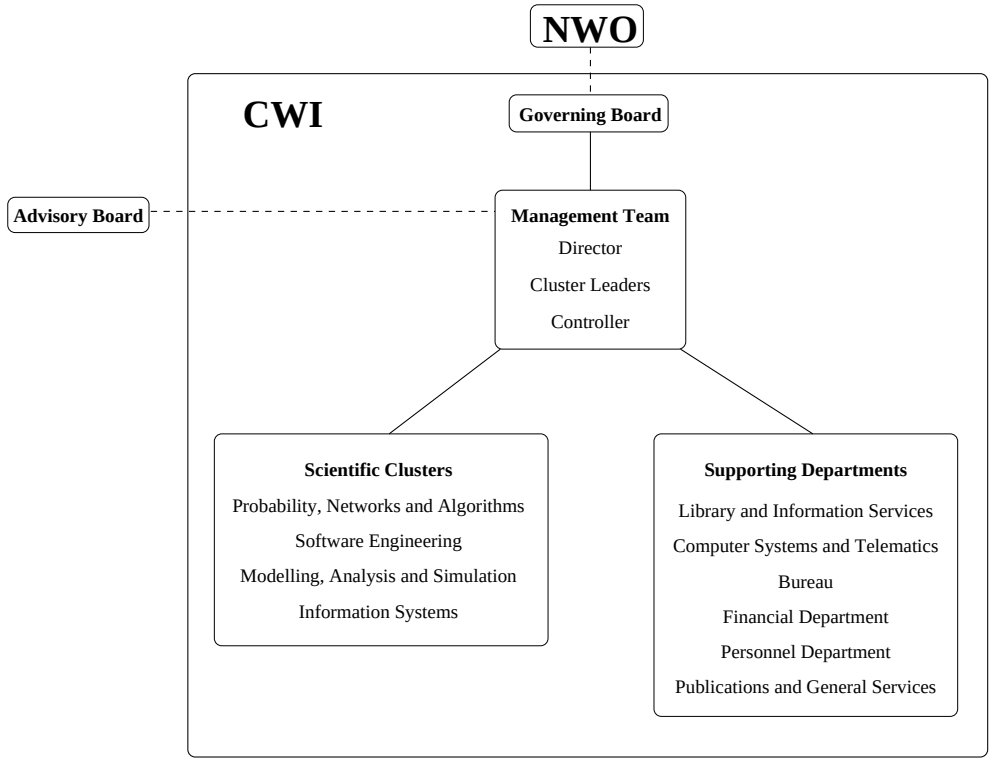

FIGURE 1. Organizational chart of CWI

information is given about the amount of external contract research over the report period. Diagrams of the various quantitative data are given in Appendix 9.

To give an impression of CWI's dynamics in research, we list some research activities that were terminated in the report period, as well as some new activities. Ended were, e.g., discrete mathematics (transferred to Eindhoven University of Technology), biomathematics (transferred to University of Utrecht), cryptography (transferred into two spin-off companies), computer algebra (transferred into spin-off company CAN and to Universities of Eindhoven and Amsterdam), intelligent CAD (transferred to TNO) and programming calculi (transferred to Universities of Utrecht and Eindhoven). Further, over the report period, the relative importance of theoretical computer science was substantially reduced. New research activities started were, e.g., wavelets, financial mathematics, mathematics of porous media, evolutionary computation, quantum computing and data mining.

2.4 Supporting Departments

2.4.1 Scope and structure

Support for CWI's Management Team and research themes falls under the following headings:

1. Library (books, journals, preprints, information services),
2. Computing infrastructure (networks, hardware, software),
3. Financial Administration (accounting, payroll, financial management information),
4. Personnel (contracts, fringe benefits, HRM, organization development),
5. Bureau (contracts, marketing/PR, scientific administration, liaisons),
6. Maintenance and facilities (building, reception, mail room, archiving, restaurant, cleaning),
7. Publications (dtp and design, prepress, printing, publishing).

This support is organized in six departments, coinciding with the above listing, where items 6 and 7 are grouped in a single department. In Appendix 4, detailed information is given about the departments belonging to the first two items: CWI's library and the Computer Systems and Telematics Department.

Personnel involved in all six departments amounted to 59 fte in 1993 and 49 fte in 1998. This reduction can be attributed completely to outsourcing (restaurant) and termination of non-core support tasks. A global overview of CWI's organization is given in Figure 1.

Theme	Senior staff [fte]	Postdocs [fte]	Other staff [fte]	PhD students [fte]	Programmers [fte]	Total [fte]
PNA1	4.0	4.2	1.0	1.0	0.9	11.1
PNA2	1.7	0.4	-	-	-	2.1
PNA3	3.4	2.0	-	1.8	0.75	7.95
PNA4	4.5	1.0	-	2.0	1.2	8.7
SEN1	4.6	2.0	1.2	1.0	-	8.8
SEN2	0.9	2.2	-	4.6	1.0	8.7
SEN3	2.5	2.0	-	1.0	3.0	8.5
SEN4	1.8	1.0	0.4	2.8	0.75	6.75
MAS1	5.6	3.8	-	4.0	1.3	14.7
MAS2	3.9	2.0	-	5.5	1.1	12.5
MAS3	1.0	2.0	-	1.0	-	4.0
INS1	1.6	2.0	-	4.0	1.0	8.6
INS2	4.4	0.7	-	-	2.0	7.1
INS3	3.0	0.5	3.0	2.0	2.0	10.5
INS4	1.8	2.0	-	5.0	-	8.8
Totals	44.7	27.8	5.6	35.7	15.0	128.8

TABLE 1. Present nett research staff in themes

	1993	1994	1995	1996	1997	1998
Permanent	52.7	58.0	56.9	58.9	56.8	58.0
Non-permanent	44.6	42.1	34.8	31.0	38.0	47.5
Seconded at CWI via NWO	25.3	29.2	30.3	29.1	26.3	25.9
Seconded at CWI otherwise	21.0	28.7	27.3	25.2	13.2	18.4
Total scientific staff at CWI	143.7	157.9	149.3	144.2	134.3	149.7

TABLE 2. Quantitative development (in fte) of CWI's gross research staff

Theme	# articles		# CWI Reports		# Books		# Other publ.		# PhD theses	
	1997	1998	1997	1998	1997	1998	1997	1998	1997	1998
PNA1	23	30	2	4	3	1	2	24	0	0
PNA2	17	24	9	6	0	0	2	16	0	0
PNA3	11	9	1	8	0	0	0	5	1	0
PNA4	20	17	6	2	0	2	5	4	0	0
SEN1	20	17	15	14	1	0	12	10	0	1
SEN2	23	19	6	11	0	1	24	10	1	1
SEN3	12	18	2	10	1	1	2	4	0	0
SEN4	7	5	2	9	0	1	1	1	0	0
MAS1	12	21	23	18	0	0	1	2	2	3
MAS2	34	28	16	17	3	0	17	11	5	1
MAS3	-	2	-	0	-	0	-	0	-	0
INS1	24	18	2	8	0	0	3	5	1	1
INS2	12	9	0	0	2	0	11	11	0	1
INS3	6	8	6	9	1	1	5	0	2	0
INS4	28	30	2	0	1	0	13	4	1	0
Totals	249	255	92	116	12	7	98	107	13	8

TABLE 3. Numbers of publications by the themes in 1997–1998

Theme	**1997** [%]	**1998** [%]
PNA1	24	14
PNA2	19	28
PNA3	14	14
PNA4	16	17
SEN1	51	46
SEN2	44	45
SEN3	13	11
SEN4	17	30
MAS1	30	28
MAS2	21	22
MAS3	–	24
INS1	47	48
INS2	34	31
INS3	21	22
INS4	32	17

TABLE 4. Total costs covered by external funding (including NWO projects)

	1993	**1994**	**1995**	**1996**	**1997**	**1998**
Articles in journals and proceedings	224	255	301	277	249	255
CWI -reports	125	135	155	116	92	116
Books	4	4	6	3	12	7
Other publications[1]	99	104	97	111	98	107
PhD Theses	8	15	8	11	13	8
CWI publications series:						
CWI Quarterly	4	4	4	4	4	4
CWI Tracts[2]	12	7	6	6	5	3
CWI Syllabi	2	3	1	3	1	1
CWI Miscellaneous	1	1	0	1	1	0

Remarks.
[1] Other publications are: technical reports published by other institutes, libri amicorum, deliverables for projects, documentation of software, articles in semi-scientific journals, etc.
[2] In 1997, the policy of the editorial board of *CWI publications* has changed with respect to PhD theses as CWI Tracts: only high-quality PhD theses are published as Tracts, after critical selection.

TABLE 5. Publications 1993–1998

	1993	**1994**	**1995**	**1996**	**1997**	**1998**
International:						
EU Projects	16	16	24	18	13	11
EU Working Groups and Networks	13	13	14	11	9	2
ERCIM working groups	2	6	8	10	12	14
Subtotal International	31	35	46	39	34	27
National:						
NWO (SION, SWON, STW, NCF, NFI, other)	40	40	35	42	45	39
ICES (HPCN, other)	-	-	5	5	4	4
Telematics Institute	-	-	-	-	-	7
Contract research (for industries, banks, large techn. institutes, etc.)	24	25	28	29	24	28
Subtotal National	64	65	68	76	73	78
Total number of externally funded activities	95	100	114	115	107	105

TABLE 6. Externally funded projects (at least NLG 5000 for contract research)

2.4.2 Trends and developments

During the last six years, there have been gradual changes in the way research is being carried out. These changes not only influence CWI's research themes, but also affect the supporting departments. Of these developments we mention:

- Increased importance of project funding and at the same time pressure on long term structural funding,
- More application-oriented research,
- Research is being carried out more and more in collaborative networks with both academic and non-academic partners,
- The demand for ICT R&D people is growing rapidly where supply cannot keep up with this trend.

More general developments that influence CWI's supporting departments are:

- Decentralizing of responsibilities within organizations,
- Outsourcing of non-core activities,
- The networked or information society,
- Reduction and greater flexibility in working hours per employee.

2.4.3 Effects on the Supporting Departments

The above developments had substantial effects on the supporting activities:

1. **Library.** CWI's library is increasingly providing access to its information through electronic networks. An on-line catalogue to the library's own collection has been installed, while CWI's preprints collection has been made available through CWI's own web but also through federated repositories (e.g. NCSTRL).
2. **Computing infrastructure.** Networking has received more and more attention over the years. Substantial investments have been made in the upgrading of CWI's internal network (glass fibre, ATM, utp), and also in upgrading the networking expertise of personnel involved. Another area that received more attention are applications on the networks, such as videoconferencing.
3. **Financial Administration.** Increased project work and decentralizing of responsibilities led to the demand for financial data on the level of projects and research themes. This information is increasingly being supplied on the institute's intranet.
4. **Personnel.** The hiring of more foreign and temporary research staff has led to an increased number of contracts to be processed by Personnel. At the same time these contracts show more variety and a growing degree of complexity.
5. **Bureau.** More projects have led to more contracts to be negotiated and managed and to a greater variety in research contracts. Next to that, as CWI is involved in a growing number of networks the

liaison activities also increase. Due to the importance of networks, substantial effort is also going into the public relations and marketing activities of the institute with the aim of securing CWI's leading research role in mathematics and computer science.

6. **Maintenance and facilities.** A recent development here are flexible workspaces to cope with the increasing and varying demand for workspace.
7. **Publications.** Due to the outsourcing of hardcopy print work (to be finalized in the course of 1999) and the increasing popularity of electronic publishing, a shift in this area is taking place from traditional to electronic publishing.

2.5 Human Resource Management

Since the restructuring of CWI Human Resource Management (HRM) is, besides through the dynamics of themes, also achieved through: (i) temporary appointments in CWI's Management Team and of the theme leaders, (ii) stimulation of the internal and external mobility of researchers, and (iii) a so-called triple-ladder career policy. Cluster leaders, who are members of the Management Team, are appointed for a period of at most five years. The management of a theme is limited in a natural way by the finite life time of a theme. (By fulfilling a management function, a researcher may build up the right to sabbatical leave.) Internal mobility is achieved by the dynamics of the themes and also by switches of researchers during a theme's life time. External mobility is stimulated, particularly secondment of CWI research staff at universities and – vice versa – university staff at CWI. In the triple-ladder structure (Figure 2), three different types of careers can be distinguished:

1. scientific career,
2. project-management career,
3. line-management career.

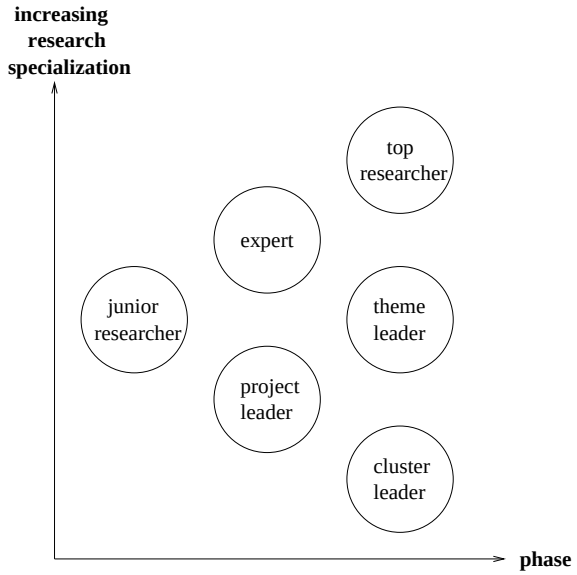

FIGURE 2. Triple ladder structure.

The three phases in the triple-ladder structure are:

1. • junior researcher (skilled researcher, project member),
2. • expert (internationally known researcher), or
   • project leader (researcher with coordinating tasks),
3. • top researcher (internationally recognized, front-rank researcher),
   • theme leader (senior project leader with initiating and coordinating tasks), or
   • cluster leader (senior researcher with general-management tasks).

In exceptional cases, as a recognition of great scientific and management achievements for CWI, a CWI researcher may obtain the status of CWI-fellow. (The first CWI-fellow is P.J. van der Houwen from the cluster MAS.)

3 CWI's environment

3.1 National

3.1.1 NWO

The Netherlands Organization for Scientific Research (NWO), the central Dutch organization in the field of fundamental and strategic scientific research, is the main subsidizer of CWI. The structure of NWO is decentralized, it consists of seven councils. Since 1998, CWI reports directly to NWO's Governing Board. In addition, CWI maintains close contacts with NWO's Physical Sciences Council (GBE).

CWI traditionally cherishes close links with academic research in mathematics and computer science. This was formalized in 1982, when NWO commissioned SMC to monitor its mathematics research projects carried out at the Dutch universities (mostly PhD grants). For similar research in computer science – then a new research discipline recognized as such in the Academic Statute – a separate foundation, SION, was created. During the 1990s it became clear that renewal of the operative management structure was necessary. Hence, following an advice of external consultants, in May 1996, NWO's National Activities in Mathematics were incorporated in the new foundation SWON (Stichting Wiskunde Onderzoek Nederland). By this restructuring, CWI's relation with NWO was made symmetrical with respect to mathematics and computer science. In recent years, a substantial part of CWI's collaboration with university researchers has taken place within SION and SWON projects. Both foundations and CWI have interacted in connection with their research programmes. For example, CWI has been involved in drawing up the strategy document *Wiskunde op Raakvlakken* (*Mathematics on Interfaces*), prepared by SWON, as well as the *National Research Agenda for Computer Science (NOAG-i)*, prepared by SION. In 1998, CWI participated in 18 SION projects, along with researchers from 9 universities. Since SWON's foundation in mid 1996, CWI has participated in 13 projects, along with 8 universities. Here the subject Mathematics of Finance deserves special attention. Being SWON's 1997 Year Theme, research in this field received additional support. CWI benefited a great deal from this support, which boosted preparations for CWI's own full-grown research theme in mathematics of finance. At the end of 1998, as a major result of a reorganization of NWO itself, the responsibilities of SWON and SION were taken over by advisory committees under the auspices of NWO's Physical Sciences Council (GBE).

CWI has also continued its participation in projects financed by NWO's Technology Foundation STW, in which industry is committed to play an active role. This participation is a proof of CWI's success in linking up its fundamental research with societal demand.

3.1.2 Universities and Graduate Schools

CWI's development keeps pace with those in the academic world, given the many existing close ties between the two. The relations continue to evolve dynamically, as is witnessed by an initiative of CWI to come to a more structured cooperation with the Dutch universities. E.g., agreements were concluded with the Eindhoven University of Technology and with the Free University of Amsterdam about mutual secondment of researchers. Particular attention has been given to the exchange of researchers and cooperation with the so-called Graduate Schools (national collaborations of alliances of partners from several universities, with as primary task the education of PhD students). Furthermore, CWI plays an active role in some nationwide research networks, structures which enhance the coherence of academic research in a certain field, for example the Operations Research network. The number of relations with academia has strongly increased over the period 1993–1998.

Involvement of CWI in the academic world may also be measured by the rate of CWI staff taking permanent positions at universities. Lack of precise data does not prevent the conclusion that, taking only the last two decades, it is a matter of several dozens. At present, 18 staff members hold a part-time full professorship at Dutch universities, including three full members of the Royal Netherlands Academy of Arts and Sciences (KNAW). Finally, it is worthwhile to mention that, on average over the last decade, ten junior CWI staff members annually completed their research with a PhD thesis defended at a Dutch university (see Table 5), usually supervised by a professor who also leads a research group at CWI. Several of these qualified young researchers continue their careers with companies (including banks) or governmental institutions, which is one of our most effective forms of knowledge transfer. In Appendix

5, we list the present affiliations of former PhD students from CWI, who have successfully defended their PhD theses in the report period. Below, an overview is given of CWI's academic relations in 1998.

Secondment of CWI staff at universities:

- 18 full professors,
- 4 researchers.

Secondment of university staff at CWI:

- 13 researchers,
- 7 advisors.

Cooperation agreements with Graduate Schools:

- Thomas Stieltjes Institute for Mathematics,
- Euler Institute for Discrete Mathematics and Applications,
- Dutch Graduate School in Logic,
- Institute for Programming Research and Algorithmics,
- Dutch Institute of Systems and Control,
- School for Information and Knowledge Systems,
- Mathematics Research Institute.

In 1997, an evaluation report[1] was published on the research in Mathematics and Computer Science at the Dutch Universities. In Appendix 6, we give the qualifications from this report of the university research groups to which full professors from CWI contributed.

3.1.3 Telematics Institute

An important event has been the governmental decision to create – after extensive pre-selection – four Technological Top Institutes, in which industry and the research world join forces. CWI actively participates in the research programme of the Telematics Institute, with Twente University, TNO (the Dutch Organization for Applied Scientific Research) and Delft University of Technology as other participating academic and technological institutions. In addition, seventeen companies are involved in the Telematics Institute, including IBM, KPN, Lucent Technologies, ING and Rabofacet as participants. In 1997 and 1998, CWI submitted several research proposals, seven of which have been granted so far.

3.1.4 ICES

Revenues from sales of Dutch natural gas to other countries are being partially invested in infrastructures in the Netherlands. Recently the knowledge infrastructure is also considered to be an important asset, and has consequently received input from this revenue fund. The commission controlling this fund is called ICES, and projects financed out of this fund are usually referred to as ICES-projects. In 1995 ICES-funds were used to establish a special foundation to finance projects in the area of High Performance Computing and Networking (HPCN). CWI secured substantial funding from this source for 4 research projects, carried out with industrial participation. These projects will all end before 2000. In 1998 ICES-funding for the amount of 30 MFl was granted for R&D projects carried out within the 'Wetenschap en Technologie Centrum Watergraafsmeer' (WTCW), the geographical grouping of research institutes in Amsterdam of which CWI forms part. Projects are intended to run for 5 years, and CWI's focus within these projects will primarily be on multimedia information engineering.

Another important ICES-project that was granted in 1998 is "Gigaport". Gigaport will make a high-bandwidth network infrastructure available to research institutes and commercial organizations to experiment with new applications on this network. Connections with similar high-bandwith infrastructures in other countries (e.g. internet2 in the USA) will be provided. CWI and the Telematics Institute will be among the main institutes that will use this infrastructure for research and development on new applications.

[1] *Quality Assessment of Research, Mathematics and Computer Science at the Dutch Universities*, VSNU, Utrecht, 1997.

3.1.5 Governmental and other institutions

Besides the important relation with the Ministry of Education, Culture and Science (OC&W), CWI now also has increasingly important contacts with the Ministry of Economic Affairs (EZ). (The participation in the Telematics Institute is an example of such a contact.)

Several large governmental institutions with research missions are ideally suited to playing the role of an intermediary between fundamental research and concrete applications (the actual making of a product). CWI has long-standing good relations with many of these institutions and is continually searching to extend these relations.

CWI's relations with the ministry of Public Works (the RWS department) date back to the fifties, when the institute started with advisory work in statistics and computational fluid dynamics to protect the Netherlands against North Sea disasters (flooding and coastal pollution) — a tradition continued up to the present. In the 1980s CWI also received commissions for research in the traffic area, and presently cooperates with RWS in, e.g., the European project DACCORD.

Cooperation with the Dutch Organization for Applied Scientific Research TNO has taken place in a number of projects concerning porous media, focusing on the modelling of transport phenomena underground as a system of partial differential equations. One application is the removal of organic contaminants from the soil by pumping or air sparging. In addition, cooperation with TNO in the field of information technology is growing rapidly, boosted also by the participation of both CWI and TNO in the TI.

Several other large institutions cooperate with CWI: the Royal Netherlands Meteorological Institute KNMI in wavelets, sparse-grid methods for time-dependent partial differential equations, and regional 3D long-term ozone models (LOTOS); the Dutch Maritime Research Institute MARIN in improved Navier-Stokes methods in ship hydrodynamics and in wavelets; and the National Institute for Public Health and Environmental Protection RIVM in sparse-grid methods and the LOTOS model. Finally, CWI's year-long cooperation with the National Energy Centre ECN in the field of Virtual Reality has been continued. For many years, contacts also exist with Delft Hydraulics (WL) and the National Aerospace laboratory (NLR).

3.1.6 The private sector

CWI's relations with Dutch companies go back to the early years of its existence. For example, the Mathematical Centre (CWI's name prior to 1983) pioneered in the building of computers in the fifties. This activity was soon taken over by the Dutch firm Electrologica; eventually, this became part of Philips.

In particular in the current decade, CWI made a deliberate policy to actively approach industry, thus aiming at the utilization of its fundamental knowledge acquired over the years. Besides contract research, these industrial contacts also led to inspiration for new research. Apart from direct contacts leading to various, sometimes long-term commissions, CWI also proceeded more indirectly. A fine example of the latter is provided by *CWI in Bedrijf*. At this annual event, always on the first Friday in October and first organized in 1992, CWI presents its research potential to the private sector, of which, on average, one hundred representatives attend.

In recent years, CWI's many contacts with the private sector have extended from traditional 'technical' research areas such as computational fluid dynamics and transport phenomena to sectors such as traffic and services, in particular financial services. In the latter field CWI, e.g., has started contract research into the renovation of legacy systems (the SOS Resolver project, including ABN AMRO as a participant) and studies on the application of (quasi-) Monte Carlo methods to financial derivatives such as options. Research at CWI includes railway traffic (an ongoing commission of Dutch Rail to develop tools for the design of a new timetable, advisory work concerning traffic control, and the safety of railway-yards) and the control of traffic flow in motorway networks, such as ring roads around large urban areas (the EU project DACCORD).

Finally, for many years, CWI has had research projects in cooperation with the largest Dutch industries: Shell, Philips, Akzo/Nobel, DSM and such like.

3.1.7 Spin-off companies

The generation of spin-off companies is an increasingly important method for institutes like CWI to convert fundamental knowledge to applications and at the same time create new high-level employment and contacts. Close links with CWI during the initial years have appeared to form a crucial success factor here. CWI researchers have successfully managed to establish a number of spin-off companies in

Company	*Profile*	*Startup year*	*# Employees by December 1, 1998*
NLnet	Internet provider	1994	90
General Design	Web design	1994	30
Data Distilleries	Datamining	1995	30
CAN Diensten	Mathematical software	1995	4
UniPay	Electronic money	1997	1
Eidetica	Text engineering	1998	2
Oratrix	Multimedia research	1998	4

TABLE 7. CWI spin-off companies since 1993

recent years. Some of these, for example Data Distilleries and General Design, now have some dozens of employees. Recently, Data Distilleries (operating in the data mining field) received a considerable capital injection from a major Dutch investor, in order to grow into a size considered necessary for a successful operation on the global scale. During the last two years, CWI searched intensively for potential new spin-offs and has a policy for stimulating the generation of such companies. Experience shows that in the preparatory phase prudence is more important than speed. CWI actively strives for joint research projects with its spin-off companies.

3.2 International

3.2.1 CWI in an international context

CWI is very active and successful in international cooperations. At present, it participates in some 20 international research projects. Contacts also exist with academic institutes throughout the world (at present, 68 in Europe, 15 in the USA and 18 elsewhere). We are of the opinion that CWI belongs to the European top in research in mathematics and computer science, with respect to both quality and efficiency. Concerning the latter, CWI's overhead costs are on a level which is common in Western Europe.

3.2.2 ERCIM

CWI has always considered active participation in the European Consortium for Informatics and Mathematics ERCIM to be of great importance. CWI was one of the three founding members (together with GMD and INRIA) of ERCIM, CWI's former scientific director P.C. Baayen was the first ERCIM president. D. Tsichritzis (chairman of the board at GMD) resigned in 1998 as the ERCIM president and was succeeded by CWI's general director G. van Oortmerssen. An important part of the collaboration within ERCIM proceeds in a number of working groups. CWI coordinates three out of the 14 current working groups: Constraints, Control and System Theory, and Parallel Processing Networks. In almost all of the other working groups CWI researchers also play an active role. The same is true for ERCIM's Digital Libraries Initiative, for instance through the DELOS working group. CWI has decided to start an active search for bilateral contacts with ERCIM institutes, whose research programme closely links up with and is complementary to CWI's research in the same field. The German ERCIM partner GMD was the first to establish such a contact, and cooperation started on the following research topics:

- embedded systems,
- environmental modelling,
- computational fluid dynamics,
- scientific visualization,
- data mining.

An NWO-subsidized bilateral contact was recently set up with the Hungarian ERCIM partner SZTAKI.

Van Oortmerssen has initiated a benchmarking process in ERCIM. First results indicate that CWI is quite efficient compared to other institutes.

For some more information about ERCIM, see Appendix 7.

3.2.3 European Union

CWI's share in research at the European level attained its peak in 1995, when it was involved in no fewer than 40 such projects. Not surprisingly, 1996 showed some decrease, mainly because EU programmes were then tending towards less basic research. Almost half of the EU-projects running at CWI have been concluded. Some new projects started, such as MERCURY (Performance Management of Commercial Parallel Database Systems), KESO (Knowledge Extraction for Statistical Offices, CWI project manager), DELOS (ERCIM Digital Library), CHAMELEON (An Authoring Environment for Adaptive Multimedia) and DACCORD (Development and Application of Coordinated Control of Corridors). At the end of 1996, in total, 25 EU projects were underway.

Notwithstanding its less favourable positioning with respect to last years' European programmes (tendency to less basic research and the conclusion of the Fourth Framework Programme), CWI has still tried hard to play an active role here; during 1997 and 1998, 15 proposals were under consideration in Brussels.

As far as 1999 is concerned, CWI looks forward with great interest to the calls for proposals in the Fifth Framework Program.

3.2.4 Further international relations

CWI has played a historic role in the development of the Internet. For many years the institute acted as the main gateway for the connections between the USA and Europe. With the emergence of the World Wide Web, CWI soon acquired an important position here. The institute is active in a number of working groups of the World Wide Web Consortium (W3C), coordinated by MIT, INRIA, and Keio University (Japan), which was founded in order to stimulate and coordinate the further development of the Web. The Multimedia interchange format CMIF (CWI Multimedia Interchange Format) developed by the theme INS2, and the former research group AA3, served as a useful model for the SMIL multimedia (Synchronized Multimedia Integration Language) application of XML.

The W3C consortium has meanwhile decided to open a national office in some countries, to act as a central point for all matters concerning the Web. The Dutch office is located at CWI. Also, CWI acts as a mirror site for the W3C server.

4 Golden jubilee

The fact that, in 1996, SMC was founded 50 years ago was celebrated with a range of activities.

The first event was a mathematical congress with 200 participants on February 6 and 7. The invited speakers, including several celebrities such as L. Nirenberg, G. Faltings, and R. Graham, covered all areas of the so-called National Activities in Mathematics administered by SMC. The following day, a policy symposium marked the formal jubilee manifestation. Speakers included A. Rinnooy Kan, at that time still chairman of the Dutch Employers' Organization, and the chairman of the NWO Board, R. van Duinen. This series of events was concluded on February 9, with a day for present and former SMC employees and their partners. Early in February, the jubilee book *Images of SMC Research 1996* appeared. Following four general articles, written by prominent Dutch experts in mathematics and computer science, 34 contributions give an impression of the research carried out at CWI and in the framework of the National Activities in Mathematics. Next, in March, 400 mathematicians and computer scientists from all over the country attended a festive evening, organized by SMC in the city of Amsterdam, with lectures by two leading exponents in computer science and mathematics: Donald Knuth and Benoit Mandelbrot. A computer science congress, jointly organized with the Academia Europaea, with among others R. Milner and B. Buchberger as speakers, took place in Amsterdam the following month. Meanwhile, preparations were made for a nation-wide puzzle competition. The problem was derived from a research project commissioned by Dutch Railways in which CWI had investigated the optimal circulation of rolling stock. More than 300 solutions were submitted. The meeting in November in Utrecht, where in front of almost 200 attendees the prize winners were announced, was also the final jubilee event. Finally, worth mentioning is the Vacation Course for mathematics teachers organized by SMC. The course given in 1996 (topic: Chaos) was the 50th in an almost uninterrupted series starting in the foundation year 1946[2]. This remarkable fact was given due attention.

[2]With only one exception when in 1954 the International Congress of Mathematicians was held in Amsterdam.

5 Conclusions

In recent years, many changes have been implemented at CWI, on the basis of both external recommendations and internal opinions. Most drastic was the institute's restructuring in 1996. Though CWI's mission has not been changed by it, a much clearer distinction can be made now between the goals of CWI and those of, e.g., faculties of mathematics and computer science at universities. CWI's financial position has been further improved during the report period (see Appendix 8 for details), particularly thanks to the intensified efforts of CWI's research staff to acquire externally funded projects. As a consequence of the increase in contract research, CWI has become more directed towards the outer world; practical problems and knowledge transfer have become more important. In the report period, CWI has evolved into a more flexible, more dynamic and more extrovert institute. Clear evidence of this is (i) the larger number of cooperations with universities, other research institutes and commercial enterprises, as well as (ii) the increased mobility of CWI's research staff, both internally (through the triple-ladder policy) and externally (through the secondment policy and spin-off policy).

A few points of future concern exist (they are discussed in Section 2 of the document "Strategy 2000–2005"), but – overall – we are satisfied about the way CWI is functioning now; CWI faces the future with confidence.

Appendix 1
Recommendations by Previous Visiting Committees

1 Computer Science, 1991

1.1 General recommendations

A. The general external image of the institute is of being theoretical and of high quality. The institute should now put emphasis on closing the gap between theory and practice, while maintaining the same high standards. A few large projects, possibly in collaboration with industry and universities, should be formed, aimed at carrying theory all the way through to practice. [3]

   In such a collaboration the practitioners should select the most appropriate theory from anywhere in the world, and local theoreticians should help them. One expedient is to set up a regular reading party/study group with both theoretical and practical participants. Once in a while this will result in the group feeling an urge to work together on some specific project.

B. The institute should have fewer and larger groups. This would enable it to get more leverage from its research body. The group structure should be made more flexible: when a project finishes, so should the project group. This will make it easier to start new things, or to embark upon the larger projects mentioned under A. [4]

   The Committee does not have an adequate basis on which to suggest specific reorganizations so as to form larger groups. However, it believes it is very desirable to capitalize on CWI's existing strengths and skills in developing a more cohesive group (or groups) whose work involves significant software prototyping and development, as well as work of a more theoretical nature.

C. The institute should establish better ties with industry. Thusfar the institute has mainly worked with the research divisions; the Committee recommends also paying attention to the product divisions.

1.2 Further recommendations

A. The Committee has the impression that the choice of new projects is sometimes too much driven by the availability of external funds. There should be a sound institutional research policy for embarking upon new projects and for deciding whether externally funded projects fit well with CWI's mission.

   The scientific policy making should be debated openly within a committee with a known membership and with a mandate to advise the director. In addition, external funds should preferably be accepted if CWI can complement them with appropriate internal funds.

B. The permanent staff of many computer science groups is too small. It is often way below the target figure of 40%.

C. In groups with much externally funded research the pressure of work is often high. With almost all the worktime preallocated there is too little room for short, interdisciplinary side-steps or for pursuing the investigation of new, speculative ideas.

D. There are three major areas in theoretical computer science: semantics, programming methodology, and algorithms. The first two are well-represented at CWI. Algorithms (including complexity) is mainly found in the (very) small research group AA1. The Committee advises to upgrade the extent of the investment in algorithms and complexity to a level normally found in similar institutions. At least one new senior researcher should be hired to increase CWI's strength in these areas. [5]

E. The study of neural networks was mentioned as a possible new subject. The Committee considers this a subject that fits in CWI's mission. Given that this subject has already been picked up at many places in the Netherlands, CWI should not embark upon it in isolation.

F. In order to incorporate more implementation-oriented work in the research groups, the support staff (programmers) should not be kept in a central pool; they should be assigned to specific projects. [6]

G. The tenure process at CWI is not well understood. It should be made more predictable and less sensitive to funding variations.

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[3] Implemented through various joint projects with Dutch industries, especially in the Telematics Institute.
[4] Implemented with the 1996 restructuring of CWI.
[5] Implemented with the expansion of INS4 (successor of AA1) and pilot theme SEN4.
[6] Implemented as part of the 1996 restructuring.

H. Under its current policy, CWI does not really seem to have room for brilliant solitary researchers. In the Committee's view, CWI should consider starting a "CWI fellows" (cf. IBM fellows) program. [7]

I. CWI must develop an active policy towards the patentability of research products. Patents are a possible source of income that should not be neglected.

J. The Committee has insufficient information to judge how the Common Research Themes come into existence. The goal, that of identifying and exploring new, large themes or paradigms for the institute, is however a laudable one.

2 Mathematics, 1995

2.1 General recommendations

CWI has played a unique and indispensable role in Dutch mathematics in the past. CWI was instrumental in having new fields of mathematics, in particular of applied mathematics, introduced in the country and it has indeed been a breeding place of talented researchers who often ended up in senior positions in universities and industry around the country. Statistics and Operations Research are examples of two areas where CWI has played this role.

The committee recommends that the CWI should continue this seminal role. However, in order to achieve this, special efforts will be required. In the past, CWI was able to move into new areas in part because of the natural throughput created by permanent staff members moving into new positions in university departments. However, because of the shrinking of mathematics departments around the country, such opportunities are, and will be, much less prevalent. Consequently, new developments will have to be achieved to a much larger extent than before by a change in focus of the permanent researchers. Most of the areas where research is carried out in the mathematics division of CWI are "mature" areas of mathematics, and it is important that activities in newer areas be enhanced. The quality and expertise of the permanent staff definitely allows for this.

The committee would like to recommend a number of ways in which CWI can play this unique role.

2.2 Mathematical modelling

Mathematical modelling is the bottle-neck between mathematical methods and successful applications. In many places at CWI, related modelling activities are carried out. However, these efforts are usually organized along lines specified by mathematical expertise. The committee understands the historical reasons for the present structure. However, it believes that the CWI is in a unique position to carry out a refocusing of part of its efforts by making mathematical modelling one of its central themes. Thus, rather than structuring the research at CWI around mathematical fields of expertise, we recommend structuring it around certain problem areas involved with mathematical modelling, with at its core a number of methodological issues. [8]

Among the methodological issues, one can think of issues related to the modelling of uncertainty, modelling procedures obtained on the basis of measurements, issues related to modelling of interconnected systems, computer assisted modelling, discrete (event) modelling, simulation, etc.

In addition to these methodological issues, we recommend selecting a number of important areas of focus. These areas can come from other fields in the physical sciences, but we recommend an emphasis on areas which are relevant to the service industry and to engineering.

The following are examples of areas which the committee has in mind:

- Mathematical finance
- Signal and image analysis and processing
- Environmental modelling
- Large scale modelling, simulation, and visualization in (bio-)chemistry and other physical sciences

There are already activities at CWI in some of these examples. [9] The committee considers the area of mathematical finance to be one of great urgency. It is a field in which advanced mathematical knowledge is applied very effectively. Also, this area is very little developed in traditional mathematics departments in the Netherlands and it has the potential of offering many interesting (employment) opportunities for

[7] Implemented with the CWI Fellows Program.
[8] Implemented with the 1996 restructuring of CWI.
[9] The above four examples have been implemented in successively the themes MAS3, PNA4, MAS1 and MAS2.

mathematicians. The committee believes that CWI has much in-house expertise which enables it to bring such an effort to a stage of effectiveness in a very reasonable time.

The committee feels that an important benefit of this effort in modelling is its interdisciplinary character. Interdisciplinary, not only in the sense that it brings mathematics into contact with other fields (physical sciences, engineering, or economics), but also in the sense that it will naturally create a collaboration and synergy among senior CWI personnel with complementary expertise. For instance, in the fast growing area of mathematical finance, the availability at CWI of experts in stochastic analysis and stochastic differential equations, optimization and optimal control, statistics for large data sets and numerical analysis techniques for model equations occurring in this area, makes CWI a very suitable environment for such an endeavor.

2.3 Knowledge transfer

The advances in computer technology have brought with it that mathematical models can be used to a much larger extent than was the case before. At the same time, one should realize that mathematics is a highly developed field whose results are not easily accessible to many potential users of mathematics, for example in engineering and economics. We believe that the CWI can and should play an important role in achieving such a knowledge transfer. Of course, the committee is well aware of the fact that CWI has been involved in a number of successful projects of this nature (with the NS scheduling project of Research Group BS1 in the limelight). However, we feel that such efforts should be much more prevalent than they are now and that ideally every senior member of CWI should be involved for a sizeable amount of his or her time in this type of work.

In this respect, the committee feels that one should not overemphasize the high scientific content of such projects as a condition for their selection. Demonstrating the feasibility of what may be considered as a straightforward application can have very beneficial effects, both to the customer, and to proving the usefulness of mathematical methods. Also, specific applications often uncover new theoretical challenges.

Finally, also with respect to knowledge transfer the committee recommends an emphasis on topics of direct importance in engineering and the service industries.[10]

2.4 International collaboration

Mathematics is a very internationally oriented field in which formalized as well as informal international contacts are indispensable and very frequent, so "internationalization" in this field has already been achieved.

In the eyes of the Visiting Committee, CWI is an especially good example of an institute which functions in a truly international mode. Among its formalized links, we would like to mention ERCIM in which institutes similar to CWI from 13 different European countries participate, and the many EU projects in which CWI researchers participate, often as coordinators. The committee was indeed very impressed by the number of successful projects which have been obtained by CWI researchers in these EU competitions. It considers this as evidence of the high international reputation which CWI enjoys.

Finally, the committee has been informed of the plans to locate EURANDOM at the CWI site. The committee views this as an excellent opportunity for CWI which, through its infrastructure, its excellent library, and its location in Amsterdam, makes it a very attractive location. Also, this activity would strengthen the position of the CWI as one of the premier places worldwide in the fields of Stochastics and Operations Research.

2.5 Management structure

From its limited experience, the Visiting Committee has concluded that CWI is excellently organized, and has perceived the institute's management to be effective, both on the administrative and the scientific level.

However, on the level of departments and groups, some members of the Visiting Committee recommend giving serious consideration to choosing for an organization in which the research is structured along research themes instead of the present situation of departments and groups, which originates more from a division along lines of mathematical expertise. They believe that an organization of research along themes can result in a more dynamic, more adaptive, and more interdisciplinary structure. Five permanent fte's per year for five years is considered as a good size for a theme. However, they recommend

[10] Implemented through various joint projects with large research institutes and enterprises.

that each theme should be led by a senior researcher, responsible for securing high quality work from the other senior and from the junior members connected to a theme. [11]

Another organizational issue is the position of CWI in the NWO organization. CWI functions presently as an institute within SMC (The Foundation for Mathematics). SION (The Foundation for Computer Science) functions as an organization parallel to SMC. The Visiting Committee recommends restoring the natural symmetry between mathematics and computer science, for example by letting CWI, SMC, and SION function as three parallel organizations. Of course, close ties are to be kept with both SMC and SION. [12]

2.6 Interactions between mathematics and computer science at CWI

One of the opportunities for CWI is to take advantage of the co-existence of projects in these two areas under a single administrative umbrella. It is difficult for this visiting committee to evaluate the extent and effectiveness of collaborations because it interviewed only representatives of the mathematics areas. Therefore, it recommends that future evaluations of the two areas should be combined, or at least coordinated. A combined evaluation is probably preferable since it would give more opportunity for a visiting committee to discuss issues from both the mathematical and computer science perspective. [13]

It is well-understood that collaboration between areas of apparent similarity is not always easy or even valuable, because the goals of the areas may be different. However, isolation of the areas removes the opportunities for the serendipitous discoveries that sometimes happen when one discipline observes or meets another.

Areas of overlap: Two joint activities were mentioned in the documents provided to the committee: the work on ACELA jointly between research projects AM1.3 and AA3.2 and the work on bus station models jointly between research projects AP3 and BS1. Other areas in which collaboration is taking place are in the department BS, in connection with data mining and discrete event control.

Areas of possible overlap: There appears to be work on neural networks and genetic algorithms in the Software Technology Department under Computational Models and in the Algorithms and Architecture Department under Algorithms and Complexity. It is not clear whether there is any interaction between the Computer Science departments and the statisticians in the department BS in Mathematics. While the interests of these departments may be very different, neural networks is a field with a strong statistical component, and it may turn out that also the analysis of genetic algorithms will be assisted by statistical tools. There is also much potential interaction between the Interactive Systems Department's work on image analysis and computation steering in group IS1 with the two mathematics departments that have related interests, namely BS (in image analysis) and NW (in interactive control of numerical simulations). Some collaboration on visualization is in fact already taking place.

The committee urges CWI to encourage those areas of joint activity that have potential for significant symbiosis. [14]

[11] The above recommendation has been implemented in the 1996 restructuring of CWI.
[12] The symmetrization has been realized with the foundation of SWON, parallel to SION.
[13] Implemented with the 1999 visiting committee.
[14] Implemented to a large extent with the 1996 restructuring of CWI.

Appendix 2 Members of Boards

1 Governing Board

Name	Function	Affiliation
prof.ir. L.A.A.M. Coolen	Chair	director, KPN Research
prof.dr. K.M. van Hee	First vice-chair and secretary	Eindhoven University of Technology, director Bakkenist Management Consultants
prof.dr. H.A. van der Vorst	Second vice-chair and treasurer	University of Utrecht
prof.dr. P.M.G. Apers	Member	University of Twente, chair former SION
prof.dr.ir. J.H.A. de Smit	Member	University of Twente, chair former SWON

2 Advisory Board

Name	Affiliation
dr. J.H.C. Gunawardena	director BRIMS, Hewlett-Packard Laboratories, Bristol
prof.dr. B. Larrouturou	president INRIA
prof.dr. J. van Leeuwen	University of Utrecht
prof.dr.ir. L.A. Peletier	University of Leiden
ir. J. Ridder	director TNO, NITG
dr.ir. G.S. Rodenhuis	director Delft Hydraulics Laboratory
dr.ir. M.F.H. Schuurmans	managing director and chairman Philips Natuurkundig Laboratorium (Philips Research)
ir. M. Westermann	director Twinning Network
prof.dr. G. Wiederhold	Stanford University

Appendix 3 Theme Overviews 1993–1998

1 Theme PNA1: Networks and Logic—Optimization and Programming

1.1 Short history of the theme and research highlights

The theme PNA1 started with the restructuring of the CWI on 1-1-97 and originates from the former CWI-groups BS1: Combinatorial Optimization and Algorithmics (leader: A. Schrijver) and IS4a: Logic programming and Computational Linguistics (until 1995: AP5a: Logic and Language; leader: K.R. Apt).

PNA1 focuses on fundamental and applied research in the areas of mathematical logic, combinatorics (in particular networks), optimization, algorithmics, complexity, and transportation. The problems studied originate from fields like networks, combinatorial optimization, computational logic and computational complexity, and from practice, in particular from production and transportation planning, routing, scheduling, and timetabling, and the design of VLSI-circuits.

The techniques developed make use of models and methods coming from mathematics (mathematical logic, geometry, topology, graph theory), operations research (linear and integer programming), and computer science (logic and constraint programming and complexity theory). This multidisciplinary approach has proven to be very fruitful. For instance, the characterization, in terms of discrete Schrödinger operators, of networks that are linklessly visualizable in 3D by L. Lovász and A. Schrijver, results from a combination of techniques from network theory, linear algebra (spectral analysis), and algebraic topology. The book *Geometry of Cuts and Metrics*[15] by M. Deza and M. Laurent is just one big 600 pages long cross-fertilization of topics like linear algebra, combinatorics, metric spaces, and geometry of numbers. J.F. Geelen, A.M.H. Gerards, and A. Kapoor heavily relied on network techniques to prove their characterization of the quaternary matroids (i.e. the solution to a certain matrix realization problem). K.R. Apt, J. Brunekreef, A. Schaerf and V. Partington developed a new programming language called Alma-0 that combines the advantages of logic and imperative programming.

Solving combinatorial optimization problems successfully, amounts often to restricting the underlying search space. One approach to this is a structural analysis of the combinatorial optimization problem at hand in order to find short search paths towards the optimum; network programming has that flavour. Another approach is the development of algorithmic tools for iteratively deriving new, stronger, constraints from the already known constraints. Cutting plane techniques are of this kind, but also constraint programming, an area in computational logic, takes this approach. The research of PNA1 considers both approaches. One of the goals is to explore the possibilities of cross-fertilization between them. CADANS, a software package for developing timetables for trains, designed by A. Schrijver and A. Steenbeek in commission of the Dutch railways, combines constraint programming with network techniques.

Much of the PNA1-research deals with the development of efficient algorithms for network optimization problems, like routing and scheduling problems. A recent graduate level source of this area is the book *Combinatorial Optimization*[16] by W.J. Cook, W.H. Cunningham, W.R. Pulleyblank, and A. Schrijver. One example of the many results by PNA1 on network optimization is a fast and sharp algorithm to route calls in a circular network of telephone centrals (consultancy for Bell Communications Research carried out by A. Schrijver, P. Seymour and P. Winkler).

The results by PNA1 on networks not only apply to optimization problems; for instance the sharpest possible asymptotic lower bound for the number of 1-factors in a regular bipartite graph derived by A. Schrijver (solving a problem of Erdös and Rényi (1968)) yields a new bound for the dimer problem in physics. Moreover, the mathematical techniques used by PNA1 are not exclusively applied to networks; an example of a result that lies more exclusively in linear algebra and geometry is the proof by H.-J. Bandelt, V. Chepoi, and M. Laurent of the conjecture that there are no more than $2m$ equidistant points in the m-dimensional ℓ_1-space when $m \leq 4$.

The second major portion of research in PNA1 deals with computational logic, in particular constraint programming. Work on constraints mostly concentrates on the study of constraint solvers and constraint propagation. K.R. Apt proposed a simple framework for classifying, comparing and deriving constraint propagation algorithms based on the concept of chaotic iterations that originated in the field of numerical analysis. Also, he provided a proof theoretic account of constraint programming that attempts to capture the essential ingredients of this programming style in a language independent way. The long term aim

[15] M. Deza and M. Laurent, *Geometry of Cuts and Metrics*, No. 15 in the series *Algorithms and Combinatorics*. Springer-Verlag, 1997, 587 + xii pages.

[16] W.J. Cook, W.H. Cunningham, W.R. Pulleyblank, and A. Schrijver, *Combinatorial Optimization*, *Wiley-Interscience Series in Discrete Mathematics and Optimization*, John Wiley & Sons, New York, 1998, 355 + x pages.

of his considerations is a construction of a language independent framework for constraint programming. The forementioned programming language Alma-0 is part of the Alma project (http://www.cwi.nl/alma). K.R. Apt, J. Brunekreef, A. Schaerf and V. Partington described programming in Alma-0, and executable semantics and implementation of the language. Further inquiries into the resulting programming style and a proposal for adding constraints to Alma-0 were elaborated by K.R. Apt and A. Schaerf, while logical underpinnings of this language were worked out by K.R. Apt and M. Bezem.

Besides on constraint programming, PNA1 also works on other aspects of programming and computational logic. In the area of program verification, K.R. Apt and E.R. Olderog revised their book[17] on sequential and concurrent programs and assertional proof systems for their verification. The new book *From Logic Programming to Prolog*[18] by K.R. Apt deals with the foundations of logic programming in Prolog and verification of Prolog programs.

1.2 Present personnel

1.2.1 Senior staff members

prof.dr. K.R. Apt (0.8 fte), dr. M.A. Bezem (0.6 fte), prof.dr.ir. A.M.H. Gerards (1.0 fte, theme leader), dr. M. Laurent (1.0 fte; on leave from CNRS since September 1997), prof.dr. J.K. Lenstra (0.2 fte), prof.dr. A. Schrijver (0.4 fte; cluster leader).

1.2.2 Total formation

6 senior staff members (4.0 fte), 5 postdocs (4.2 fte), 1 PhD student (1.0 fte), 1 ERCIM fellow (1.0 fte), 1 programmer (0.9 fte).

1.3 Selected publications

prof.dr. K.R. Apt

- K.R. Apt, The essence of constraint propagation, *Theoretical Computer Science*, 33 pages. In press.
- K.R. Apt, J. Brunekreef, A. Schaerf and V. Partington, Alma-0: an imperative language that supports declarative programming, *ACM Toplas*, 54 pages. In press.

prof.dr.ir. A.M.H. Gerards

- J. Geelen, A. Gerards and A. Kapoor, *The Excluded Minors for GF(4)–Representable Matroids*, CWI Report PNA-R9711, 1997 (submitted).
- A.M.H. Gerards and F.B. Shepherd, The graphs with all subgraphs t-perfect, *SIAM Journal of Discrete Mathematics* **11** (1998) 524–545.

dr. M. Laurent

- M. Laurent, Cuts, matrix completions and graph rigidity, *Mathematical Programming* **79** (1997) 255–283.
- M. Laurent, A connection between positive semidefinite and Euclidean distance matrix completion problems, *Linear Algebra and its Applications*, **273** (1998) 9–22.
- H.-J. Bandelt, V. Chepoi, and M. Laurent Embedding into rectilinear spaces, *Discrete and Computational Geometry* **19** (1998) 595–604.

prof.dr. J.K. Lenstra

- E.H.L. Aarts and J.K. Lenstra (editors), *Local Search in Combinatorial Optimization*, Wiley, Chichester 1997, 512 pp.

prof.dr. A. Schrijver

[17] K.R. Apt and E.-R. Olderog, *Verification of Sequential and Concurrent Programs*, Springer-Verlag. Second edition: Graduate Texts in Computer Science, 1997, 364 + xviii pages.

[18] K.R. Apt, *From Logic Programming to Prolog*, Prentice Hall, International Series in Computer Science (C.A.R. Hoare, editor), 1997, 328 + xviii pages.

- L. Lovász and A. Schrijver, A Borsuk theorem for antipodal links and a spectral characterization of linklessly embeddable graphs, *Proceedings of the American Mathematical Society* **126** (1998) 1275-1285.
- A. Schrijver, Counting 1-factors in regular bipartite graphs, *Journal of Combinatorial Theory, Series B* **72** (1998) 122–135.
- A. Schrijver, P. Seymour and P. Winkler, The ring loading problem, *SIAM Journal on Discrete Mathematics* **11** (1998) 1–14.

1.4 External projects and funding

- From 1990 till 1994, FAPESP (Brasil) funded a 4 year PhD student (J. Coelho de Pina).
- Project 'Computational aspects of non-monotonic reasoning' (1992-1996). Funded by NWO: salary of a four year PhD student (F. Teusink).
- Project 'Integer Polyhedra and binary spaces' (1996-2000). Funded by NWO: salary of a four year PhD student (T. Fleiner).
- Esprit Basic Research Action 'Compulog 2' (1992-1995). Funded by the European Union: salary of a three year postdoc (E. Marchiori).
- 'Human Capital and Mobility' project 'EUROFOCS' (1994). Funded by the European Union: salary of a one year postdoc (M. Gabbrielli).
- In 1995, 'Stieltjes', a dutch graduate school for mathematics, funded the salary of a 4 month postdoc (E. Győry).
- In 1995, EIDMA, a dutch graduate school for discrete mathematics, funded the salaries of three postdocs: J.F. Geelen and A. Kapoor (both 4 months), and T. Jordán (12 months).
- Project 'Constraint-Based Graphics' (1996-1997). Funded by NWO: salary of a one year postdoc (E. Monfroy).
- Project 'Computational intelligence for constraint logic programming' (1996-1998). Funded by NWO: salary of a two year postdoc (E. Marchiori).
- Project 'Parallel declarative programming' (1997-2000). Funded by NWO: salary of a two year postdoc (F. van Raamsdonk).
- Project 'Spectral parameters and embeddability of graphs' (1998-2000). Funded by NWO: salary of a two year postdoc (A. Kotlov).
- Three ERCIM-fellows: S. Etalle (1995), A. Schaerf (1995-1996), and J.-H. Rety (1998-1999).
- 'SCIENCE'-network 'Algorithmic approaches to large and complex combinatorial optimization problems' (1992-1995). Funded by the European Union.
- 'Human Capital and Mobility'-network 'Discrete mathematics network (DIMANET)' (1993-1996). Funded by the European Union.
- 'Human Capital and Mobility'-network 'Discrete optimization: theory and applications (DONET)' (1994-1997). Funded by the European Union.
- EU-working group: 'Concurrent constraint programming for time-critical applications (COTIC)' (1997-1999). Funded by the European Union.
- EU-working group: 'Deductive constraint database for intelligent geographical information systems (DEDUGIS)' (1998-2000). Funded by the European Union.
- 'Training and Mobility of Researchers'-network 'Discrete optimization: theory and applications (DONET)' (1998-2002). Funded by the European Union, including salary of 30 postdoc-months (12 months: R. Rizzi).
- Terminal allocation for a bus company (on contract basis for Nederland-Haarlem).
- Railway stock routing (on contract basis for NS-reizigers).
- Time table development for the Dutch Railways (on contract basis for Railned).
- Scheduling of trainee posts for medical students (on contract basis for Maastricht University and Vrije Universiteit).

In 1997 and 1998, the percentages of the total costs of PNA1 covered by external funding were: 24% and 14%, respectively.

1.5 PhD theses

- H. van der Holst, *Topological and Spectral Graph Characterizations* University of Amsterdam, 1996 (thesis advisor: A. Schrijver).
- F. Teusink, *Non-monotonic Reasoning via Logic Programming* University of Amsterdam, 1996 (thesis advisor: K.R. Apt).
- J. Coelho de Pina, *Applications of Shortest Path Methods* University of Amsterdam, 1995 (thesis advisor: A. Schrijver).
- S. Etalle, *Transformation and Analysis of (Constraint) Logic Programs*, University of Amsterdam, 1995 (thesis advisor: K.R. Apt).
- B. Veltman, *Multiprocessor Scheduling with Communication Delays*, Eindhoven University of Technology, 1993 (thesis advisor: J.K. Lenstra).
- External PhD theses with A. Schrijver as advisor: Keijsper (1998), Pendavingh (1998), De Graaf (1994).
- External PhD thesis with K.R. Apt as advisor: Kalsbeek (1995).

1.6 Academic relations

1.6.1 Secondment of senior staff members at universities

- K.R. Apt, full professor at University of Amsterdam (0.2 fte).
- A. Schrijver, full professor at University of Amsterdam (0.2 fte).

1.6.2 Secondment of university staff at CWI

- M. Laurent, on leave from CNRS (Centre National de la Recherche Scientifique), since September 1997 (1.0 fte.).
- J.K. Lenstra, full professor at Eindhoven University of Technology (0.2 fte).
- M.A. Bezem, associate professor at University of Utrecht (0.6 fte.).

1.7 Services to the research community

prof.dr. K.R. Apt

- President Association for Logic Programming, Chairman and co-founder ERCIM Working Group on Constraints, Scientific Commission for Computer Science of the Belgian National Fund for Scientific Research, Coordinator of ESPRIT Basic Research Action 'COMPULOG 2' (until 1996).
- Editorial activities: managing editor *CWI Tracts* and *CWI Syllabi*, *Fundamenta Informaticae*, *Information and Computation*, *Journal of Logic and Computation*, *Journal of Logic Programming*, *Science of Computer Programming*, *Wiley/Teubner Series in Computer Science*.

dr.ir. A.M.H. Gerards

- KNAW Akademie Raad voor de Wiskunde Commissie "Toekomst Wiskunde onderzoek in Nederland", Vice-chairman werkgemeenschap Mathematische Besliskunde en Systeem Theorie.
- Editorial activities: *SIAM Journal on Discrete Mathematics*, *CWI Quarterly*, *Discrete Mathematics and Theoretical Computer Science*.

prof.dr. J.K. Lenstra

- Board KNAW Akademie Raad voor de Wiskunde, Board Wiskundig Genootschap (until 1996), Science council Stichting Wetenschappelijk Onderzoek Verkeersveiligheid (until 1995), Mathematical Programming Society (chairman until 1995, vice-chairman until 1997), Visiting committee DIKU, Kopenhagen (1995), Publications Committee Mathematical Programming Society, TMR Networks Panel on Mathematics & Information Sciences.
- Editorial activities: Advisory Board *ACM Journal of Experimental Algorithmics*, *CWI Tracts*, *CWI Syllabi*, Advisory Board *Excerpta Informatica*, Area Editor for Design & Analysis of Algorithms *INFORMS Journal on Computing*, associate editor *International Journal of Foundations of Computer Science*, editorial Advisory Board *Kluwer Series in Operations Research/Computer Science Interface*, Guest Editor of issues in memory of E.L. Lawler *Mathematical Programming Series B*, Advisory Board *SCIMA Special Series*, advisory editor *Wiley/Interscience Series in Discrete Mathematics and Optimization*.

prof.dr. A. Schrijver

- Fields Medal Committee 1994, KNAW Akademie Raad voor de Wiskunde, chairman Fulkerson Prize Committee 1994, Board (treasury) Stichting Wiskunde Onderzoek Nederland, Board EIDMA – Euler Institute for Discrete Mathematics and Its Applications, Science council Stichting Mathematisch Centrum (until 1995), Science Council Stieltjes Instituut voor Wiskunde, Governing Board Landelijk Netwerk Mathematische Besliskunde, Symposium Advisory Committee of the Mathematical Programming Society, Science Council Werkgemeenschap Mathematische Besliskunde en Systeemtheorie, Science Council Werkgemeenschap Discrete Wiskunde.
- Editorial activities: editor-in-chief *Combinatorica*, *Discrete Applied Mathematics*, advisory editor *Journal of Combinatorial Optimization*, *Journal of Combinatorial Theory, Series B*, *Journal of Combinatorics, Information and System Sciences*, associate editor *Mathematics of Operations Research*, advisory editor *North-Holland Mathematical Library*, *SIAM Journal on Discrete Mathematics*, *SIAM Journal on Optimization*, editorial board *SIAM Monographs on Discrete Mathematics and Applications*.

1.8 Awards and honours

- In 1997, J.K. Lenstra received the EURO Gold Medal from EURO (Association of European Operational Research Societies).
- A. Schrijver is member of Royal Netherlands Academy of Arts and Sciences.

2 Theme PNA2: Traffic and Communication - Performance and Control

2.1 Short history of the theme and research highlights

The theme has in 1997 been created from the research group 'Analysis and control of information flows in networks' and part of the research group 'System and Control Theory' which both belonged to the Department of 'Operations Research, Statistics, and System Theory'. The research focus of the theme is on the development of mathematical analysis of queueing systems, and of control and system theory. The research is primarily motivated by the technological advances in communication networks and in other areas of engineering.

Queueing theory and performance evaluation Queueing theory is concerned with the fundamental analysis of congestion phenomena encountered in stochastic service systems. Models and techniques from queueing theory provide valuable tools for the performance evaluation of computer systems and communication networks.

Until 1996, queueing research at CWI centred around (i) polling systems and (ii) two-dimensional random walks. Polling systems constitute a broad class of queueing models that arise when several traffic classes contend for the exclusive use of a common resource, like a single processor or a shared communication medium. Powerful structural properties of polling systems were obtained, including decomposition principles and pseudo-conservation laws. A combined probabilistic and analytic (boundary-value) approach led to the detailed analysis of an important class of two-dimensional random walks. This enabled the solution of various classical performance models, like the 2×2 switch, coupled processors, and the shorter-queue model.

Since 1996, the research has focused on queueing models with heavy-tailed traffic characteristics. Besides theoretically challenging, these models also have great practical relevance, since traffic in modern communication networks often exhibits heavy-tailed characteristics. Current topics include: (i) tail behavior of the performance characteristics (buffer content, waiting time, busy period); (ii) the influence of service disciplines; (iii) heavy-traffic limit theorems. This line of fundamental research will be continued in the coming years. In parallel, as part of the project "Quality in Future Networks" of the Telematics institute, research will be initiated on resource allocation issues in integrated-services networks, including best-effort services for elastic traffic, link dimensioning, admission control, and packet scheduling.

Control and system theory The research is motivated by engineering problems of control and signal processing. The strength of the research group is mainly in system theory and in the system theoretic approach to control.

Control of nondeterministic discrete-event systems has been studied using the concept of failure semantics. In decentralized control of discrete-event systems it has been established that a Nash equilibrium is equivalent to a maximal solution. For decentralized control of discrete-event systems the existence and the minimality of a communication channel between supervisors have been studied. Recently a research effort has started on control of hybrid systems with a focus on reachability and control synthesis. Applied research on routing control of motorway networks has been carried out in cooperation with the national road authority of The Netherlands.

The stochastic realization problem for Gaussian stochastic control systems was solved in case both the input and the output process are observed. For the realization problem of positive linear systems the existence and the minimality of the state space have been investigated. In system identification results have been published on identifiability of systems from input-output signals and on the approximation problem of Gaussian stochastic systems. Recently an effort has started on realization of hybrid systems and of classes of discrete-event systems using concepts of algebra and of complexity theory. Applied research in system identification has been carried out on compartmental systems in cooperation with the Rijksinstituut voor Volksgezondheid en Milieuhygiëne (Governmental Institute for Public Health and Environmental Protection).

2.2 Present personnel

2.2.1 Senior staff members

Dr. J. van den Berg (0.1 fte), Prof.dr.ir. S.C. Borst (0.6 fte, since October 1998), Prof.dr.ir. O.J. Boxma (0.2 fte, since September 1998; till that time 0.8 fte), Prof.dr.ir. J.H. van Schuppen (0.8 fte, theme leader).

2.2.2 Total formation

4 senior staff members (1.7 fte), 1 postdoc (0.4 fte).

2.3 Selected publications

prof.dr.ir. S.C. Borst

- S.C. Borst, D. Mitra. Asymptotically achievable performance in ATM networks. *Advances in Applied Probability* **30** (1998), 568-585.

dr. R.J. Boucherie

- Richard J. Boucherie and Michel Mandjes, Estimation of performance measures for product form cellular mobile communications networks, *Telecommunication Systems*, to appear 1998.

prof.dr.ir. O.J. Boxma

- S.C. Borst, O.J. Boxma. Polling models with and without switchover times. *Operations Research* **45** (1997), 536-543.
- O.J. Boxma, J.W. Cohen. Heavy-traffic analysis for the GI/G/1 queue with heavy-tailed distributions. *Queueing Systems* (1999), to appear.
- S.C. Borst, O.J. Boxma, P.R. Jelenkovic. Generalized processor sharing with long-tailed traffic sources. *Report, October 1998; submitted for publication.*

prof.dr.ir. J.H. van Schuppen

- G. Picci, J.M. van den Hof, J.H. van Schuppen. Primes in several classes of the positive matrices, *Linear Algebra and its Applications 277* (1998), 149-185.
- A. Overkamp, J.H. van Schuppen. A characterization of maximal solutions for decentralized discrete-event control systems, *Proceedings of the International Workshop on Discrete Event Systems 1996 (WODES96)*, IEE, London, 1996, 278-283.
- J.H. van Schuppen, Tuning of Gaussian stochastic control systems, *IEEE Trans. Automatic Control 39* (1994), 2178-2190.

2.4 External projects and funding

The research effort in performance analysis has been financially supported by: ERCIM fellowships (post-doctoral fellowships for 9 resp. 6 months). NWO Nationale Faciliteiten Informatica (NFI) Project 62-354 (1 PhD student, 1990-1994). Dutch Graduate Network for Operations Research (1 PhD student, 1990-1994). Shell (postdoctoral fellowship 1990-1994). ESPRIT Basic Research Action (project QMIPS = Quantitative Modelling In Parallel Systems; 1992-1995). NWO-SWON (1 PhD student, 1997-2001). NWO-SWON (1 postdoctoral fellowship, 1998-2000). STW (0.4 postdoctoral fellowship, 1997-2001). INTAS (project: Limit theorems for stochastic discrete event systems, 1995-1996 and 1997-1998). Telematics Institute (1998-2002).

The research effort in control and system theory has been financially supported by: ERCIM fellowship (1 post-doc for 9 months in 1996-1997). NWO Nationale Faciliteiten Informatica (NFI) Project 62-354 (2 post-docs in the period 1994-1997). Department of Mechanical Engineering of the Eindhoven University of Technology (1 master level student for 4 months in 1996-1997). EU TMR SI Project (1 post-doc position for 30 months, ECU 149k for CWI team, 1998 - 2002). EU ESPRIT LTR VHS Project (ECU 30k, 1998 - 2000). EU PECO Project System Identification (ECU 6k, 1993). EU Transport Telematics project DACCORD (ECU 35k, 1996-1998). EU Road Telematics Project DYNA (ECU 21, 1994).

In 1997 and 1998, the percentages of the total costs of PNA2 covered by external funding were: 19% and 28%, respectively.

2.5 PhD theses

- J.M. van den Hof, *System theory and system identification of compartmental systems*, University of Groningen, 1996 (thesis advisor: J.H. van Schuppen).
- A.A.F. Overkamp, *Discrete event control motivated by layered network architectures*, University of Groningen, 1996 (thesis advisor: J.H. van Schuppen).
- M.B. Combé, *Queueing Models with Dependence Structures*, Tilburg University, 1995 (thesis advisor: O.J. Boxma).
- S.C. Borst, *Polling Systems*, Tilburg University, 1994 (thesis advisor: O.J. Boxma).
- P. Wartenhorst, *Performance Analysis of Repairable Systems*, Tilburg University, 1993 (thesis advisor: F.A. van der Duyn Schouten).
- External PhDs with O.J. Boxma as advisor: Van den Hout (1996), R.D. van der Mei (1995).
- External PhD with J.H. van Schuppen as advisor: D. Brigo (1996).

2.6 Academic relations

2.6.1 Secondment of senior staff members at universities

- J. van den Berg, lecturer at the University of Amsterdam (0.1 fte).
- S.C. Borst, full professor at the Eindhoven University of Technology (0.2 fte).
- O.J. Boxma, full professor at Tilburg University (0.2 fte; until September 1998).
- J.H. van Schuppen, full professor at the Eindhoven University of Technology (0.2 fte).

2.6.2 Secondment of university staff at CWI

- R.J. Boucherie, post-doc at the University of Amsterdam.
- O.J. Boxma, full professor at the Eindhoven University of Technology (since September 1998).
- F.A. van der Duyn Schouten, full professor at Tilburg University (until September 1997).

2.7 Services to the research community

prof.dr.ir. S.C. Borst

- Referee activities for various journals and conferences.
- Task manager in "Quality of Future Networks" project of Telematics institute.

dr. R. Boucherie

- Coordinator of STW project 'Stochastic network analysis for the design of self optimising cellular mobile communications systems'.

prof.dr.ir. O.J. Boxma

- Member editorial board of the journals *Markov Processes and Related Fields*, *Mathematics of Operations Research*, *Performance Evaluation*, *Queueing Systems*.
- Member of IFIP Working Group 7.3 (also secretary/treasurer, resp. member of its election committee)
- Member of the Committee for Conferences in Stochastic Processes of the Bernoulli Society (1989-1997).
- Member of the Science Committee of SMC (until 1994), of the board of the Dutch Graduate Network of Operations Research, and of the Scientific (daily) Board of the Research School Stieltjes (since 1998).
- Member of about 20 PhD committees.
- Member of about 15 program committees; organizer of several workshops and of the conferences *Stochastic Processes and their Applications* (1993) and *SMC50* (1996).
- (Co-)coordinator of the project *Stochastic Networks* of EURANDOM and of one STW-project and two SWON-projects.

prof.dr.ir. J.H. van Schuppen

- Co-Editor of *Mathematics of Control, Signals, and Systems*; Department Editor of *Discrete-Event Dynamics Systems*; Associate Editor at Large of *IEEE Transactions on Automatic Control*.
- Coordinator of EU TMR SI Project and coordinator of two projects of the SCIENCE and HCM programs.
- Chairman of Steering Committee of the ERCIM Working Group Control and System Theory.
- Member of 9 program committees. Organizer of 6 sessions at conferences. Organizer of a one-day symposium. Member of two steering committees of conference series. Co-Chairman of 2nd International Workshop Hybrid Systems - Computation and Control, Berg-en-Dal, March 1999.
- Director of Netwerk Systeem- en Regeltheorie (Network of Systems and Control in The Netherlands) which organized courses for Ph.D. students (1990 - 1995 on a part-time temporary appointment at the University of Groningen).

2.8 Awards and honours

Borst's thesis "Polling Systems" received the Gijs de Leve Prize for the best thesis in the area of the Mathematics of Operations Research in The Netherlands in the period 1994-96.

3 Theme PNA3: Stochastics

3.1 Short history of the theme and research highlights

This theme is the central structure at CWI in the area of Probability and Statistics. It started in 1997 and originates from parts of the former groups 'Analysis and control of information flows in networks' and 'Image analysis and spatial stochastics'. At present, it has a staff of four senior scientists, with widely spread interests and talents. The biweekly seminar acts as an integrating forum.

The emphasis is on fundamental, theoretical research for roughly 70%, the remaining 30% being devoted to high-level industrial and economic applications and service to the outside community. Many problems in our theoretical work originate from the physical and biological sciences, finance, image analysis, communication and information systems etc. From a mathematical point of view our research involves (apart from stochastics) ergodic theory and dynamical systems, number theory, classical analysis (Von Neumann algebra's), as well as combinatorial tools. Depth and diversity are key concepts; new ideas created by members of the group have become basic tools for international research.

At the service and applications level, we serve as advisors and contractors for a number of well-known institutions, such as Philips Research Laboratories, Hewlett Packard Laboratories, Pricewaterhouse Coopers, Eurandom, and the university world. The team leader is a member of the Royal Netherlands Academy of Arts and Sciences and is substantially involved in scientific policy-making on the national and international level. Some recent work of each of the four senior members will be discussed briefly:

(i). The emphasis in **Van den Berg**'s work is on discrete spatial processes: interacting particle systems, percolation and Markov random fields. Coupling techniques, correlation inequalities and rescaling arguments, in combination with other tools, play a crucial role. Using a new method Van den Berg

(1997, see publication below) has extended a result on spatial mixing properties of Gibbs measures by Martinelli, Olivieri and Schonmann (whose proof works only for fixed interactions) to the case of random interactions (spin glass models). This method involves the so-called disagreement percolation approach which was introduced by Van den Berg around 1992, and which has been further developed with J. Steif and with C. Maes. Currently Van den Berg works on applications of this tool to Markov Chain Monte Carlo and approximate counting problems. Joint work with G. Grimmett and R. Schinazi (1998) gives (besides other results) one of the first relevant applications of the so-called generalized BK inequality (which was conjectured by Van den Berg and Kesten in 1984, and proved ten years later by D. Reimer). The inequality is used here to show exponential decay results for a large class of subcritical spatial epidemics models. The paper with H. Kesten describes a new method to obtain the asymptotic density in a system of randomly moving, coalescing particles. This method seems considerably more robust than the classical method of Bramson and Griffeath. A follow-up paper (in which conditions on the dimension are relaxed) is in progress.

(ii) Most of the attention in the work of **Dzhaparidze** is devoted to general principles of statistical inference for stochastic processes. Dzhaparidze, Spreij and Valkeila (Helsinki) have completed a contribution to the *Liptser Festschrift*, in which basic notions such as Hellinger integrals and Hellinger processes are extended from usual binary experiments to abstract parametric families of experiments. At the same time the work on Gelfond's modification of the Abel-Goncharov interpolation series has been carried out by Dzhaparidze, with a view to the same theory of Hellinger processes. As to applications, statistical and stochastic/analytical methods in Finance have been reviewed in a paper submitted to *Statistica Neerlandica* by Dzhaparidze, Spreij and van Zanten. The basics of an important special subject of mathematical finance - Option Theory - has been discussed by Dzhaparidze in a series of papers in the *CWI Quarterly*.

(iii) The focus of **Helmers**'s work is on statistical estimation and bootstrap/Edgeworth/saddlepoint based methods. In joint work with M. Wegkamp a new resampling scheme for finite populations, called 'two-stage wild bootstrapping' was introduced and studied. With R. Zitikis a new nonparametric estimator of the intensity function of an inhomogeneous Poisson process was investigated. We prove consistency in the case that the true intensity is a parametric function of spatial location. The unique feature of this result is that it is applicable in presence of only one realization, provided the sampling window gets large. The research of PhD student I.W. Mangku (supervised by Helmers) is also in this area. Inference on rare errors was the topic of a research project with PricewaterhouseCoopers. Current work with B.Y. Jing on saddlepoint approximations for trimmed means and with M. Hušková and A.J. van Es on bootstrap resampling in various statistical settings is in progress.

(iv) The work of **Keane** is very diverse and spreads over (and beyond) the four subthemes (Probability, Stochastic Analysis, Statistics, and Ergodic theory). An interesting example of a single paper which involves three of the four subthemes is *Random coin tossing* (with M. Harris). It studies a deep question concerning the possibility (or impossibility) to distinguish between two random sequences which have been generated by almost (but not exactly) the same mechanism. This paper has drawn much attention and has triggered further research on this subject, e.g. by Y. Peres (Berkeley) and co-workers. Examples of recent ergodic theoretical (and dynamical systems) work are *A simple proof of the ratio ergodic theorem* (with T. Kamae) and *Computing invariant measures for expanding circle maps* (with R. Murray and Lai-Sang Young). As to more applied work, Keane has recently worked on disk scheduling, (with D. Maslen (Dartmouth)) and J. Korst (Philips Research Laboratories), and on robotic control (with D. Maslen).

3.2 Present personnel

3.2.1 Senior staff members

dr. J. van den Berg (0.9 fte), dr. K.O. Dzhaparidze (0.8 fte), dr. R. Helmers (1.0 fte), prof.dr. M.S. Keane (0.7 fte, theme leader)

3.2.2 Total formation

4 senior staff members (3.4 fte), 2 postdocs (2 fte), 5 PhD students (1.8 fte), 1 advisor (0.2 fte), 1 long term (1 year) visitor (1 fte), 1 programmer (0.75 fte).

3.3 Selected publications

dr. J. van den Berg

- A constructive mixing condition for 2-D Gibbs measures with random interactions, *Annals of Probability* 25, 1316-1333 (1997).
- Dependent random graphs and spatial epidemics, *Annals of Applied Probability* 8, 317-336 (1998). With G. Grimmett and R. Schinazi.
- *Asymptotic density in a coalescing random walk model* (1998), CWI report PNA-R9815, 56 pages, 1998 (submitted). With H. Kesten.

dr. K.O. Dzhaparidze

- On Hellinger processes for parametric families of experiments (1997), in: *Statistics and Control of Stochastic Processes* (The Liptser Festschrift) 41-62, (eds. Yu. Kabanov, B. Rozovskii and A. Shiryaev). World Scientific, Singapore. With P.J.C. Spreij and E. Valkeila.
- On optimality of regular projective estimators for semimartingale models, *Stochastics and Stochastics Reports* 56 (1996), 63-74. With P.J.C. Spreij.

dr. R. Helmers

- Wild bootstrapping in finite populations with auxiliary information (1998), *Scandinavian Journal of Statistics* 25, 383-399. With M. Wegkamp.
- On estimation of Poisson intensity functions; to appear in the *Annals of the Institute of Statistical Mathematics* 51 (1999), 19 pages. With R. Zitikis.
- Inference on rare errors using asymptotic expansions and bootstrap calibration (1998), tentatively accepted by *Biometrika*; 10 pages; A shorter version has appeared in *Proceedings of the 51th ISI meeting* (1997), 93-96.

prof.dr. M.S. Keane

- Random coin tossing, *Probability Theory and Related fields* 109, 27-37 (1997). With M. Harris.
- A simple proof of the ratio ergodic theorem, *Osaka Journal of Mathematics* 34, 653-657 (1997). With T. Kamae.
- Computing invariant measures for expanding circle maps, *Nonlinearity* 11, 27-46 (1998). With R. Murray and Lai-Sang Young.

3.4 External projects and funding

dr. J. van den Berg

- Involvement in the national NWO project CIMS (1993-1997): funding of an PhD student position and of a workshop held in Renkum (1995).
- Project 'Large random systems and combinatorial probability' (1998-2000; vd Berg and Keane). Funded by NWO: salary of a two-year postdoc (Andras Lukacs).

dr. J. van den Berg and prof.dr. M.S. Keane

- NWO-OTKA Hungary-Netherlands scientific cooperation. Current grant of 100 kf for three-years (second grant).

dr. K.O. Dzhaparidze

- 1993-1996 HCP project: Statistical inference for stochastic processes
- 1992-1995 Secondment of PhD student R.H.P. Janssen, TU Delft.

dr. R. Helmers

- Cooperation project 'Applied Mathematics and Computational Methods' (1995-1999) with Indonesia.
- Ph.D. student I.W. Mangku 1996-2000; topic: Statistical estimation of Poisson intensity functions.
- Research workshop 'Bootstrap methods' in 1995. Evaluation research workshop ' System and Control' in 1998.

- Consultancy for the Netherlands Postal services (1994) , with M. Wegkamp (Leiden/Yale); topic: efficient stratification in finite populations. Consultancy for Ministry of Transport and Public Works (Rijkswaterstaat); (1995- 1996) ; topic: Oil pollution in the North Sea. Advisor Statistical Audit Group PricewaterhouseCoopers (1993-).

prof.dr. M.S. Keane

- Advisor for Philips Research Laboratories, Eindhoven, one day a week. PRL pays CWI an amount of 20% of Keane's salary.
- Advisor for Eurandom, Eindhoven, one-half day a week. Eurandom pays CWI 20 kf per year for his services.
- Senior fellow for Hewlett-Packard Laboratories BRIMS Bristol, one month a year (twice two weeks). HPL pays CWI full travel and expenses for this period, and in addition GBP 2000 per year.
- Various contracts for Ph.D.students, postdoctoral fellows (2), and visitors (1).

In 1997 and 1998, the percentages of the total costs of PNA3 covered by external funding were: 14% and 14%, respectively.

3.5 PhD theses

- A.B. Ermakov, Percolation and Coalescing Particle Systems, Delft University of Technology, 1997. (Thesis advisors M.S. Keane and J. van den Berg)
- R.H.P. Janssen, Construction of Orthogonal Polynomials Associated with Time Series and Random Fields, Delft University of Technology, 1995. (Thesis advisors: C.L. Scheffer and K.O. Dzhaparidze)
- M.C.J. van Pul, *Statistical Analysis of Software Reliability Methods*, University of Utrecht, 1993. (Thesis advisor: R.D. Gill).
- External PhD theses with M.S. Keane as advisor: Harris (1997), Serafin (1996).

3.6 Academic relations

3.6.1 Secondment of senior staff members at universities

- M.S. Keane, full professor at University of Amsterdam (0.2fte).
- J. van den Berg, courses at the University of Amsterdam in 1997-1998.
- J. van den Berg, supervision of the (Master's) thesis work of a student at the University of Amsterdam, 1998-1999.

3.6.2 Secondment of university staff at CWI

- M.L. Eaton, full professor at University of Minnesota (one year sabbatical in 1998-1999)
- S.M. Verduyn Lunel, full professor at Free University Amsterdam (0.2fte, advisor PNA3)

3.7 Services to the research community

dr. J. van den Berg

- Co-organizer of a month of activities (on Percolation, Particle Systems and related fields), June 1993, of the workshop Probability and Physics in Renkum, 1995, of the workshop Probability and Physics of Disordered Systems, to be held in Budapest, August 1999.
- Member of the thesis committee of D. Reimer (Rutgers University, USA, April 1997).
- Participation (as visiting researcher) in research programs, e.g.: "Random Spatial Processes" (Isaac Newton Institute, Cambridge, UK, August-November 1993) and "Discrete Probability" (DIMACS, Rutgers University, USA, February-June 1997).
- Invited lectures at Statistical Laboratory Cambridge, UK; DIMACS distinguished lecturer series 1997; Meeting on Randomized Algorithms, Edinburgh, 1998; Microsoft Research, Redmond, USA, 1998.

dr. K.O. Dzhaparidze

- Activities in the framework of the HCP project: Statistical inference for stochastic processes
- Participation in the special issues of CWI Quarterly on Mathematics of Finance

- Contribution to The Liptser Festschrift, in cooperation with Valkeila (Helsinki) and Spreij (VU, Amsterdam)

dr. R. Helmers

- R. Helmers was member of Ph.D. committees of M. Wegkamp (1996, Leiden) and S. Borovkova (1998, Groningen).
- R. Helmers was member of the organizing committee for the annual Lunteren conference on Stochastics (until 1996).
- R. Helmers is member of the Steering committee Research Statistical Auditing of the Limperg Institute, the Inter University Research Institute for Accountancy in the Netherlands.

prof.dr. M.S. Keane

- Coordinating editor of the KNAW journal Indagationes Mathematicae; member ARW.
- Member of the governing board of the research school MRI, since 1994.
- President of the research committee, research school Stieltjes, until 1997.
- Various editorial board memberships in international mathematical journals.
- Various evaluation committee memberships (countries: USA, Germany, Chile, France).
- Organization of numerous international conferences.

3.8 Awards and honours

Prof.dr. M.S. Keane is member of the Royal Netherlands Academy of Arts and Sciences (elected 1991).

4 Pilot theme PNA4: Signals and Images

4.1 Short history of the theme and research highlights

The "Signals and Images" research theme (PNA4) started as a pilot at January 1, 1997, after the restructuring of CWI. Also in the years before, CWI housed a research group, the "Image Analysis and Spatial Stochastics" research group in the former department BS, that was partially active in the area of image processing. The restructuring of CWI was considered a good opportunity to combine these activities with those of members of a different department (AM) working on wavelets and their applications in seismology. The establishment of the "Signals and Images" research pilot was completed with the appointment of M.N.M. van Lieshout, a prominent researcher in the area of stochastic geometry and image analysis. Compared with the old situation, the research carried out in PNA4, though still fundamental in nature, is more directed towards concrete applications. In the first two-years of its existence, great efforts have been made towards the following goals:

(*i*) To enlarge the coherence among the different subthemes. A common denominator in a substantial part of the research in this theme is "multiresolution", i.e., the analysis of signals/images at different levels of resolution (or scales). It plays an important role in fractal image coding, wavelet analysis, and mathematical morphology.

(*ii*) To extend ongoing research by means of externally financed projects. An example is the new project *Multiresolution image analysis and synthesis*, sponsored by STW (PhD student and postdoc).

(*iii*) To explore and set up new research directions, preferably building on existing expertise within the group. As an importance instance we mention the new research project *Multiresolution image indexing and retrieval* to be initiated in 1999.

A highlight of PNA4 in 1998 was the organization of the IV'th International Symposium on Mathematical Morphology (ISMM'98) in Amsterdam with approximately 80 participants (proceedings published by Kluwer).

The research within PNA4 is subdivided into four subthemes, which are briefly described below.

Coding, Indexing and Retrieval: Image and video coding and compression on the one hand and indexing and retrieval on the other are applications which are becoming increasingly important with the rapid growth of the world-wide-web. This subtheme focuses on new mathematical techniques in probability and ergodic theory on the one hand and multiresolution imaging techniques such as quadtrees, wavelets, and fractal coding on the other.

Wavelets: Although the theory of wavelets is relatively young, it has become clear that they provide excellent tools for signal and image analysis, data compression, and for the development of efficient numerical algorithms, e.g. for solving partial differential equations. The research in this subtheme is directed towards the application of wavelet techniques in seismology, e.g. for the removal of unwanted information from geophysical data and the analysis of seismograms.

Morphological Image Processing: Mathematical morphology is a geometrical approach in image processing with a strong mathematical flavour. Morphological algorithms have shown to be eminently suited for applications where shape and structure of objects are relevant. This technique, moreover, is tailormade to provide multiresolution description of images. During the next two or three-years, the research in this subtheme will be directed mainly towards morphological multiresolution decomposition of signals, in particular the development of an axiomatic theory for morphological pyramids and wavelets. This will also increase the coherence with the previous subtheme. As an important application of the aforementioned decompositions, we foresee their use in feature extraction and image indexing, thus establishing a link with the first subtheme.

Stochastic Geometry: Stochastic geometry is concerned with random geometric structures, ranging from simple points or line segments to compact objects. Although it has roots in geometric probability and integral geometry, the modern theory of random sets was developed in the seventies. Stochastic geometry techniques can be applied in a wide range of fields, for instance material science, cell biology, image analysis, forestry and environmental research. Several projects are carried out within this subtheme, ranging from spatial statistics, inference for random sets, and image segmentation with applications to agriculture.

4.2 Present personnel

4.2.1 Senior staff members

dr.ir. H.J.A.M. Heijmans (1.0 fte; theme leader), prof. dr. M.S. Keane (0.1 fte)[19], dr. A.AM. Kuijk (1.0 fte), dr. M.N.M. van Lieshout (1.0 fte), dr. N.M. Temme (0.6 fte).

4.2.2 Total formation

5 senior staff members (3.7 fte), 1 postdoc (1.0 fte), 2 PhD students (2.0 fte), 2 programmers (1.2 fte).

4.3 Selected publications

dr.ir. H.J.A.M. Heijmans

- H.J.A.M. Heijmans and A.V. Tuzikov, Similarity and symmetry measures for convex shapes using Minkowski addition *IEEE Transactions on Pattern Analysis and Machine Intelligence* **20**, 980–993 (1998)
- H.J.A.M. Heijmans, Composing morphological filters, *IEEE Transactions on Image Processing* **6**, 713-723 (1997)
- H.J.A.M. Heijmans, *Morphological Image Operators*, Academic Press, Boston (1994)

dr. A.A.M. Kuijk

- T. van Rij, A.A.M. Kuijk, Using Eiffel to adaptively render 3 dimensional images, *Eiffel Outlook*, **4, 5**, 1, 16-25.
- Dutch patent 1003363 on a Multi Sample Engine, Assignee: Stichting Mathematisch Centrum, Inventor: A.A.M. Kuijk.

dr. M.N.M. van Lieshout

- O. Barndorff-Nielsen, W.S. Kendall and M.N.M. van Lieshout, *Stochastic Geometry: Likelihood and Computation*, CRC Press (Chapman and Hall list), London (1998)
- M.N.M. van Lieshout, *Markov Point Processes and their Applications*, Imperial College Press/World Scientific, 1999. To appear.
- M.N.M. van Lieshout and I.S. Molchanov, Shot-noise-weighted processes: a new family of spatial point processes, *Stochastic Models* **14**, 715-734 (1998)

[19] The research by Keane is described under PNA3.

dr. N.M. Temme (and other researchers in subtheme on "Wavelets")

- N.M. Temme, Asymptotics and numerics of zeros of polynomials that are related to Daubechies wavelets. *Appl. Comput. Harmon. Anal.* **4**, 414 - 428 (1997).
- P.J. Oonincx, The discrete wavelet transform as a tool for automatic phase pickers, Proceedings *IEEE-SP Int. Symposium on Time-Frequency and Time-Scale Analysis*, Pittsburgh, October 1998, 201-204 (1998).
- R.A. Zuidwijk, P.M. de Zeeuw, Fast algorithm for directional time-scale analysis using wavelets, SPIE proceedings 3458, *Wavelet Applications in Signal and Image Processing VI* (1998).

4.4 External projects and funding

The research in "Signals and Images" started as a pilot in 1997 with only few externally funded projects. The potential for external funding by European projects like ESPRIT is not very high due to the fundamental nature of the research carried out in this theme. National funding, e.g. by STW and NWO is much more within reach. It is our aim to increase the percentage of externally funded costs to at least 30% by the end of the year 2000. Currently, the following projects are externally funded:

(*i*) Fractal image coding: 1 PhD student (NWO, ending in 2000)

(*ii*) Wavelets: analysis of seismic signals: 1 PhD student and 1 postdoc (STW, ending in 1999)

(*iii*) Multiresolution image analysis and synthesis: 1 PhD student and 1 postdoc (STW, ending in 2002)

(*iv*) Research in "Stochastic Geometry" subtheme (NWO/CIMS; till March 1999).

Additional fundings, mostly for traveling and visitors, have been obtained from ERCIM, the EC-funded progammes INTAS (with CWI/PNA4 as coordinator), and KIT (with University of Cape Town and the University College London), NATO (Collaborative research grant with The Johns Hopkins University in Baltimore, USA), and the Australian Research Council. At the moment of writing several research proposals for external funding are in preparation.

In 1997 and 1998, the percentages of the total costs of PNA4 covered by external funding were: 16% and 17%, respectively.

4.5 PhD theses

- P.J. Oonincx, *The Wavelet Transform and its Applications in Seismology*, University of Amsterdam, 1999 or 2000 (thesis advisor: T.H. Koornwinder, co-advisor: N.M. Temme).
- A.A.M. Kuijk, *On a Layered Object-Space Based Architecture for Interactive Raster Graphics*, University of Amsterdam, 1996 (thesis advisor: L.O. Hertzberger, co-advisor: E.H. Blake).
- A.J. Cabo, *Set Functionals in Stochastic Geometry*, Technical University of Delft, 1994 (thesis advisors: A. J. Baddeley, P. Groeneboom).
- P.F.M. Nacken, *Image Analysis Methods Based on Hierarchies of Graphs and Multi-Scale Mathematical Morphology*, University of Amsterdam, 1994 (thesis advisor: F. Groen , co-advisors: H.J.A.M. Heijmans and A. Toet).
- M.N.M. van Lieshout, *Stochastic Geometry Models in Image Analysis and Spatial Statistics*, Free University of Amsterdam, 1994 (thesis advisor: A. J. Baddeley, co-advisor: J. Oosterhoff).

4.6 Academic relations

4.6.1 Secondment of senior staff members at universities

- H.J.A.M. Heijmans: teaches course (bi-yearly) at the Technical University of Delft and at the University of Leiden (first semester 1999); teacher in PhD student course "Mathematical Morphology: Principles, Algorithms, and Applications" (ASCI research school, 0.1 fte, bi-yearly).
- M.S. Keane: full professor at University of Amsterdam (0.2 fte)
- M.N.M. van Lieshout: three courses at University of Utrecht (1998-1999); PhD student course Markov point processes (National Network Stochastics, 0.3 fte in 1998)

4.6.2 Secondment of university staff at CWI

- F.M. Dekking: full professor from Technical University of Delft (0.1 fte)
- A.W.M. Smeulders (advisor of PNA4): full professor from University of Amsterdam (0.1 fte)
- H.G. ter Morsche: associate professor from University of Eindhoven (0.1 fte)

4.7 Services to the research community

dr.ir. H.J.A.M. Heijmans

- (with **M.N.M. van Lieshout**) Guest editor of special issue (1998) of *CWI Quarterly* on image processing; Guest editor (with J. Goutsias) of a special issue of *Fundamenta Informaticae* on mathematical morphology (to appear in 1999).
- Member of editorial board of *Journal of Mathematical Imaging and Vision* (Kluwer); Editor of electronic newsletter *Morphology Digest* (approximately 1100 subscribers).
- Conference Chair of the IV'th International Symposium on Mathematical Morphology (ISMM'98); Member of three technical committees of workshops and conferences.
- Examiner of PhD thesis of Wu Fang-Nong, *New Morphological Representation Theory*, National University of Singapore 1997

dr. A.A.M. Kuijk

- Program Committee member Eurographics/SIGGRAPH Workshop on Graphics Hardware (since 1987)

dr. M.N.M. van Lieshout

- External examiner of 2 PhD theses (Gothenburg and Utrecht).
- Organiser on behalf of the Bernoulli Society of a session on 'Spatial interaction in stochastic systems' at the 22nd European Meeting of Statisticians held in Vilnius, August 1998; Organiser on behalf of the European research institute Eurandom of a workshop on stochastic geometry to be held in The Netherlands in the academic year 1998-1999.
- Member of steering committee *Complex stochastic models* of the European research institute Eurandom.

dr. N.M. Temme

- See MAS2.

5 Theme SEN1: Interactive Software Development and Renovation

5.1 Short history of the theme and research highlights

5.1.1 ASF+SDF Meta-Environment

The language definition formalism ASF+SDF and the first version of the associated ASF+SDF Meta-Environment form the starting point for the research period described here (1993–1998). The work has primarily been driven by the demands made by an increasing number of applications, in areas like formal semantics (Action Semantics, with P.D. Mosses, University of Aarhus), intermediate data descriptions for compilers (fSDL, Esprit COMPARE), domain-specific languages (the RISLA financial product specification language with MeesPierson and Cap Gemini), program transformation (source-to-source transformation of scientific code with the University of Bergen, Norway), and system renovation (analysis and restructuring of COBOL systems with ABN AMRO and ROCCADE). All these applications require more functionality, higher performance, and more flexibility.

Studies and implementations of new functionality for the ASF+SDF Meta-Environment include incremental rewriting, higher-order specifications, partial evaluation, prettyprinting, origin tracking, and program slicing.

Efficient execution of ASF+SDF specifications has been a growing concern in the project. Various approaches toward compilation have been explored. The most notable are compilation to various abstract machines and, recently, direct generation of C code. Today, ASF+SDF has an execution speed comparable to that of Standard ML, Clean or Opal and a memory usage that is significantly lower.

Given its ongoing development and extensions needed for applications, the renovation of the ASF+SDF Meta-Environment itself has become a topic of research on its own. A new coordination architecture (ToolBus) has been designed and implemented and the major components of the system have already been renovated. The standard approach is to specify a component in ASF+SDF, compile it to C, and connect it to other components via the ToolBus. In this way, various stand-alone applications for industrial problems have already been realized and we believe that we are now approaching a situation in which both new research directions can be explored and new, challenging, industrial problems can be addressed.

5.1.2 Software renovation

Software renovation aims at making legacy software systems more comprehensible, extensible, robust and reusable. As a typical industrial or governmental organization has millions of lines of legacy code in continuous maintenance, well-applied software renovation can lead to significant information technology budget savings. In cooperation with companies such as bank ABN AMRO and software house Roccade, a generic architecture (based on the ASF+SDF Meta-Environment) for renovation tools has been constructed, and applied to real-life COBOL legacy systems.

Software renovation at the source code level includes automated program transformations for the purpose of step-by-step code improvement, by means of, e.g., goto elimination, dialect migration (between COBOL 85 and COBOL 74) and modifications in the conventions for calling library utilities. For this purpose, the University of Amsterdam has developed an ASF+SDF grammar for COBOL, as well as rewrite rules describing the desired transformations. This grammar is being used by us for analyzing COBOL legacy code at the system level, finding dependencies between modules, databases, and so on. In particular, techniques have been developed to support the migration of procedural COBOL code to object technology. Issues addressed include type inference, identification of business data items, metrics-based program selection, visualization, cluster analysis, and concept analysis. These techniques were successfully applied to support object identification in COBOL legacy systems consisting of 100,000 lines of code.

5.1.3 Optimization of scientific software

This subtheme is the successor to "Generic Tools for Program Analysis and Optimization", which was funded by NWO in the period 1994–1998. It focuses on:

(1) PIM, a toolkit for compilers, in cooperation with the IBM T.J. Watson Research Center. PIM is an equational logic for symbolic execution and optimization of programs in imperative languages such as C. It has been implemented at IBM and a C program slicing tool was based on it. Furthermore, it has been the subject of extensive theoretical analysis. This work is an intermediate step in a larger program to develop a set of well-founded tools for manipulation of imperative programs by compilers and other systems that perform program analysis.

(2) Sophus, a domain-specific style for partial differential equation solvers, in cooperation with the University of Bergen (Norway) and the University of Wales, Swansea. Sophus attempts to close the gap between the underlying coordinate-free mathematical theory and the way actual solvers are written. Its purpose is to reduce development time and improve maintainability and flexibility of numerical codes. A C++ source-to-source optimizer for Sophus style programs was written in ASF+SDF. Positive preliminary results were obtained for a Sophus style commercial seismic simulation code on the Silicon Graphics/Cray Origin 2000. A special issue of *Scientific Programming* on the Sophus style was recently accepted for publication.

5.1.4 Domain-specific languages

A domain-specific language (DSL) provides a notation that can be used to compose applications from a set of concepts tailored towards a specific application domain. The research area of domain-specific languages aims at developing theory, methodology, tools, and experience to support effective use of DSLs in real life software engineering projects.

Starting from 1992, we have been in close cooperation with software house CAP Gemini and bank MeesPierson concerning a domain-specific language called RISLA for describing interest rate products. ASF+SDF was used for design, prototyping and part of the RISLA tooling. Given a high-level RISLA product description, the RISLA compiler automatically generates data structures, screens, and COBOL code that are executable in the target mainframe environment. CAP Gemini has reported a significant reduction of lead-time to market for new products, and a 50% IT cost reduction. Currently, the use of RISLA in Dutch banks is still increasing, and research cooperation with CAP Gemini is still expanding.

5.1.5 Interactive visualization environments

This group is the continuation of the Computational Steering Group from the Department of Interactive Systems. In the past two-years, the focus was on three tracks: (1) computational steering, (2) high performance visualization, and (3) virtual reality techniques for scientific visualization.

(1) The computational steering track, partially funded by SION, studied interactive techniques for simulation steering. The research focused on the application of point based graphics for computational steering. In addition, the use of constraints for high-level input for interactive scientific visualization was studied.

(2) The high-performance visualization track, partially funded by the Dutch HPCN chapter, studied techniques for manipulating very large data sets. The research focused on data representation and architectural issues in managing very large data sets for interactive analysis. The problem of the analysis of very large and complex flow data sets was taken as the application area.

(3) The new virtual reality track, partially funded by ALW/NCF, has started studying the use of advanced display techniques for interactive scientific visualization. The primary application area is the presentation and manipulation of biological structures.

5.2 Present personnel

5.2.1 Senior staff members

dr. M.G.J. van den Brand (1.0 fte), dr. A. van Deursen (1.0 fte), J. Heering (1.0 fte), prof.dr. P. Klint (0.6 fte, theme leader), ir. R. van Liere (1.0 fte).

5.2.2 Total formation

5 senior staff members (4.6 fte), 2 postdocs (2.0 fte), 1 PhD student (1.0 fte), 2 other employees (1.2 fte).

5.3 Selected publications

dr. M.G.J. van den Brand

- M.G.J. van den Brand, A. Sellink, and C. Verhoef, Current parsing techniques in software renovation considered harmful, in: *Proceedings 6th International Workshop on Program Comprehension*, IEEE Computer Society, 1998, 108–117.
- M.G.J.van den Brand, P. Klint and C. Verhoef, Core technologies for system renovation, in: *Theory and Practice of Informatics (SOFSEM '96)*, Lecture Notes in Computer Science, Vol. 1175, Springer-Verlag, 1996, 235–255.

dr. A. van Deursen

- A. van Deursen and L. Moonen, Type inference for COBOL systems, in: *Proceedings of the 5th Working Conference on Reverse Engineering*, IEEE Computer Society, 1998, 220–230.
- A. van Deursen and P. Klint, Little languages: Little maintenance?, *Journal of Software Maintenance*, **10** (1998), 75–92.

J. Heering

- J. Field, J. Heering, and T.B. Dinesh, Equations as a uniform framework for partial evaluation and abstract interpretation, *ACM Computing Surveys*, **30**, 3es (September 1998). (electronic copy only)
- J.A. Bergstra, T.B. Dinesh, J. Field, and J. Heering, Toward a complete transformational toolkit for compilers, *ACM Transactions on Programming Languages and Systems*, **19**, 5 (1997), 639–684.

prof.dr. P. Klint

- J.A. Bergstra and P. Klint, The discrete time ToolBus—A software coordination architecture, *Science of Computer Programming*, **31** (1998), 205–229.
- P. Klint, A meta-environment for generating programming environments, *ACM Transactions on Software Engineering and Methodology*, **2** (1993), 176–201.

ir. R. van Liere

- R. van Liere, J. Harkes and W. de Leeuw, A blackboard architecture for interactive data visualization, in: R. Yagel and H. Hagen (eds.), *Proceedings IEEE Visualization '98*, , IEEE Computer Society, 1998, 235–244.

- W. de Leeuw and R. van Liere, Divide and conquer spot noise, in: *Proceedings Super Computing '97*, http://scxy.tc.cornell.edu/sc97/program/TECH/DELEEUW/INDEX.HTM, 1997. (electronic copy only)

Miscellaneous

- A. van Deursen, J. Heering, and P. Klint (eds.), *Language Prototyping*, AMAST Series in Computing, Vol. 5, World-Scientific, 1996.

5.4 External projects and funding

The main external projects/contracts were/are:

- NWO project "Generation of Program Transformation Systems"
- TI project "Domain-Specific Languages"
- TriLoc contract "Advanced Topics in Software Renovation"
- CAP Gemini contract "RISLA Financial Product Specification Language Expander"
- ALW/NCF project "Analysis of Biological Structures by Virtual Reality Techniques"
- NWO project "Scientific Visualization—From Data Visualization to Interactive Exploration"
- HPCN project "High-Performance Visualization"
- Esprit project 21871 "Scientific Computing and Algebraic Abstractions" (SAGA)
- SENTER project "Program Analysis for System Renovation" (RESOLVER)
- NWO project "Generic Tools for Program Analysis and Optimization"
- CAP Volmac and MeesPierson contract "Update RISLA Financial Product Specification Language"
- NWO Computer Science Priority Program project "Incremental Program Generation"
- Esprit project 5399 "Compiler Generation for Parallel Machines" (COMPARE)
- Esprit project 2177 "Generation of Interactive Programming Environments II" (GIPE II)

In 1997 and 1998 the percentages of total costs of SEN1 covered by external funding, were 51% and 46% respectively.

5.5 PhD theses

- J. Mulder, *Computational Steering with Parametrized Geometric Objects*, University of Amsterdam, 1998 (Thesis advisor: F.C.A. Groen, co-advisor: J.J. van Wijk)
- J.F.Th. Kamperman, *Compilation of Term Rewriting Systems*, University of Amsterdam, 1996 (Thesis advisor: P. Klint, co-advisor: H.R. Walters)
- F. Tip, *Generation of Program Analysis Tools*, University of Amsterdam, 1995 (Thesis advisor: P. Klint)
- N.W.P van Diepen, *Modular Algebraic Specifications and Transformational Program Development*, University of Nijmegen, 1994 (Thesis advisors: H.A. Partsch and P. Klint)
- A. van Deursen, *Executable Language Definitions—Case Studies and Origin Tracking Techniques*, University of Amsterdam, 1994 (Thesis advisor: P. Klint)
- E.A. van der Meulen, *Incremental Rewriting*, University of Amsterdam, 1994 (Thesis advisor: P. Klint)
- External PhD's with P. Klint as advisor: Visser (1997), Üsküdarli (1997), Watson (1995), Koorn (1994), Helmink (1993)

5.6 Academic relations

5.6.1 Secondment of senior staff members at universities

- Prof.dr. P. Klint, full professor at University of Amsterdam (0.4 fte)

5.6.2 Secondment of university staff at CWI

- Dr. M.G.J. van den Brand, assistant professor from University of Amsterdam (1.0 fte)

5.7 Services to the research community

dr. M.G.J. van den Brand

- Member of 1 international conference program committee

dr. A. van Deursen

- Member of 3 program committees for international conferences and workshops

J. Heering

- Member of 6 program committees for international conferences and workshops
- External PhD examiner of two PhD candidates (University of Wales, Swansea).

prof.dr. P. Klint

- Member of 8 program committees for international conferences
- President European Association for Programming Languages and Systems (EAPLS)
- Member Steering Committee ETAPS (European Joint Conferences on Theory and Practice of Software)
- Various advisory boards

ir. R. van Liere

- Member of 6 program committees for international conferences and workshops

6 Theme SEN2: Specification and Analysis of Embedded Systems

6.1 Short history of the theme and research highlights

The theme SEN2 is the result of merging the groups AP2, led by F.W. Vaandrager till 1996, and subsequently by J.F. Groote, and AP4, led by J.W. Klop.

Till 1996 AP2 concentrated on timed and hybrid automata together with Nancy Lynch of the MIT. This theory was applied to several case studies, generally obtained via Philips research. The Philips Audio Control Protocol as well as the Bounded Retransmission Protocol have become standard benchmarks in the literature. Since that time, after a switch of leadership, AP2 moved towards the study of process algebras with data, focusing on the language μCRL which is in essence ACP (Algebra of Communicating Processes) with equational datatypes. During this period major improvements have been achieved in verification techniques for processes, and it has been shown using a.o. the theorem checker COQ that it is quite feasible to check these proofs achieving a very high degree of reliability. Noteworthy are also results on using confluence in processes to simplify them and the 'cones and foci theorem' that employs structural properties of implementations to simplify proving these equal to specifications.

The work within AP4 consisted in developing several extensions of the usual first-order term rewriting format. Specifically, these extensions concern term graph rewriting and infinitary rewriting. Another line of investigation within AP4 was the analysis of origin tracking, both in first-order rewrite systems and infinitary lambda calculus. Using this technique an analysis of the sequential nature of lambda calculus was given that improves the classical sequentiality theorem of Berry.

After the advent of SEN2, focus has shifted to process algebras with time (in particular μCRL with time), to the development of new techniques for automatic verification of processes, to an enhanced attempt to test and apply more modern techniques in industrial contexts and to writing a set of books covering the field of term rewriting.

Timed process algebras became a popular subject in the late 80's, leading to (continuous) real time process algebras primarily developed by Baeten and Bergstra. Major contributions to the fundamental understanding of the axiomatic treatment of this subject have been provided by Steven Klusener (PhD thesis, 1993) and Willem Jan Fokkink (PhD thesis, 1994). However, the use of these formalisms for verification purposes turned out to be harsh, and the field was abandoned, in favour of timed I/O automata and discrete time process algebras. Given the very encouraging improvements in verification techniques for process algebras, and the growing importance of hybrid systems, (continuous) timed μCRL has been defined, which being as powerful as its predecessors, is structurally simpler in design and theory. Basic theory has been investigated, and its applicability to for instance hybrid systems has been shown.

When verification techniques for process algebras reached a form of maturity, it became clear that the major bottleneck in the application of these techniques is the length of the description of protocols and distributed systems. If such a description exceeds a few pages, it is not reasonable anymore to manipulate it by hand. This motivated a move towards large scale automation of techniques in the form of a toolset for μCRL. One major observation is that virtually all verification techniques for distributed systems focus around the notion of a transition system or automaton. Even for small systems, these tend to grow far beyond any form of manageability, severely limiting the applicability of these techniques. Therefore, it was decided to focus the tools around a meta format, called a linear process, which had turned out an essential ingredient in the improved hand-based verification techniques. This format can essentially be understood as providing a state consisting of data variables over potentially infinite domains, and a set of action/effect rules on this vector. An effective translation scheme and tool from both finite and infinite state process algebra descriptions to this format has been provided, translating easily descriptions up to 100 pages with numerous parallel components. In order to facilitate a connection with the existing tools, a translation tool to an automaton has been provided, outperforming on virtually all aspects state of the art tools in process algebra, such as Ceasar/Aldebaran, and being comparable to the best known tools, for the analysis of parallel sequential languages, such as SPIN. Essential ingredients in these tools are the superior rewriting techniques and term manipulation techniques developed within the theme SEN1. The focus of this toolset is however on symbolic data manipulation, and an algorithm for symbolically handling modal formulas has been provided, as well as a set of simplification rules for linear processes, which also have been implemented. Work has been done to connect a locally developed very efficient proposition checker HeerHugo, which helped to prove safety of several Dutch railway stations, where state spaces of approximately 10^{1000} states were involved. For reasons that are not yet properly understood up till now, this turned out not too effective.

Applicability is as strong a motivation underlying the research as mathematical elegance. Therefore, continuous effort is undertaken to apply the developed techniques within industrial contexts. Although the outcome of these applications has generally been satisfactory, it did in general not lead to the adoption of the techniques, although a growing interest is clearly observable. We intend to change this situation using the toolset. Projects that have been carried out are the verification of parts of the remote control RC6 standard, the Philips Audio Control Protocol, design of protocols for the KidCom (some toy device), conformance testing for Digital Video Broadcast (MPEG2) decoder IC, testing and verifying the IEEE 1394 or Firewire bus, analysing the HAVI (Home Audio Video Interoperability) protocols and some other projects for Philips. For the Dutch Railway company a new railway specification language has been designed (LARIS 1.0) with proper syntax and semantics, inspired by the graphical language EURIS (European Railway Interlocking Specification). It has been shown that specifications of railway yards in this language can be formally analysed on correctness.

6.2 Present personnel

6.2.1 Senior staff members

prof.dr.ir. J.F. Groote (0.8 fte, theme leader), prof.dr. J.W. Klop (0.1 fte).

6.2.2 Total formation

2 senior staff members (0.9 fte), 3 postdocs (2.2 fte), 6 PhD students (4.6 fte), 1 programmer (1.0 fte).

6.3 Selected publications

prof.dr.ir. J.F. Groote

- R.N. Bol and J.F. Groote. The meaning of negative premises in transition system specifications. In *Journal of the ACM*, 43(5):863–914, 1996.
- M.A. Bezem, R.N. Bol and J.F. Groote. Formalizing Process Algebraic Verifications in the Calculus of Constructions. *Formal Aspects of Computing*, 9:1–48, 1997.
- J.F. Groote, J.W.C. Koorn and S.F.M. van Vlijmen. The safety guaranteeing system at station Hoorn-Kersenboogerd (Extended abstract). In proceedings 10th Annual Conference on Computer Assurance (COMPASS'95), pp. 57-68, Gaithersburg, Maryland, 1995.
- J.F. Groote and M.P.A. Sellink. Confluence for Process Verification. In S.A. Smolka editor, proceedings of CONCUR'95, pp. 204-218, LNCS 962, Springer Verlag, 1995.

- J.F. Groote and J.C. van de Pol. A bounded retransmission protocol for large data packets. A case study in computer checked verification. In M. Wirsing and M. Nivat, Editors, *Proceedings of AMAST'96*, Munich, Lecture Notes in Computer Science 1101, Springer Verlag, pages 536-550, 1996.

prof.dr. J.W. Klop

- J.C.M. Baeten, J.A. Bergstra, J.W. Klop, Decidability of bisimulation equivalence for processes generating context-free languages. JACM 40 (1993) no.3, p. 653-682.
- Y. Toyama, J.W. Klop, H.P. Barendregt. Termination for direct sums of left-linear complete term rewriting systems. JACM 42(6), 1995, p.1275-1304.
- Z.M.Ariola, J.W. Klop. Cyclic lambda graph rewriting. In: Proc. 9th Symp. on Logic in Comp. Sci. (LICS '94), Paris, France, p.416-425, 1994.

prof.dr. F.W. Vaandrager

- N.A. Lynch and F.W. Vaandrager. Forward and backward simulations, I Untimed systems. *Information and Computation*, 121(2):214-233, September 1995, II: Timing based systems. *Information and Computation*, 128(1):1-25, July 1996.
- D.J.B. Bosscher, I. Polak and F.W. Vaandrager. Verification of an audio control protocol. In H. Langmaack, W.P. de Roever, and J. Vytopil, editors, *Proceedings* 3^{rd} *International School and Symposium on Formal Techniques in Real Time and Fault Tolerant Systems (FTTRTFT'94)*, Lübeck, Germany September 1994, LNCS 863, pages 170-192. Springer-Verlag.

Miscellaneous

- L. Feijs, F. Meijs, J. Moonen and J. van Wamel. Conformance testing of a multimedia system using PHACT. Proceedings of the TACAS'98 workshop, Tomsk (to appear).
- J.R. Moonen, J.M.T. Romijn, O. Sies, J.G. Springintveld, L.M.G. Feijs, and R.L.C. Koymans. A two-level approach to automated conformance testing of VHDL designs. In M. Kim, S. Kang, and K. Hong, editors, *Testing of Communicating Systems*, volume 10, pages 432–447. Chapman and Hall, 1997.

6.4 External projects and funding

Externally funded activities:

- ESPRIT Working Group Semagraph
- BRA Confer
- HCM Cooperation Network EXPRESS
- SMC-SION project WINST
- SION project Classifying Proof Techniques for Propositional Logic.
- Philips/CWI project: Specification, testing and verification of software for technical applications.
- SION project: A modular toolset for μCRL.
- SION project: PRIME TIME, Protocols, Reference models and Interaction schemes for Multimedia Environments.
- Rail Infra Beheer: Definition of the LARIS 1.0 (LAnguage for Railway Interlocking Specification).
- Philips: conformance testing for Digital Video Broadcast (MPEG2) decoder IC.
- Telematics institute: Systems Validation Centre.

In 1997 and 1998, the percentages of the total costs of SEN2 covered by external funding were: 44% and 45%, respectively.

6.5 PhD theses

- H.J. Elbers, *Connecting Informal and Formal Mathematics*, Eindhoven University of Technology, 1998 (thesis advisors: prof.dr. A.M. Cohen and prof.dr. J.W. Klop).
- D.J.B. Bosscher, *Grammars Modulo Bisimulation*, University of Amsterdam, 1997 (thesis advisor: Prof.dr. J.A. Bergstra, co-advisor(s): dr. A. Ponse).

- F. van Raamsdonk, Confluence and normalization for higher-order rewriting, 1996 (thesis advisor Prof.dr. J.W. Klop).
- W.J. Fokkink, *Clocks, Trees and Stars in Process Algebra*, University of Amsterdam, 1994 (thesis advisors: Prof.dr. J.C.M. Baeten and Prof.dr. J.A. Bergstra).
- H.P. Korver, *Protocol Verification in μCRL*, University of Amsterdam, 1994 (thesis advisors: Prof.dr. J.C.M. Baeten and Prof.dr. J.A. Bergstra).
- A.S. Klusener, *Models and Axioms for a Fragment of Real Time Process Algebra*, Eindhoven University of Technology, 1993 (thesis advisors: Prof.dr. J.C.M. Baeten and Prof.dr. J.A. Bergstra).

6.6 Academic relations

6.6.1 Secondment of senior staff members at universities

- J.F. Groote, full professor at Eindhoven University of Technology (0.2 fte)
- J.W. Klop, full professor at Free University Amsterdam (0.5 fte), researcher at Nijmegen University (0.4 fte).
- F.W. Vaandrager, full professor at Nijmegen University (1.0 fte; since 1996).

6.6.2 Secondment of university staff at CWI

- S. Mauw, assistant professor from Eindhoven University of Technology (0.2 fte).

6.7 Services to the research community

prof.dr. F.W. Vaandrager (at CWI till 1996)

- Member of program committees: 19 times.
- Member IPA, NVTI, IFIP Working Group 2.2, ACM.
- Editor of journals or proceedings: 1 times.
- Moderator of CONCURRENCY email forum (concurrency@cwi.nl) until 1997.
- Referee of research proposals for ESPRIT, SION, STW and NSF.
- Invited lectures at international meetings: 9 times.
- Reviewer of research projects: 1 time.
- Involvement in PhD. defenses: 21 times.

prof.dr. J.W. Klop

- Member of program committees: 15 times.
- Member IPA, NVTI (chairman and scientific secretary). Invited lectures at international meetings: 3 times.
- Organization of conferences and workshops: 2 times.

prof.dr.ir. J.F. Groote

- Member of program committees: 8 times.
- Member IPA, NVTI, IEEE.
- Editor of journals or proceedings: 5 times.
- Moderator of CONCURRENCY email forum (concurrency@cwi.nl) from 1997.
- Referee of research proposals for SION and STW.
- Invited lectures at international meetings: 5 times.
- Involvement in PhD. defenses: 4 times.
- Organization of conferences and workshops: 6 times.

7 Theme SEN3: Coordination Languages

7.1 Short history of the theme and research highlights

This theme is a combination of two groups from two of the former six CWI departments before the restructuring: the Computational Models Group (CMG) from the Department of Software Technology, with De Bakker and Rutten, and the Interaction and Parallelism Group (IPG) from the Department of Interactive Systems, headed by Arbab.

Research in CMG has always been on the semantical foundations of computing, notably of concurrent programming. At an early stage, both operational and denotational models for a real-life parallel object-oriented programming language (POOL) have been designed, in close cooperation with Philips Research Laboratories. During the years preceding the restructuring of CWI, research has developed into two related directions. On the one hand, the metric techniques of De Bakker and co-workers have been further refined, giving rise both to a theory of generalized metric spaces, and to applications to a large variety of programming concepts, including constructs for parallelism, object-orientation, refinement, logic programming, and true concurrency, culminating in the monograph 'Control Flow Semantics', by De Bakker and De Vink. On the other hand, the theory of (metric) domain equations gave rise to the insight that in semantics, *(final) coalgebras* play a role that is at least as important as that of the more traditional (initial) algebras. Partly inspired by Aczel's nonwellfounded-set theory, and in analogy to universal algebra, this has led Rutten to develop the theory of *universal coalgebra*, where the emphasis is on *coinduction*, a definition and proof principle based on the notion of bisimulation. This new field of research, which is rapidly receiving much interest from various research communities, aims both at the unification of different approaches to the modelling of computation, including dynamical systems, (probabilistic) transition systems, control theory, but also modal logic and automata theory, and at finding further applications of the new principle of coinduction. A recent example of the latter is the use of coinduction for proving equality of formal power series.

The work in IPG during the eight years prior to the restructuring was focused on coordination models and languages, with an emphasis on the experimental and systems-oriented research. In this context, Arbab had produced IWIM, a novel model for control-oriented coordination; MANIFOLD, a pure coordination language based on the IWIM model; preliminary studies on the formal semantics of MANIFOLD; and **Visifold**, a visual programming environment for MANIFOLD. IWIM stands for *Idealized Worker Idealized Manager* and is a generic, abstract model of communication that supports the separation of responsibilities and encourages a weak dependence of workers (processes) on their environment. Two major concepts in IWIM are separation of concerns and anonymous communication. Based on IWIM, MANIFOLD is a coordination language for managing complex, dynamically changing interconnections among sets of independent, concurrent, cooperating processes. The processes that comprise an application are either computation or coordinator processes. Computation processes can be written in any conventional programming language, whereas coordinator processes are written in the MANIFOLD language. The purpose of a coordinator process is to establish and manage the communications among other (computation or coordinator) processes. The MANIFOLD system runs on multiple platforms and consists of a compiler, a run-time system library, a number of utility programs, and libraries of builtin and predefined processes of general interest. MANIFOLD has been successfully used: -to implement parallel and distributed versions of a semi-coarsened multi-grid Euler solver algorithm in MAS2 at CWI; -in modelling cooperative Information Systems; -for the coordination of the Hydra software architecture for modelling and simulation of shallow water phenomena, as contract research for Delft Hydraulics; -for the coordination of Loosely-Coupled Genetic Algorithms on parallel and distributed platforms; -to coordinate geometric constraint solvers, multiple solvers in a concurrent constraint programming system in PNA1, and a distributed propositional theorem checker in SEN2.

The motivations for joining both the groups CMG and IPG into one new theme on Coordination Languages was to exploit the synergy of the combination of experimental and theoretical work, now aimed at cross-fertilization of formal and applied research on coordination. The activity in this theme is on (1) development of formal methods, notably (operational) semantic models as a unifying basis for the development of debugging and visualization tools for coordination languages; (2) enhancements to and experiments with the MANIFOLD language and its visual programming and debugging environment; and (3) using MANIFOLD to work on real applications of coordination programming in areas such as numerical computing, distributed constraint satisfaction, and shallow water modelling.

As an outcome of this synergy, a major achievement of our theme has been the design of a formal (operational) semantics of MANIFOLD, defined in terms of a two-level transition system. The first

level consists of a (large) number of transition systems, each of which defines the semantics of a single process, independently of the rest. The second level consists of a single transition system that defines the interactions among the first-level transition systems. This two-level approach to formal semantics reflects the dichotomy of computation vs. coordination that is inherent in MANIFOLD, as well as in some other coordination languages. The key concept here is that the second level abstracts away the (computational) semantics of the first level processes, and is concerned only with their (mutually engaging) externally observable behavior. This recently obtained operational model will next serve as a formal basis for the further development of a visual programming environment for MANIFOLD, extending earlier work in that direction that had already resulted in a prototype **Visifold**.

At present, we are in the process of submitting a project proposal on software architectures for coordination together with the University of Leiden and the company Hollandse Signaalapparaten, with whom we have already collaborated on formal methods for coordination in both a Dutch and a EU project. Moreover, we are involved in the preparations of a project in the context of the Telematica Institute, on business process coordination.

7.2 Present personnel

7.2.1 Senior staff members

dr.ir. F. Arbab (1 fte), prof.dr. J.W. de Bakker (0.3 fte; SEN cluster leader), dr. F.S. de Boer (0.2 fte), dr. J.J.M.M. Rutten (1 fte; theme leader).

7.2.2 Total formation

4 senior staff members (2.5 fte), 2 postdocs (2 fte), 1 PhD student (1 fte), 3 programmers (3 fte).

7.3 Selected publications

dr. F. Arbab, prof.dr. J.W. de Bakker, dr. J.J.M.M. Rutten

- A transition system semantics for the control-driven coordination language Manifold. M.M. Bonsangue, F. Arbab, J.W. de Bakker, J.J.M.M. Rutten, A. Scutella, G. Zavattaro, Technical Report SEN-R9829, CWI, 1998. Accepted for publication in *Theoretical Computer Science.*

dr. F. Arbab

- F. Arbab, Coordination of Massively Concurrent Activities, CWI tech. report CS–R9565, November 1995.
- F. Arbab, C. L. Blom, F. J. Burger, C. T. H. Everaars, Reusable Coordinator Modules for Massively Concurrent Applications, Software: Practice and Experience, vol. 28, no. 7, pp. 703-735, June 1998.
- G. A. Papadopoulos and F. Arbab, Coordination Models and Languages, Advances in Computers, vol. 46, Academic Press, 1998.
- F. Arbab, P. Ciancarini, and C. Hankin, Coordination Languages for Parallel Programming, Parallel Computing, vol. 24, no. 7, July 1998.

prof.dr. J.W. de Bakker

- J.W. de Bakker and E.P. de Vink. *Control Flow Semantics.* Foundations of Computing Series. The MIT Press, 1996.

dr. J.J.M.M. Rutten

- J.J.M.M. Rutten. Universal coalgebra: a theory of systems. Technical Report CS-R9652, CWI, Amsterdam, 1996. To appear in Theoretical Computer Science.
- E.P. de Vink and J.J.M.M. Rutten. Bisimulation for probabilistic transition systems: a coalgebraic approach (extended abstract). Proceedings of ICALP'97 (P. Degano et al, eds.). LNCS Vol. 1256, 1997, pp. 460-470. To appear in TCS.
- M.M. Bonsangue, F. van Breugel, and J.J.M.M. Rutten. Generalized metric spaces: completion, topology, and powerdomains via the Yoneda embedding. Fundamental Study in Theoretical Computer Science Vol. 193, 1998, pp. 1–51.
- J.J.M.M. Rutten. Automata and coinduction (an exercise in coalgebra). Invited paper in: Proceedings of CONCUR '98, D. Sangiorigi and R. de Simone (eds.), LNCS 1466, Springer, 1998, pp. 194-218.

7.4 External projects and funding

SEN3 is and has been involved in many externally funded projects, both national and international.

- The NFI project REX (Research and Education in Concurrent Systems) paid for the salary (until 1993) of the PhD F. van Breugel. He graduated in 1994. In the same year, NFI paid for the final REX activity: an international scientific symposium entitled 'A decade of concurrency'.
- Until 1995, we have been involved in the Science Programme working group MASK (Mathematical structures in the Semantics of Concurrency), which has paid for various trips as well as the organisation of an international workshop at CWI.
- On the basis of Austrian funding, H. Wiklicky has worked at CWI as a post-doc in the period 1993-1995.
- In the period until 1996, we have been involved in the HCM network EUROFOCS, which paid for the post-doc salary of P. di Gianantonio (1995) and F. van Breugel (at the University of Pisa), as well as for a stay at the University of Edinburgh of the CWI PhD D. Turi.
- D. Turi has worked as a PhD (until 1996) paid by the SION project 'Nonwellfounded sets and programming language semantics", which resulted in his graduation in 1996.
- The SION project HOOP (Higher-order Object-Oriented Processes) paid for the post-doc salary of B. Jacobs in the years 1994-1996, who was to become a KNAW fellow after his stay at CWI.
- Since 1997 (until 2001), we participate in the SION project CoLa (Formal methods for Coordination Languages), for which PhD student A. Scutella is working.
- Since the end of 1998 (and until 2000), we are participating in the SION project ProMACS (Probabilistic Methods for the Analysis of Continuous Systems), which pays for the post-doc salary of A. Baltag. His appointment is partly funded by contributions from the SPINOZA project, of Prof.dr. J. van Benthem (UvA), and the Dutch Research School OzsL (Onderzoeksschool Logica).
- We are involved in the ESPRIT Working Group COORDINA (From coordination models to applications), until the end of 2000, which pays for a number of trips as well as visits from colleagues in the project. The PhD G. Zavattaro (University of Bologna) visited us in 1998 for a period of three months.
- A. Corradini worked in the period 1996-1997 in our group as a post-doc, paid by the TMR project 'Categorical techniques for the abstract semantics of structured transition systems'.
- The NFI project IIICAD paid for one postdoc (R.C. Veltkamp) and 3 programmer and PhD student positions working on an earlier version of Manifold during 1993-1994. This same project also paid for another postdoc position (P. Bouvry) during 1994-1996 working on the visual programming environment for Manifold and developing Manifold applications.
- The Esprit project MADE supported the part-time activity of F. Arbab on developing the core object model for multimedia programming used in this project, and the design and development of the C++ based language (mc++) built on top of this core model, used by the partners in MADE.
- The SION project Interactive Geometric Constraint Satisfaction supported the work of R. H. M. C. Kelleners during 1994-1996, on his PhD, using Manifold and C++ to build a geometric constraint system for interactive CAD.
- The SION project "Constraint-based Graphics" paid for a postdoc (R. C. Veltkamp) in 1995 working on the development of a formal framework to handle higher-order constraint networks of subnetworks. This project also paid for the work of another postdoc (E. Monfroy) during 1996, on the use of coordination for constraint solvers.
- The Esprit INCO-DC KIT project "Software Engineering Environments for Distributed Information Systems" supports the collaboration of CWI with other international partners (1999-2001) to use coordination models to develop software architectures for distributed information systems.
- The HPCN project NICE (Dutch Initiative for CFD in Engineering) supported the collaboration of CWI with Delft Hydraulics Laboratory (1996-1998) on using Manifold for coordination of shallow water modelling applications.
- The HPCN project High Performance Visualization supported the work of F. Arbab, P. Bouvry, and A. Fagot (1996-1998) on the graph visualization work within INS3 for the software company ACE.

In 1997 and 1998, the percentages of the total costs of SEN3 covered by external funding were: 13% and 11%, respectively.

7.5 PhD theses

- M.M. Bonsangue, *Topological Dualities in Semantics*, Vrije Universiteit Amsterdam, 1996 (thesis advisors: J.W. de Bakker, J.N. Kok).
- D. Turi, *Functorial Operational Semantics and its Denotational Dual*, Vrije Universiteit Amsterdam, 1996 (thesis advisor: J.W. de Bakker, co-advisors: B.P.F. Jacobs, J.J.M.M. Rutten).
- F. van Breugel, *Topological Models in Comparative Semantics*, Vrije Universiteit Amsterdam, 1994 (thesis advisor: J.W. de Bakker, co-advisor: E.P. de Vink).
- E. Horita, *Fully Abstract Models for Concurrent Languages*, Vrije Universiteit Amsterdam, 1993 (thesis advisor: J.W. de Bakker, co-advisor: J.J.M.M. Rutten).

7.6 Academic relations

7.6.1 Secondment of senior staff members at universities

- J.W. de Bakker, full professor at Vrije Universiteit Amsterdam (0.2 fte, permanent)

7.6.2 Secondment of university staff at CWI

- F.S. de Boer, assistant professor from University of Utrecht (0.2 fte, 1998)

7.7 Services to the research community

dr. F. Arbab

- Member editorial boards of Parallel Computing and of Computers and Graphics. Guest co-editor of Parallel Computing.
- Member of program committees for 15 international conferences and workshops.

prof.dr. J.W. de Bakker

- Editor *JCSS, TCS, Fundamenta Informaticae, Cambridge Tracts in Theoretical Computer Science.*
- Member Panel on Mathematics and Computing, EU HCM Programme 1994-1997. Member EU European Science and Technology Assembly, 1994-1997. Reviewer/referee for ESPRIT BRA, ESPRIT LTR, EU INTAS.
- Advisor/referee for NSF, (Dutch) NWO, Italian Research Council, Finnish Research Council, Danish Research Council, EPSRC.
- Member Steering Committee European Educational Forum, selection committee chair Oxford University, committee Blaise Pascal chair (Leiden University).
- External referee 11 PhD theses, member 3 program committees.
- Member IFIP WG2.2 on Formal Description of Programming Concepts.

dr. J.J.M.M. Rutten

- Editor of Electronic Notes in Computer Science. Guest editor of two special issues of Theoretical Computer Science.
- Member of program committees for 10 international conferences and workshops.
- External referee for various (international) PhD theses.

7.8 Awards and honours

prof.dr. J.W. de Bakker

- Member Royal Netherlands Academy of Arts and Sciences.
- Member Academia Europaea (Chair Section on Informatics, 1994-1996).

8 Pilot Theme SEN4: Evolutionary Computation and Applied Algorithmics

8.1 Short history of the theme and research highlights

The pilot theme started as such in the fall of 1997. In the meantime, the pilot theme was characterized by being in the building-up phase, where several new people joined the theme, and where new research was developed or initiated. Due to the recent start of the theme, the format of the sections about the theme differs from the already established themes. Currently, several new research projects are developed and started.

The theme focusses on evolutionary algorithms, neural networks, and discrete algorithms, especially for management-related problems.

For evolutionary algorithms, research has been done on fundamentals of evolutionary computation and on optimization problems. New insights were established for transmission function models of genetic algorithms, for both finite and infinite populations. Also, new hybrid GA techniques were developed, thus improving the balance between exploration and exploitation in evolutionary algorithms, and novel approaches for penalty functions in constrained numerical optimization were obtained. As application problem, results were achieved for air traffic flow management. Currently, a new emphasis is put on the arising application area of evolutionary economical systems and emergent behaviour.

For neural networks, research and development has been done on the application of various networks in visualization and classification applications. This has resulted in a software system for visualization and clustering of high dimensional data. Discrete algorithms are developed for dynamic optimization problems and fundamental theory, like on-line process management in information technology. Several dynamic algorithms have been achieved for fundamental discrete and optimization problems. New results are also established for unsupervised classification problems in remote sensing data. This has recently lead to both novel research results and a novel software system, which seems to be able to become an innovative step in RS classification software systems.

8.2 Present personnel

8.2.1 Senior staff members

dr.ir. J.A. La Poutré (1 fte)

8.2.2 Total formation

5 senior staff members (1.8 fte), 1 postdoc (1 fte), 3 PhD students (2.8 fte), 1 project member (0.4 fte), 3 programmers (0.75 fte).

8.3 Selected publications

dr.ir. J.A. La Poutré

- A. Amir, M. Farach, R.M. Idury, J.A. La Poutré and A.A. Schäffer, Improved dynamic dictionary matching, *Information and Computation* **119**, 1995, 258-282.
- J.A. La Poutré, Lower bounds for the union-find and the split-find problem on pointer machines, *Journal of Computer and System Sciences***52**, 1996, 87-99.
- J.A. La Poutré and J. Westbrook, Dynamic two-connectivity with backtracking, *SIAM Journal on Computing*, to appear.
- C.H.M. van Kemenade, J.A. La Poutré, and R.J. Mokken, Density-based unsupervised classification for remote sensing, In: Proceedings of Machine Vision in Remotely Sensed Image Comprehension (MAVIRIC), Lecture Notes in Computer Science, Springer-Verlag, Berlin, to appear.

dr. W.B. Langdon

- W. B. Langdon and P. C. Treleaven, Scheduling maintenance of electrical power transmission networks using genetic programming, In: Kevin Warwick, Arthur Ekwue, and Raj Aggarwal, editors, Artificial Intelligence Techniques in Power Systems, chapter 10, pages 220–237. IEE, 1997.
- W. B. Langdon, Data Structures and Genetic Programming: Genetic Programming + Data Structures = Automatic Programming!, Kluwer, Boston, 1998.

8.4 External projects and funding

Several externally funded projects are carried out in SEN4. Some of them have just finished, others have just started.

- Neural Vision 1 & 2. Projects for visualization and exploration of high-dimensional data by means of neural networks. The project is carried out for and funded by Rijkswaterstaat.
- Dynamic Algorithms for On-Line Optimization. The project concerns the design of efficient algorithms for on-line optimization problems that are fundamental to various management and design problems in computer systems and networks. Funded by NWO.
- Quality of Service for Multimedia Systems. In the project, the on-line scheduling for multimedia processes is managed and optimized using quality of service as flexible parameter for concurrent service handling. (Joint project with Philips Research.) Funded by NWO. Start: medio 1998.
- Remote Sensing. Project for Unsupervised image classification for remote sensing data, focusing on blending and mixing of substances over the earth surface. The project is carried out for CRREL (USA) together with CCSOM (UvA), and it is funded by ERO, the European Research Office of the USA.

In 1997 and 1998, the percentages of the total costs of SEN4 covered by external funding were: 17% and 30%, respectively.

8.5 PhD theses

- C.H.M. van Kemenade, *Recombinative Evolutionary Search*, University of Leiden, 1999. (thesis advisor: prof.dr. J.N. Kok).

8.6 Academic relations

8.6.1 Secondment of senior staff members at universities

- dr.ir. J.A. La Poutré, at Free University Amsterdam (0.2 fte)

8.6.2 Secondment of university staff at CWI

- prof.dr. J.N. Kok, full professor from University of Leiden (0.2 fte)
- dr. A.E. Eiben, assistant professor from University of Leiden (0.2 fte)
- prof.dr. J. Treur, full professor from Free University Amsterdam (0.2 fte)
- dr. W. Kowalczyk, assistant professor from Free University Amsterdam (0.2 fte)

8.7 Services to the research community

dr.ir. J.A. La Poutré

- program co-chair NAIC
- journal, conference, and book referee (7 journals, 3 conferences)
- research proposal reviews

dr. W.B. Langdon

- program committee member (12 times)
- journal referee (4 journals)

8.8 Awards and honours

KNAW fellowship (J.A. La Poutré, 1992-1995)

9 Theme MAS1: Environmental and Porous Media Applications

9.1 Short history of the theme and research highlights

9.1.1 Field, history, future

The research within this theme rests on two important mathematical disciplines:

- Applied analysis of nonlinear partial differential equations.

- Numerical analysis and scientific computing.

The research is biased to real-life applications. In recent years we dealt with ordinary differential equations (ODEs) and partial differential equations (PDEs) emerging from environmental and porous media applications. The porous media applications focus on groundwater flow and transport and oil reservoir simulation. The environmental applications emerge from flow and pollutant transport and chemistry in the atmosphere and surface water. The mathematical research covers a wide range of subjects:

- Applied analysis - nonlinear transport phenomena, free boundary problems, nonlinear hyperbolic systems, homogenization problems, stability of fluid flow, pattern formation.
- Numerical analysis - evolutionary differential equations with emphasis on time integration in more dimensions, stiff/parallel ODE solvers, adaptive grids, parallel computing.

To foster cooperation on applied and numerical PDE research, at the restructuring MAS1 arose from the former groups AM2 (Modelling and Analysis), headed by C.J. van Duijn since October 1995, and NW1 (Discretization of Evolution Problems), headed by J.G. Verwer. Members of the two groups now cooperate on porous media applications. In the near future the cooperation will be extended along with the exploration of new research areas.

Previous work within NW1 had a stronger theoretical bias (method of lines, convergence, stability). Two less theoretical subjects were adaptive and moving-grid methods (2 PhD projects) and parallel ODE solvers (4 PhD projects). In recent years the research has become more applied, focusing on transport-chemistry and high-performance scientific computing. The adaptive and moving-grid work terminated in '95. The work on parallel ODE solvers is still continued in MAS2.

New MAS1 activities are the following ones. End of 1998 we employed two researchers working on the analysis of pattern formation in reaction-diffusion systems. One is aiming at applications from geological structures and the other at gas discharge problems. Active cooperation takes place with the universities of Bath, Leiden and Münster. The pattern formation research will be extended to a long term activity. End of 1998 we also started a new numerical project on atmospheric dynamics, in cooperation with GMD/SCAI in Bonn. This concerns research into future generation, grid-point based, weather forecast and climate models with grid resolutions far beyond existing ones based on spectral methods.

9.1.2 Highlights

Applied analysis The work with H.W. Alt (Bonn) on the formation of cusp singularities in elliptic free boundary problems arising in models for fresh and salt groundwater flow and the work with J. Bruining (Delft) on uniqueness conditions for 2x2 systems of hyperbolic first order conservation equations, which arise in models for three phase flow through porous media.

Numerical analysis The work on 3D systems of nonlinear advection-diffusion-reaction equations modelling pollutant transport and chemistry in the atmosphere and surface water. New advection schemes and integration methods based on operator splitting, implicit-explicit and approximate matrix factorization techniques have been developed. The research has led to a large number of well received publications and extensive contacts and joint projects with atmospheric researchers.

9.2 Present personnel

9.2.1 Senior staff members

dr. J.G. Verwer (1.0 fte, theme leader MAS1, former group leader NW1)
prof.dr.ir. C.J. van Duijn (0.6 fte, cluster leader MAS, former group leader AM2 (from October 1995–December 1996)
prof.dr. P.J. van der Houwen (0.5 fte, CWI fellow, former department head NW)
J.G. Blom, MSc (0.9 fte), dr. W. Hundsdorfer (1.0 fte)
dr. M.A. Peletier (since 1-9-'98, 0.8 fte), dr. B.P. Sommeijer (0.8 fte)

9.2.2 Total formation

7 senior staff members (5.6 fte), 4 postdocs (3.8 fte), 4 PhD students (4 fte), 2 programmers (1.3 fte).

9.3 Selected publications

J.G. Verwer

- J.G. Verwer and B.P. Sommeijer: Stability Analysis of an Odd-Even Hopscotch Method for Three-Dimensional Advection-Diffusion Problems, *SIAM J. Numer. Anal.*, 34, 376–388, 1997.
- J.G. Verwer, E.J. Spee, J.G. Blom and W. Hundsdorfer: A Second Order Rosenbrock Method Applied to Photochemical Dispersion Problems, *SIAM J. Sci. Comput.*, to appear in '98/'99 (*Report MAS-R9717*).

C.J. van Duijn

- C.J. van Duijn and P. Knabner: Travelling wave behaviour of crystal dissolution in porous media flow, *Euro. J. of Applied Mathematics*, 8, 49–72, 1997.
- H.W. Alt and C.J. van Duijn: A free boundary problem involving a cusp. Part 2: Local analysis, *Advances in Mathematical Sciences and Applications*, 8, 845-900, 1998.

P.J. van der Houwen

- P.J. van der Houwen and J.J.B. de Swart: Triangularly Implicit Iteration Methods for ODE-IVP Solvers, *SIAM J. Sci. Comput.*, 18, 41–55, 1996.
- P.J. van der Houwen and W.A. van der Veen: Waveform Relaxation Methods for Implicit Differential Equations, *Advances in Computational Mathematics*, 7, 183–197, 1997.

J.G. Blom

- J.G. Blom and J.G. Verwer: Algorithm 759: VLUGR3: A Vectorizable Adaptive Grid Solver for PDEs in 3D. II. Code Description, *ACM Trans. Math. Softw.*, 22, 329–347, 1996.
- J.G. Blom, W.M. Lioen and J.G. Verwer: HPCN and Air Quality Modelling, *Lecture Notes in Computer Science*, 1401, pp. 141–150, Procs. HPCN Europe '98, eds. P. Sloot, M. Bubak, and B. Hertzberger, 1998.

W. Hundsdorfer

- W. Hundsdorfer and E.J. Spee: An Efficient Horizontal Advection Scheme for Modelling of Global Transport of Constituents, *Monthly Weather Review*, 123, 3554–3564, 1995.
- A.C. Petersen, E.J. Spee, H. van Dop and W. Hundsdorfer: An Evaluation and Intercomparison of four new Advection Schemes for Use in Global Chemistry Models, *J. Geophys. Res.*, 103, 19253-19270, 1998.

B.P. Sommeijer

- B.P. Sommeijer and J. Kok: Splitting Methods for Three-Dimensional Bio-Chemical Transport, *Appl. Numer. Math.*, 21, 303-320, 1996.
- B.P. Sommeijer, L.F. Shampine and J.G. Verwer: RKC: An Explicit Solver for Parabolic PDEs, *J. Comp. Appl. Math.*, 88, 315–326, 1997.

9.4 External projects and funding

The work on porous media is part of the Dutch interaction platform 'Nonlinear Transport Phenomena in Porous Media', which brings together mathematicians and groundwater/petroleum engineers. Part of the work on air and water pollution takes place in the framework of the Dutch HPCN Programme, within the project 'HPCN for Environmental Applications'.

For the applied analysis research, main contacts and cooperations exist with the universities of Delft, Leiden, Bonn, Erlangen, Bath, Paris VI, UT at Austin and with CSIRO in Australia. For the numerical analysis research, main contacts and cooperations exist with the universities of Leiden, Utrecht/IMAU, Iowa, Cologne, TNO in the Netherlands, INRIA in France and GMD in Germany.

Through different special programmes of NWO, the Netherlands Organization for Scientific Research, we externally finance three PhD students and three Postdocs. For example, we take part in the priority programme 'Nonlinear Systems' and the programme 'Wiskunde Toegepast'. A fourth Postdoc is funded

by the European Union/TUD. The HPCN programme, the Computing Facilities Foundation NCF and Cray Research Inc., provide substantial financial support for our scientific computing research. Substantial financial support for porous media work has been obtained from the NAM (Nederlandse Aardolie Maatschappij) and the NOBIS programme.

In 1997 and 1998, the percentages of the total costs of MAS1 covered by external funding were: 30% and 28%, respectively.

9.5 PhD theses

- E.J. Spee, *Numerical Methods in Global Transport-Chemistry Models*, University of Amsterdam, 1998 (Thesis advisor: P.J. van der Houwen; co-advisors: J.G. Verwer and W. Hundsdorfer).
- R.J. Schotting, *Mathematical Aspects of Salt Transport in Porous Media*, Delft University of Technology, 1998 (Thesis advisor: C.J. van Duijn).
- M.I.J. van Dijke, *Multi-phase Flow Modelling of Soil Contamination and Soil Remediation*, Wageningen Agricultural University, 1997 (Thesis advisors: C.J. van Duijn, F.A.M. de Haan (LUW); co-advisor: S.E.A.T.M. van der Zee (LUW)).
- M.A. Peletier, *Problems in Degenerate Diffusion*, Leiden University, 1997 (Thesis advisor: C.J. van Duijn).
- M. van Loon, *Numerical Methods in Smog Prediction*, University of Amsterdam, 1996 (Thesis advisor: P.J. van der Houwen; co-advisors: J.G. Verwer and F.A.A.M. de Leeuw (RIVM)).
- Nguyen huu Cong, *Parallel Runge-Kutta-Nyström Methods*, University of Amsterdam, 1994 (Thesis advisor: P.J. van der Houwen; co-advisor: B.P. Sommeijer).
- R. Trompert, *Local Uniform Grid Refinement for Time-Dependent Partial Differential Equations*, University of Amsterdam, 1994 (Thesis advisor: P.J. van der Houwen; co-advisor: J.G. Verwer).
- Two theses on parallel ODE solvers prepared in the NW1 group (J.J.B. de Swart, W.A. van der Veen) are listed in the MAS2 section.

9.6 Academic relations

9.6.1 Secondment of senior staff members at universities

- C.J. van Duijn, full professor in Applied Mathematics at Delft University of Technology (0.2 fte).
- P.J. van der Houwen, full professor in Numerical Mathematics at University of Amsterdam (0.2 fte).

9.6.2 Secondment of university staff at CWI

- dr. J. Hulshof, University of Leiden (0.2 fte, Advisor).

9.6.3 Courses at universities

- B.P. Sommeijer lectures in the course Parallel Scientific Computing & Simulation (University of Amsterdam).
- W. Hundsdorfer lectures in the PhD course on Numerical Methods for Initial Value Problems at the Thomas Stieltjes Institute (University of Leiden).

9.7 Services to the research community

J.G. Verwer

- Senior Editor of *Applied Numerical Mathematics*.
- Coordinator of Dutch research consortium TASC (Transport Applications and Scientific Computing) and of the 4-year TASC project 'HPCN for Environmental Applications', funded by the Stichting HPCN.
- Member Advisory Committee of CMUC (Centre for Mathematics, University of Coimbra, Portugal).
- Miscellaneous activities: Organizer 1996 HCM Workshop on 'Time Integration', with J.M. Sanz-Serna, Univ. Valladolid (proceedings in special issue of *Applied Numerical Mathematics*). Member Committee APMS'98 (INRIA Conference on Air Pollution Modelling and Simulation) and guest editor for *Environmental Modelling and Software* for the special issue on APMS'98. Symposium organizer at SciCADE Meeting (Grado, '97), SIAM Annual Meeting (Toronto, '98).

C.J. van Duijn

- Editor-in-Chief of *Computational Geosciences*.
- Member editorial board *Interfaces and Free Boundaries: Modelling, Analysis and Computation*.
- Chairman of the Panel of the NWO Priority Programme 'Nonlinear Systems'.
- Coordinator of the Dutch Interaction Platform 'Nonlinear Transport Phenomena in Porous Media'.
- Member of the Steering Committee of the ESF Programme 'Free Boundary Problems, Theory and Applications'.
- Member of the Scientific Council (Beirat) of the Institute for Applied Analysis and Stochastics, the Weierstrass Institute, in Berlin.

P.J. van der Houwen

- Managing editor Letter Section of *Computational and Applied Mathematics* and associate editor of *Zeitschrift für Angewandte Mathematik und Mechanik*.
- Co-chairman biennial conference on Numerical Methods for Differential Equations, Halle, and proceedings editor for special issues of *Applied Numerical Mathematics*.
- Member Board of International Association for Mathematics and Computers in Simulation (IMACS).
- Member Committee Wetenschappelijk Gebruik Supercomputers.
- Member Scientific Committee Institute for Advanced Studies 'Stieltjes'.

9.8 Awards and honours

In 1998 C.J. van Duijn received the prestigious 'Max Planck Research Award for International Cooperation'.

10 Theme MAS2: Industrial Applications

10.1 Short history of the theme and research highlights

In this theme several groups from three of the six former Scientific Departments (NW, BS and AM) were combined, all having their own relations with industrial applications. Initially, seven subthemes were counted, with a diversity of expertise in mathematical analysis. In the period 1997–98, the projects on chemical and biological modelling were closed and financial mathematics became an independent pilot theme. The remaining activities all root strongly in numerical analysis, in particular in the numerical treatment of partial differential equations (PDEs) and number theoretical problems. In the large field of PDEs, the theme wants to continue and build on its earlier work in multigrid/multiscale techniques and in implementing large-scale problems on modern architectures.

In agreement with this longer term aim, at the end of 1998 the theme has been restructured according to its main activities. Now there remain three subthemes: (i) Computational Fluid Dynamics, (ii) Computational Number Theory, and (iii) Initial Value Problems. New and existing projects are embedded in these groups.

Computational fluid dynamics. The objective of this subtheme is the computation of fluid flows for various kinds of industrial applications. The fluids can be gases, liquids or combinations of these (multiphase flows). Research topics are: advanced discretization methods for systems of nonlinear conservation laws, multigrid and sparse-grid solution methods, local grid adaptation and parallel computing (in synergy with the SEN3 subtheme of F. Arbab). A research highlight was the development of a sparse-grid algorithm for three-dimensional equations of gas dynamics and the computation with this algorithm of the flow around an aircraft wing.

Before 1995, all research was directed towards applications in aircraft manufacturing industries, such as the Dutch Fokker company and the French Dassault company (the latter with its R&D work on the Hermes space plane). Starting in 1995 (two-years before the bankruptcy of Fokker), we have successfully shifted our attention to other industrial application areas, the major one being ship hydrodynamics.

Initial value problems. The work focuses on the code PSIDE and the CWI Test Set. In 1997, within the STW project 'Parallel software for implicit differential equations' we started changing the research version of the code PSIDE into an operational code with various user facilities. PSIDE aims at the fully automatic integration on parallel computers of a large variety of initial-value problems occurring in the technical sciences and in industry. In order to test this code and to compare its performance with

other state-of-the-art codes, a public set of real-life test problems is under development. This test set is available via WWW and is widely used by the international scientific community.

Plasma physics computations. A Jacobi-Davidson code for computing eigenvalues and eigenvectors in the Alfvén part of the spectrum of plasma physics problems has been developed, The code has been implemented on several parallel architectures and has been successfully applied to very large plasma physics problems (up to $2.5\ 10^5$ grid points). This affirmatively answers the question from plasma physicists whether (massively) parallel computers with distributed memory can outperform large shared-memory computers for the large eigenproblems which are of current interest in plasma physics. The present step is to develop techniques which give a-posteriori estimates of the accuracy of the computed eigenvalues and -vectors.

Discontinuous dynamical systems. Work in this area has concentrated on the development of the concept of *complementarity systems*. These can be viewed alternatively as systems of ordinary differential equations to which certain inequality constraints have been added, or as systems of inequalities with added dynamics. There are applications in mechanics, electrical networks, dynamic optimization, piecewise linear dynamical systems, and mathematical finance. Complementarity systems exhibit regime switches, and so these systems are not covered by the standard theory of ordinary differential equations.

Computational number theory and data security. Research has been carried out aiming at improving the factorization method known as the "Number Field Sieve". Two numbers of 181 and 186 decimal digits respectively, belonging to a special class have been factored in 1997 and 1998, establishing two new world records. Such results offer cryptographers a reliable estimate of what is still a safe key size in practical RSA public-key cryptosystems. The next step will be to attack the 140-digit number RSA-140 (which does not belong to any special class of numbers), whose factorization would establish a new factoring world record for general numbers (the present record is the 130-digit number RSA-130). One crucial step in modern factoring methods is the solution of large sparse systems of linear equations over the finite field F_2. A complicated block-iterative method of Wiedemann for solving such equations has been implemented and compared with other methods.

The so-called Goldbach Conjecture, which states that every even number greater than 2 can be written as a sum of two prime numbers, has been proved to be true up to the bound 10^{14} with the help of a very fast computer program. A probabilistic model has been derived to estimate the number of steps needed to confirm this conjecture up to a given bound: this turns out to agree well with the experiments.

Asymptotics and Special Functions. In this project research was focused on numerical algorithms for several types of uniform asymptotic expansions, new uniform expansions for certain special functions, and Hermite-type asymptotic approximations of orthogonal polynomials.

10.2 Present personnel

10.2.1 Senior staff members

prof.dr. P.W. Hemker (0.6 fte, theme leader), prof.dr. P.J. van der Houwen (0.5 fte), dr.ir. B. Koren (0.6 fte), dr.ir. H.J.J. te Riele (0.7 fte), prof.dr. J.M. Schumacher (0.7 fte), dr. B.P. Sommeijer (0.2 fte), dr. N.M. Temme (0.4 fte). Beginning of 1999 the staff is reduced by the transfer of 2 senior researchers to MAS1 and MAS3 (1.1 fte).

10.2.2 Total formation

7 senior staff members (3.7 fte), 2 postdocs (2 fte), 6 PhD students (5.5 fte), 2 programmers (1.1 fte).

10.3 Selected publications

prof.dr. P.W. Hemker

- P.W. Hemker, C. Pflaum: Approximation on partially ordered sets of regular grids. *Applied Numerical Mathematics* **25** 55–87, 1997.
- P.W. Hemker, G.I. Shishkin, L.P. Shishkina: The use of defect correction for the solution of parabolic singular perturbation problems. *ZAMM*, **76**, 59–74, 1997.

prof.dr. P.J. van der Houwen

- P.J. van der Houwen, B.P. Sommeijer: The use of approximate factorization in stiff ODE solvers, *Journal Computational and Applied Mathematics*, to appear in 1998.

- P.J. van der Houwen, E. Messina, J.J.B. de Swart: Parallel Störmer-Cowell methods for high-precision orbit computations, *Applied Numerical Mathematics* to appear in 1999.

dr.ir. B. Koren

- C.T.H. Everaars, B. Koren: Using coordination to parallelize sparse-grid methods for 3D CFD problems, *Parallel Computing*, **24**, 1081–1106, 1998.
- B. Koren: Improving Euler computations at low Mach numbers, *International Journal of Computational Fluid Dynamics*, **6**, 51–70, 1996.

dr.ir. H.J.J. te Riele

- G.L. Cohen, H.J.J. te Riele: On phi-amicable pairs, *Mathematics of Computation*, **67**, 399-411, 1998.
- J.-M. Deshouillers, H.J.J. te Riele, Y. Saouter: New experimental results concerning the Goldbach conjecture, pp. 204-215 in: J.P. Buhler (ed.), *ANTS-III, Algorithmic Number Theory*, LNCS nr 1423, Springer, 1998.

prof.dr. J.M. Schumacher

- A.J. van der Schaft, J.M. Schumacher: The complementary-slackness class of hybrid systems. *Mathematics of Control, Signals and Systems*, **9**, 266–301, 1996.
- A.J. van der Schaft, J.M. Schumacher: Complementarity modelling of hybrid systems. *IEEE Transactions on Automatica Control*, **43**, 483–490, 1998.

dr. N.M. Temme

- N.M. Temme, *Special Functions: An Introduction to the Classical Functions of Mathematical Physics*, Wiley, 1996.
- N.M. Temme Numerical algorithms for uniform Airy-type asymptotic expansions, *Numerical Algorithms* **15**, 207 – 225, 1997.

10.4 External projects and funding

Computational fluid dynamics.

1998-2000: Fundamental research financed by CWI and the German National Research Center for Information Technology (GMD, 90 kf): development of sparse grid methods and overlapping grid methods for steady, three-dimensional flow problems, joint work with GMD's Institute for Algorithms and Scientific Computing (Prof.Dr. U. Trottenberg).

1997–2001: Fundamental research financed by the Netherlands Organization for Scientific Research (NWO, 90 kf): development of sparse-grid methods for unsteady, three-dimensional flow problems, joint work with MAS1 (dr. J.G. Verwer).

1997–2001: Contract research financed by the Maritime Research Institute Netherlands (MARIN, 205 kf): improvement and extension of (existing) viscous ship-hydrodynamics software (improvement with better numerical techniques, extension to free-surface wave making by ships).

1996–1999: Fundamental research on the subject 'Numerical Methods for Singular Perturbation Problems', cooperation with Russian colleagues, sponsored by NWO (45 kf).

1996–1997: Small project financed by Akzo/Nobel (12.5 kf): computation of Navier-Stokes flow in nozzle, which is used in so-called melt-spinning processes.

1996–1997: Two consultancy projects financed by MacNeal-Schwendler (2×15 kf): advising on computational solid mechanics (forging) and multiphase flow computations (forging and sloshing).

1995–1996: Pilot project for Dutch shock-absorber manufacturer (KONI): computation of oil flow in hydraulic shock absorbers, which are used in European high-speed trains, such as the French TGV.

until 1995: Contract research financed by European Union (BRITE/EURAM, ± 400 kf) for the major European aircraft manufacturers of that time (Aeritalia, Aerospatiale, British Aerospace, Dassault, Dornier and Fokker): development of numerical methods or the Euler and Navier-Stokes equations. A detailed account of this finished project has been given in[20].

Initial value problems.

1998-2001: Fundamental research financed by NWO (STW-project, 2 postdocs): development of parallel software for implicit differential equations.

Plasma-physics computations.

1995-1999: Cooperation in a project "Parallel Computational Magneto-Fluid Dynamics" financed by the NWO Priority Programme on Massively Parallel Computing (1 postdoc per year).

1996-1997: Cray Research Grant, awarded by the Dutch National Computing Facilities Foundation, for research on "Parallel numerical algorithms for large generalized non-Hermitian eigenvalue problems in linear magneto-hydrodynamics" (Kf 90).

Discontinuous dynamical systems.

1996-2000: Fundamental research financed by the Netherlands Organization for Scientific Research (NWO, PhD student 4yrs) through the program ('Groot Project') 'Modelling of Open Dynamical Systems'.

Computational number theory and data security.

1993-1994: Grant from Thomas Stieltjes Institute for Mathematics (Leiden University) to support P.L. Montgomery's visit during the period October 1993 - August 1994 (Kf 50).

1998: Licence agreement with Microsoft allowing Microsoft to use CWI's number field factorization code for research purposes (Kf 8). CWI's number field sieve factorization code has been made available to researchers at the Dutch Ministry of Defense, the University of Groningen, and the Australian National University in Canberra. Difficult numbers factored in our project have been contributed to the international computer algebra software project called 'Magma'.

In 1997 and 1998, the percentages of the total costs of MAS2 covered by external funding were: 21% and 22%, respectively.

10.5 PhD theses

- W.J.H. Stortelder: *Parameter Estimation in Nonlinear Dynamical Systems*, University of Amsterdam, 1998 (thesis advisor: P.W. Hemker, co-advisor: C.A.J. Klaassen).
- P.M. de Zeeuw: *Acceleration of Iterative Methods by Coarse Grid Corrections*, University of Amsterdam, 1997 (thesis advisors: P.W. Hemker and P. Wesseling).
- M. Elkenbracht-Huizing, *Factoring Integers with the Number Field Sieve*, Leiden University, 1997 (thesis advisor: R. Tijdeman, co-advisor: H.J.J. te Riele).
- H. Boender, *Factoring Large Integers with the Quadratic Sieve*, Leiden University, 1997 (thesis advisor: R. Tijdeman, co-advisor: H.J.J. te Riele).
- W.A. van der Veen, *Parallelism in the Numerical Solution of Ordinary and Implicit Differential Equations*, University of Amsterdam, 1997 (thesis advisor: P.J. van der Houwen, co-advisor: B.P. Sommeijer).
- J.J.B. de Swart *Parallel Software for Implicit Differential Equations*, University of Amsterdam, 1997 (thesis advisor: P.J. van der Houwen, co-advisor: W. Hoffmann).
- J. de Does: *The Gap Topology for Linear Systems. A Geometric Approach*, Tilburg University, 1994 (thesis advisor: J.M. Schumacher)

[20] H. Deconinck and B. Koren (eds.): Euler and Navier-Stokes Solvers Using Multi-Dimensional Upwind Schemes and Multigrid Acceleration, European Community Research in Aeronautics, *Notes on Numerical Fluid Mechanics*, **57**, Vieweg, Braunschweig (1997).

- M.S. Dijkhuizen: *On Compact Quantum Groups and Quantum Homogeneous Spaces*, University of Amsterdam, 1994 (thesis advisor: T.H. Koornwinder).
- H.T.M. van der Maarel: *A Local Grid Refinement Method for the Euler Equations*, University of Amsterdam, 1993 (thesis advisor: P.W. Hemker).
- A.B. Olde Daalhuis: *Uniform, Hyper- and q-Asymptotics,* University of Amsterdam, 1993 (thesis advisor: T.H. Koornwinder; co-advisor: N.M. Temme).
- External PhD's with P.W. Hemker as thesis adviser: Maes (1997), Ferket (1997).
- External PhD's with J.M. Schumacher as thesis adviser: Rijkeboer (1998), Weeren (1994).

10.6 Academic relations

10.6.1 Secondment of senior staff members at universities

- P.W. Hemker, full professor at University of Amsterdam (0.2 fte, 0.4 fte in 1998)
- P.J. van der Houwen, full professor at University of Amsterdam (0.2 fte)
- B. Koren, associate professor Delft University of Technology (0.2 fte as of January 1999)
- H.J.J. te Riele, visiting professor at University of Technology, Sydney, August-November 1995.
- J.M. Schumacher, full professor at Tilburg University (0.2 fte)

10.6.2 Secondment of university staff at CWI

- P. Wesseling, full professor from Technical University of Delft (advisor, 0.1 fte)
- A.J. van der Schaft, associate professor at Twente University (seconded, 0.1 fte)

10.7 Services to the research community

prof.dr. P.W. Hemker

- member scientific board of the 'Amsterdam Centre for Computational Sciences'.
- member of the IFIP Working Group 2.5 on Mathematical Software.
- member of 10 program committees for (inter)national conferences and workshops.
- guest editor for 2 special issues of scientific journals (*Applied Numerical Mathematics* and *CWI Quarterly*).
- co-organizer of the Oberwolfach meetings on 'Multilevel Methods and Applications' (1995) and 'Numerical Methods for Singular Perturbation Problems' (1995, 1998).

dr.ir. B. Koren

- co-worker CWI's scientific policy making (since 1998, 0.4 fte).
- lecturer PhD-course Stieltjes Institute (1997).
- secretary Dutch Society for Numerical Mathematics (until 1996).
- co-editor two books (Vieweg Verlag's *Notes on Numerical Fluid Mechanics*, **45** and **57**) and *CWI Quarterly.*
- member of 5 PhD committees (twice Amsterdam, once Delft, twice Brussels).

prof.dr. P.J. van der Houwen

- See MAS1

dr.ir. H.J.J. te Riele

- editor of *Nieuw Archief voor Wiskunde*; reviewer for *Mathematical Reviews* and the *Zentralblatt für Mathematik*; referee for numerous scientific journals.
- chairman of ERCIM's Parallel Processing Network.
- co-organizer of international meeting on Algorithmic Number Theory (ANTS IV) in Amsterdam (July 2000).
- three ERCIM fellows have worked in our large scale computing projects in the past five years (each during nine months).

prof.dr. J.M. Schumacher

- editorial work for 3 scientific journals (*SIAM Journal on Control and Optimization*, *Systems & Control Letters*, *Automatica*); member editorial board *CWI Tracts & Syllabi*.
- council member *European Union Control Association*; member *TC on Linear Systems, IFAC*.
- lecturer in the national graduate program of the Dutch Institute of Systems and Control (course *Hybrid Systems*, spring 1998).
- organizer *Benelux Meeting on Systems and Control 1996* and *1998*; member of various program committees.

dr. N.M. Temme

- Member of the editorial committee of the update project of the *Handbook of Special Functions* (Abramowitz & Stegun).
- Member of the governing board of the Stieltjes Institute for Mathematics and CWI-coordinator for the Dutch research schools in mathematics and computer science.
- CWI-coordinator for the Indonesian-Dutch cooperation project *Applied Mathematics and Computational Methods*.
- Organizer of the CWI general monthly seminar *CWI Scientific Meetings*
- member of the editorial board of *Mathematics of Computation*, *SIAM Journal on Mathematical Analysis, Zeitschrift für Angewandte Mathematik und Physik (ZAMP), Methods and Applications of Analysis*, and *CWI Quarterly*.
- Co-advisor for the PhD thesis of Olde Daalhuis (Amsterdam, 1993), member of PhD committees of Marée (Wageningen, 1995), Lin (Winnipeg, 1995), Floris (Leiden, 1995), and Woon (Cambridge UK, 1998).

10.8 Awards and honours

- Award for best MSc-work in Mathematics at Delft University of Technology (work in 1996–1997 at Akzo/Nobel-project of subtheme Computational Fluid Dynamics), ir. D. Lanser, trainee in MAS2.

11 Theme MAS3: Mathematics of Finance

11.1 Short history of the theme and research highlights

Following recommendations by a visiting committee, an effort to build up a group in financial mathematics at CWI was begun in August of 1996. As part of the restructuring of CWI, a project Mathematics of Finance was created within MAS2 starting January 1, 1997. One year later, the project became a Pilot Theme. In 1999, activities in the area of Discontinuous Dynamical Systems will be incorporated within the pilot theme, on the basis of an already existing overlap in personnel and of certain connections in the subject areas which have emerged. As a pilot theme, MAS3 will exist until the end of 1999. At that time it will have to be decided whether the pilot theme will be continued as a full-blown research theme.

The establishment of the group in financial mathematics has taken place on the basis of involvement of permanent staff, hiring by CWI of temporary staff, and acquisition of outside funding also for temporary staff. All permanent staff members involved in financial mathematics also have commitments in other projects, hence these staff members take part on a part-time basis (0.2 to 0.3). In May of 1997, a postdoc was hired by CWI for a period of two-years to work full-time in financial mathematics; in the summer of 1998, another postdoc and a PhD student were appointed on the basis of successful applications with the national science foundation NWO.

Although it might in principle be preferable to hire temporary staff who already have a background in financial mathematics, market conditions practically rule out such an approach. At the time they were appointed, the two postdocs and the PhD student had a definite interest in but little experience with financial mathematics. In addition, extensive experience with this research area was not available within the permanent staff of CWI. The main purpose of the group has therefore initially been to acquaint itself with the field and to look for areas in which the expertise that is available at CWI can be brought to bear on problems in mathematical finance. Subjects that in particular have drawn the group's attention are: the statistics of stochastic processes; Monte Carlo and quasi-Monte Carlo methods for derivative pricing and risk management; the relations between binomial trees and continuous-time processes; and processes with heavy-tailed distributions. Research in these areas has been started up and has partially already led to results.

At the same time, contacts with the financial industry have been built up. The most substantial effort in this direction so far has been the establishment of a course program in financial mathematics, intended for employees of financial institutions. The 1998/99 program, which has been developed in cooperation with colleagues from the two Amsterdam universities, consists of courses on Financial Time Series Analysis and on Financial Engineering. The second course is taught mainly by CWI staff; the first part of this course has drawn 18 participants, whereas registration for the second part, which can be taken independently, is closed since the maximum number of participants that can be accommodated (25) has been reached.

11.2 Present personnel

11.2.1 Senior staff members

dr. K. Dzhaparidze (0.2 fte), dr. M.A. Peletier (0.2 fte), dr.ir. H.J.J. te Riele (0.3 fte), prof.dr. J.M. Schumacher (0.3 fte; theme leader).

11.2.2 Total formation

4 senior staff members (1.0 fte), 2 postdocs (2 fte), 1 PhD student (1 fte).

11.3 Selected publications

dr. K. Dzhaparidze

- K. Dzhaparidze: Introduction to Option Pricing in a Securities Market. II. Poisson Approximation. *CWI Quarterly* **10** 65-100, 1997.
- K. Dzhaparidze: Introduction to Option Pricing in a Securities Market. III. Gaussian Approximation. To appear in *CWI Quarterly*, 1998.

prof.dr. J.M. Schumacher

- C. Heij, J.M. Schumacher, B. Hanzon, C. Praagman (eds.), *System Dynamics in Economic and Financial Models*. Series in Financial Economics and Quantitative Analysis, Wiley, Chichester, 1997.

11.4 External projects and funding

1998-2002 PhD project "Statistics for random processes with applications to mathematical finance", supported by the Dutch organization for scientific research NWO. Total amount of support over a four-year period approx. 200 kf.

1998-2000 Postdoc project "Monte Carlo and quasi-Monte Carlo simulation for efficient valuation and risk assessment of financial derivatives", partially supported by NWO. This project is part of a national program "Financial Derivatives" in which NWO provides partial funding for four postdocs at four different institutions in the Netherlands (University of Groningen, Delft University of Technology, Twente University, and CWI).

1998-1999 Course program "Financiële Wiskunde Amsterdam" (Mathematics of Finance Amsterdam), jointly with Vrije Universiteit and University of Amsterdam. Courses for employees of financial institutions. Total gross income in the academic year 1998/99 about 100 kf.

In 1998, the percentage of the total costs of MAS3 covered by external funding was: 24%.

11.5 Services to the research community

dr. K. Dzhaparidze

- editor of two special issues of *CWI Quarterly* devoted to financial mathematics
- see also PNA3

dr. M.A. Peletier

- see MAS1

dr.ir. H.J.J. te Riele

- see MAS2

prof.dr. J.M. Schumacher

- member organizing committee Workshop "Dynamic Models in Economics and Finance", Oegstgeest, 1995, sponsored by the European Research Network on System Identification with additional funding from the Dutch Institute of Systems and Control
- coordinator of Special Year on the Mathematics of Finance, 1997. Activities in this special year, which was sponsored by the mathematics branch of the national science organization NWO with additional funding from the Royal Academy of Arts and Sciences, have included five lecture days on various aspects of financial mathematics, a five-day course on Mathematical Finance at the University of Groningen, and a three-day workshop in Amersfoort with twelve foreign experts.
- see also MAS2.

12 Theme INS1: Data Mining and Knowledge Discovery

12.1 Short history of the theme and research highlights

This theme is the continuation of the Database Research Group (DBRG) from the Department of Algorithms and Architecture (one of the six old Scientific Departments). In the last four to five years of DBRG's existence, the architecture of database management systems (DBMSs) has been one of the important research tracks. The development, in close cooperation with the University of Amsterdam, of the so-called MONET DBMS, has been a central theme within this research track. This development initiated research in core as well as in new database issues.

Query processing. A prime example of a core database topic is query processing and optimization. Research in this area started with Carel van den Berg (PhD thesis in 1994), it was continued by Arjan Pellenkoft (PhD thesis in 1997) and is now further performed by Florian Waas (PhD thesis expected in 1999), Stefan Manegold (PhD thesis expected in 1999) and Arjan Pellenkoft. Another example of a core database topic is that of data structures. Research into scalable distributed data structures is performed by Jonas Karlson (PhD thesis expected in 1999).

Triggers and active databases. Examples of new issues in the DBMSs topic are triggers and active databases. Research in this area started with Leonie van der Voort (PhD thesis in 1994) and was continued by Johan van den Akker (PhD thesis in 1998). Another example in this area is that of database integration, which was studied by Christiaan Thieme (PhD thesis in 1995).

Data mining. In parallel with the development of MONET, research in specific application areas was initiated in the final years of the DBRG, the best example being data mining. A first prototype data mining system, called DATA SURVEYOR, was developed on top of MONET. The responsible PhD student (Marcel Holsheimer) subsequently left CWI to start the spin-off company Data Distilleries. Today, Data Distilleries is one of CWI's major spin-off companies (30 fte at this moment, 60 fte expected next year, recipient of a significant capital investment in 1997 and presently developing into an international company). Data Distilleries holds close research contacts with INS1. Research in the architecture of data mining systems, in the KESO project, has led to a new version of DATA SURVEYOR. Moreover, typical data mining problems are addressed. For example, Zbigniew Struzik (post-doc) works on mining databases of time-series via wavelet transforms. Robert Castello (PhD thesis expected in 2002) works on the recovery of (large) Bayesian Networks from noisy incomplete databases. Finally, Arno Knobbe (Syllogic, PhD thesis expected in 2002) recently started research in multi-relational data mining.

Multimedia databases. Another, more recent example is that of research in multimedia databases. Some experience in this area had already been built during the MADE project (Multimedia Application Development Environment), but the focus has shifted considerably. The key point in this recently started project is the retrieval of multimedia data via automatic feature-detection based indices. This research direction is complemented with WWW-directed research (P. De Bra). The WWW is a good example of a large Multimedia Warehouse.

12.2 Present personnel

12.2.1 Senior staff members

prof.dr. P.M.E. De Bra (0.2 fte), prof.dr. M.L. Kersten (0.4 fte), and dr. A.P.J.M. Siebes (1.0 fte, theme leader).

12.2.2 Total formation

3 senior staff members (1.6 fte), 2 postdocs (2 fte), 4 PhD students (4 fte), 2 programmers (2 fte).

12.3 Selected publications

prof.dr. P.M.E. De Bra

- De Bra, P.M.E., Teaching Hypertext and Hypermedia through the Web, *Journal of Universal Computer Science (JUCS)* **2**, nr 12, id. 797 (8p), December 1996. ISSN 0948-6968.
- De Bra, P.M.E., Teaching Through Adaptive Hypertext on the WWW, *Int. Journal of Educational Telecommunications* **3** nr 2/3, pp. 163-180, 1997. (Special Double Issue on the WWW in use in higher education.)
- Calvi, L. and De Bra, P.M.E., Proficiency-Adapted Information Browsing and Filtering in Hypermedia Educational Systems, *User Modelling and User-Adapted Interaction* **7** nr. 4, pp. 257-277, 1997. (Kluwer Academic Publishers)

prof.dr. M.L. Kersten

- A. Pellenkoft, C.A. Galindo-Legaria and M.L. Kersten: The complexity of transformation-based join enumeration, *Proceedings of the 23rd International Conference on Very Large Data Bases*, Athens, August 1997 (Matthias Jarke et al., eds.), 306-315, Morgan Kaufmann (1997).
- P.A. Boncz, A.N. Wilschut and M.L. Kersten: Flattening an object algebra to provide performance, *Proceedings of the 14th International Conference on Data Engineering*, Orlando, FL, February 1998, IEEE Computer Society Press (1998).
- P.G.M. Apers and M.L. Kersten: Content-based retrieval in multimedia databases based on feature models, *Proceedings of the International Conference ACMP*, Osaka, November 1998 (to appear).

dr. A.P.J.M. Siebes

- J. van den Akker and A. Siebes: Degas: a database of autonomous objects, *Information Systems*, **22**, 121-138 (1997).
- A. Siebes and M.L. Kersten: KESO: minimizing database interaction, *Proceedings of the Third International Conference on Knowledge Discovery and Data Mining*, Newport Beach, August 1997 (D. Heckerman et al, eds.), 247-251, AAAI Press, Menlo Park, CA (1998).
- Z.R. Struzik and A. Siebes: Wavelet transform in similarity paradigm, *Proceedings of the Pacific Asian Conference on Knowledge Discovery and Data Mining*, Melbourne, April 1988 (X. Wu and R. Kotagiri, eds.), *Lecture Notes in Artificial Intelligence*, **1394**, 295-309, Springer, Berlin (1998).

12.4 External projects and funding

Traditionally, INS1 has many externally funded projects, through both national and international programs.

Nationally, funding has been granted by SION, HPCN and the Telematics Institute, internationally by ESPRIT and DOSIS (ESPRIT projects managed by Eurostat). SION has funded the projects DEGAS (1 PhD student, finished December 31, 1997) and AMIS (1 PhD student, vacancy). HPCN is funding the project IMPACT (1 post-doc and 1 co-worker). The Telematics Institute is funding the Digital Media Warehouse project, which started July 1, 1998 (1 post-doc (vacancy), 1 programmer and 1 senior researcher). ESPRIT has funded the Mercury project, which ended December 31, 1998 (1 programmer) and DOSIS is funding the KESO project, which ends December 31, 1999 (1 senior researcher and 1 co-worker).

Through these projects, the theme collaborates with many academic institutes and partners, both in the Netherlands and abroad.

In 1997 and 1998, the percentages of the total costs of INS1 covered by external funding were: 47% and 48%, respectively.

12.5 PhD theses

- J. van den Akker, *Degas, An Active, Temporal Database of Autonomous Objects*, University of Amsterdam, 1998 (thesis advisors: M.L. Kersten and C.A. Galindo-Legaria, co-advisor: A.P.J.M. Siebes).
- J. Pellenkoft, *Probabilistic and Transformation based Query Optimization*, University of Amsterdam, 1997 (thesis advisor: M.L. Kersten, co-advisor: A.P.J.M. Siebes).
- C. Thieme, *Schema Integration Based on Structure and Behaviour*, University of Amsterdam, 1995 (thesis advisor: M.L. Kersten, co-advisor: A.P.J.M. Siebes).
- C.A. van den Berg, *Dynamic Query Processing in a Parallel Object-Oriented Database System*, University of Twente, 1994 (thesis advisors: P.M.G. Apers and M.L. Kersten).
- M.H. van der Voort, *A Design Theory for Database Triggers*, University of Amsterdam, 1994 (thesis advisor: M.L. Kersten, co-advisor: A.P.J.M. Siebes).

12.6 Academic relations

12.6.1 Secondment of senior staff members at universities

- M.L. Kersten, full professor at University of Amsterdam (0.2 fte)

12.6.2 Secondment of university staff at CWI

- P. De Bra, full professor from Eindhoven University of Technology (0.2 fte)

12.7 Services to the research community

prof.dr. P.M.E. De Bra

- Program Committee Member of AACE WebNet'98 Conference (Orlando, 1998). Program Committee Member of the IEEE Multi Media Conference'99 (Florence, 1999)
- Program Co-Chair of the AACE WebNet'99 Conference (Honolulu, 1999).

prof.dr. M.L. Kersten

- (non-executive) board member of Consult Data and Data Distilleries,
- member editorial boards *VLDB Journal* (Springer Verlag) and *Distributed and Parallel Databases* (Kluwer),
- member of 11 program committees for (inter)national conferences and workshops, of IFIP working group 2.6 Databases and of various ESPRIT-IV committees.
- Board member of the VLDB Endowment

dr. A.P.J.M. Siebes

- member editorial board *CWI Quarterly* and *Journal of Knowledge Discovery and Data Mining* (Kluwer).
- member of 9 program committees for (inter)national conferences and workshops.

13 Theme INS2: Multimedia and Human-Computer Interaction

13.1 Short history of the theme and research highlights

This theme developed out of the Multimedia Kernel Systems (MKS) group of the Computing Systems and Telematics department and the Ergonomics of Computer Systems group of the Algorithms and Architecture department (one of the six old scientific departments). The MKS group has carried out work on the development of a document model and authoring environments for multi-/hypermedia and the investigation of hardware and software support for delivering distributed multi-/hypermedia documents. While the research within the group does not address fundamental HCI issues, the importance of the author and reader plays a central role throughout the research.

Hypermedia Document Modelling. Document modelling work was initiated with the development of the CMIF document format in 1991 and continued with the development of the Amsterdam

Hypermedia Model. This work resulted in the completion of Hardman's PhD thesis in 1998. The modelling work formed a base for the development of the W3C language SMIL (Synchronized Multimedia Integration Language) developed within the W3C working group on Synchronized Multimedia. This became an official W3C recommendation in June 1998.

Multimedia Authoring Systems. The complexity of hypermedia documents requires some form of authoring support. Development of the CMIFed authoring system for providing document editing support was started as a research prototype and continued in more recent years as the key part of the ESPRIT project CHAMELEON (EU/Esprit-IV 20597). The work within the CHAMELEON consortium resulted in the development of a pre-competitive system, called GRiNS, which was updated to the new SMIL document format. The GRiNS software is being used as a vehicle for spinning off a company, Oratrix Development B.V., which will commercially exploit the authoring system.

Distributed Multimedia Applications. Infrastructure support for multimedia applications requires both investigation into the underlying high-speed (ATM) network infrastructures, and payment algorithms for electronic commerce. Work within the SEMPER project was conducted in both these areas.

Interactive Structured Documents. Well-designed software infrastructure is required for documents where logical structure is independent from presentation means and combined when the information is presented to the end-user. A large amount of work has been carried out in the context of the W3C (World Wide Web Consortium) contributing to a number of working groups, including CSS (Cascading Style Sheets).

13.2 Present personnel

13.2.1 Senior staff members

dr. D.C.A. Bulterman (1.0 fte, theme leader), dr. L. Hardman (1.0 fte), prof. L.G.L.T. Meertens (0.4 fte), S. Pemberton (1.0 fte) , dr. L. Rutledge (1.0 fte).

13.2.2 Total formation

5 senior staff members (4.4 fte), 2 postdocs (0.7 fte), 2 programmers (2 fte).

13.3 Selected publications

dr. D.C.A. Bulterman

- D.C.A. Bulterman: User-Centered Abstractions for Adaptive Hypermedia Presentations, *Proceedings of the Sixth ACM International Multimedia Conference*, Bristol, UK, September 1998, 247-256.
- D.C.A. Bulterman, L. Hardman, J. Jansen, K.S. Mullender and L. Rutledge: GRiNS: A GRaphical INterface for Creating and Playing SMIL Documents, *Proceedings of Seventh International World Wide Web Conference (WWW7)*, April 1998, Sydney Australia.
- D.C.A. Bulterman and L. Hardman: Multimedia Authoring Tools: State of the Art and Research Challenges, *Lecture Notes in Computer Science*, **1000**, 1995, 575-591

dr. L. Hardman

- H.L. Hardman, J. van Ossenbruggen, L. Rutledge, K.S. Mullender and D.C.A. Bulterman: Do You Have the Time? Composition and Linking in Time-based Hypermedia, *Proceedings of the Tenth ACM Conference on Hypertext and Hypermedia*, Darmstadt, Germany, February 1999.
- H.L. Hardman, D.C.A. Bulterman and G. van Rossum: The Amsterdam Hypermedia Model: Adding Time and Context to the Dexter Model, *Communications of the ACM*, **37** (2), 194, 50-62.

S. Pemberton

- S. Pemberton (ed.), Proceedings of ACM CHI97 Conference on Human Factors in Computing Systems.
- S. Pemberton, How do you make an electronic journal readable?, *CWI Quarterly* **8**(4), 1995.

dr. L. Rutledge

- L. Rutledge, H.L. Hardman, J. van Ossenbruggen and D.C.A. Bulterman: Mix'n'Match: Exchangeable Modules of Hypermedia Style, *Proceedings of the Tenth ACM Conference on Hypertext and Hypermedia*, Darmstadt, Germany, February 1999.

- L. Rutledge, J. van Ossenbruggen, H.L. Hardman and D.C.A. Bulterman: Structural Distinctions Between Hypermedia Storage and Presentation, *Proceedings of the Sixth ACM International Multimedia Conference*, Bristol, UK, September 1998, 145-150.
- L. Rutledge, J. van Ossenbruggen, H.L. Hardman and D.C.A. Bulterman: "Practical Application of Existing Hypermedia Standards and Tools, *Proceedings of the Third ACM Conference on Digital Libraries*, Pittsburg, USA, June 1998, 191-199.

13.4 External projects and funding

The main source of funding for the group in the previous four years has been the CHAMELEON project (EU/Esprit-IV 20597). This supported the development of multimedia authoring systems for adaptive documents.

Additional European involvement has been with the SEMPER (EU/ACTS-0032) on multimedia support within secure electronic marketplaces and STEM (EU/Telematics) on telematics support for distributed multimedia for environmental management.

National funding was acquired for the ACELA (NL/STW) on the construction of interactive structured documents.

In 1997 and 1998, the percentages of the total costs of INS2 covered by external funding were: 34% and 31%, respectively.

13.5 PhD theses

- H.L. Hardman, *Modelling and Authoring Hypermedia Documents*, University of Amsterdam, 1998 (thesis advisor: A.W.M. Smeulders, co-advisor: D.C.A. Bulterman).
- J.T. Jeuring, *Theories for Algorithm Calculation*, University of Utrecht, 1993 (thesis advisor: L.G.L.T. Meertens).

13.6 Academic relations

Contributions from D. Bulterman and L. Hardman to multimedia/hypermedia courses given at the University of Amsterdam and the Free University, Amsterdam. Close collaboration with drs. J. van Ossenbruggen from the Free University.

13.7 Services to the research community

dr. D.C.A. Bulterman

- member editorial boards *Multimedia Systems Journal* (ACM/Springer Verlag) and *Multimedia Tools and Applications* (Kluwer),
- member of numerous international conference program committees,
- member SION multimedia steering group,
- reviewer for numerous international journals and conferences,
- member of W3C SYMM working group.

dr. L. Hardman

- member editorial board *New Review of Hypertext and Hypermedia* (Taylor Graham),
- member of 3 international conference program committees,
- member of Informatiewetenschap (Information Science) committee,
- reviewer for numerous journals and conferences,
- member of W3C SYMM working group.

S. Pemberton

- editor in chief ACM Interactions, editor in chief ACM SIGCHI Bulletin,
- chair ACM CHI 97, Conference on Human Factors in Computing Systems,
- chair W3C HTML working group, member of W3C CSS working group.

dr. L. Rutledge

- reviewer for numerous journals and conferences,
- member of W3C SYMM working group.

13.8 Awards and honours

dr. D.C.A. Bulterman, dr. L. Hardman, drs. K.S. Mullender, J. Jansen

- Business plans written around the GRiNS authoring system won the top prizes in the prestigious Dutch New Venture 98 business competition.

S. Pemberton

- Five ACM Recognition of Service awards.

14 Theme INS3: Interactive Information Engineering

14.1 Short history of the theme and research highlights

The theme was newly formed at the end of 1996 from previous research groups: Interaction and Multimedia, Logic and Computational Linguistics and Concept Building for Digital Libraries. The focus for all the projects involved is to provide information engineering methods and tools to automatically create user-friendly access and control environments for large data and information collections based on the analysis of the contents. Existing experience within the groups allowed for several lines of approach:

- Finding structure in documents based on a linguistic approach through dictionary and key concept building, mathematical (statistical) methods to define relations among documents in a corpus, and represent this information as a thesaurus for a domain, and as a clustered structure graph.
- Generate layout for trees, directed graphs and for networks, with the property that the layout remains stable under local changes. This forms the basis for automatic presentation of contents in context, together with automatically induced hierarchical views based on structure-, spatial- or subject focal hierarchies.
- Generate humanoid presenters (e.g. avatars), that guide users through the information. A performer driven facial animation system has been developed for this purpose, which allows to study the automatic coupling with a combination of contents and presentation goals.
- Introduce applied logic tools such as inference engines to enrich hyperlinked document contents with user interaction. As a first approach these engines are included in instruction material for logic students, later they will be applied in other areas such as linguistic processes.

The above activities have produced results which are included in the more detailed descriptions of the various theme projects:

14.1.1 Information Engineering Framework

Members of the theme have been active in the development of the PREMO[21] standard from the very beginning (1992). The work involved a number of research issues on software architectures, on multimedia synchronization, media integration, formal specification techniques, etc. The initial draft was based on the object kernel of the ESPRIT MADE project, developed by CWI. The bulk of the editing work on PREMO was also done at CWI; the Standard is currently at the ISO Central Secretariat, and is planned to be published before the end of 1998. Starting in the second half of 1997, the group at CWI also engaged in a proof-of-concept implementation of PREMO using Java as an implementation platform, concentrating on the most critical aspects of the software architecture. This implementation work was done in parallel to the preparation of a manuscript, which is to be published by Springer Verlag in 1999. The implementation was finished in September 1998; the manuscript is to be finished in December 1998, which also ends the PREMO project as a whole.

The work was done in an active cooperation with industry and academia, both within the ISO community, and within an ERCIM/EEC Graphics Network programme. The most important cooperation partners were: Jim Van Loo (Sun Microsystems, USA), David Duke (University of York, UK), David Duce (RAL, UK), Giorgio Faconti (CNUCE, Italy), Nuno Correia (then INESC, now University of Lisbon, Portugal).

[21] PREMO is an ISO IEC/JTC1 SC24 standard, *Programming Environment for Multimedia Objects.*

14.1.2 Applied Logic and Linguistic Processing

The area in which Van Eijck and his group have worked can be broadly described as 'Applied Logic at the Crossroads of Natural Language Analysis and Computer Science'. From 1991 – 1995 this was funded in a substantial way by an NFI grant for an interdisciplinary project 'Structural and semantic parallels in natural languages and programming languages', which has resulted in numerous workshops and publications.

Van Eijck's present interest is the study and application of dynamic logics. In 1998, he has devised the first sound and complete proof system for dynamic predicate logic, and he is now developing dynamic predicate logic into a full-fledged programming language, *dynamo*, an example of an 'inference engine' for computational logic. See `www.cwi.nl/~jve/dynamo`. Van Eijck is also involved in the development of an innovative textbook, 'Logic, Representations and Proofs' (together with Kees Doets of the University of Amsterdam) that combines training in mathematical reasoning with implementation of mathematical definitions in a modern functional programming language. See `www.cwi.nl/~jve/LRP`.

By blending the work of two PhD researchers from the theme, on linguistics and mathematical clustering of dependency networks for textual domains, a high-tech spin-off company was formed (Eidetica), which managed to be selected for the Twinning Institute.

14.1.3 Concept building from Key phrases

Hazewinkel produced several key phrase dictionaries for mathematics and computer science. Van Dongen successfully developed a method to develop a structure over a corpus of mathematical texts using these dictionaries. Next the relational clusters found allowed for enriching the dictionaries to full thesauri. Many interesting research questions have been raised. Their solutions will lead to further sophisticated semantic text processing.

14.1.4 Facial Animation

This project (FASE) is partly supported by STW. Its aim is to produce models of human faces capable of animating expressions, such as emotions, speech and facial gestures. The model can be driven by synthetic, live or animators input and drive in turn a facial presentation model. The system should become useful as an animators tool, as a support for facial communication and for automatic humanoid information presentation. So far a working animation environment, capable of accepting performer data has been produced. The aim is to use this system through the application of constraints for the above purpose. In addition a novel method will be designed to build reusable repertoires of animations by integrating the constraints in the repertoire. The project has been extended by an action of the Telematics Institute on mediated communication for which FASE will provide the experimental environment.

14.2 Present personnel

14.2.1 Senior staff members

P.J.W. ten Hagen, MSc (0.8 fte, theme leader INS3, former head of department IS), dr. I. Herman (1.0 fte, project leader), prof.dr. D.J.N. van Eijck (0.4 fte, project leader), prof.dr. M. Hazewinkel (0.8 fte, senior researcher).

14.2.2 Total formation

4 senior staff members (3.0 fte), 1 postdoc (0.5 fte), 2 PhD students (2 fte), 3 project members (3 fte), 2 programmers (2 fte).

14.3 Selected publications

dr. I. Herman

- D. Wang, I. Herman, G.J. Reynolds, "The Open Inventor Toolkit and the PREMO Standard", in: Computer Graphics Forum, pp. 159-176, 16(3) (1997).
- D.J. Duke, I. Herman, T. Rist, M. Wilson. "Relating the primitive hierarchy of the PREMO standard to the Standard Reference Model for Intelligent Multimedia Presentation Systems" in: Computer Standards & Interfaces, 18(6-7), pp. 525-535 (1997).

- I. Herman, N. Correia, D.A. Duce, D.J. Duke, G.J. Reynolds, J. Van Loo, "A Standard Model for Multimedia Synchronization: PREMO Synchronization Objects", in: Multimedia Systems, 6(2), pp. 88-101 (1998).
- D.J. Duke, I. Herman. "A Standard for Multimedia Middleware". Proceedings of the 6th ACM International Conference on Multimedia (MM'98), Bristol, eds. W. Effelsberg and B.C. Smith, ACM Press (1998).
- D.J. Duke, I. Herman, "Programming Paradigms in an Object-Oriented Multimedia Standard", in: Computer Graphics Forum, 17(4) (1998).

drs. P.J.W. ten Hagen

- Zs. Ruttkay, P. ten Hagen, H. Noot: Constrant-based keyframing Proc. of the ECAI'98 workshop "Constraint Techniques for Artistic Applications"; 25 August 1998, Brighton
- D.A. Duce, D.J. Duke, P.J.W. ten Hagen, G.J. Reynolds. PREMO- an initial approach to a formal definition. Computer Graphics Forum, Vol 13 No. 3 1994

prof.dr. D.J. van Eijck

- 'The Dynamics of Description', Journal of Semantics, Vol 10, 1993, 239–267.
- 'Quantification and Partiality', in Van der Does and Van Eijck, eds, Quantifiers, Logic, and Language, CSLI, 1996, 105–144.
- 'Representing Discourse in Context' (with Hans Kamp), in Van Benthem and Ter Meulen, eds, Handbook of Logic and Language, Elsevier 1996, 179–237.
- 'Typed Logics With States', Logic Journal of the IGPL, Vol 5, 1997, 623–945.

prof.dr. M. Hazewinkel

- M. Hazewinkel, A.A. Ivanonv, A.J. Woldar (eds). *Algebra and combinatorics: interactions and applications*, Special volume **52** for *Acta Applicandae Mathematicae*, KAP, 1998.

14.4 External projects and funding

INS3 has a history of involvement with start-up companies. They have been involved in several that made it into successful companies (XELION, ARCOBEL-Graphics, PRIOR Data Systems). Currently we are related to Eidetica, Humanoid (Denmark), ACE and XELION. National funding has been instrumental in this effort through programs, like STW (on Raster Graphics), SION, NFI(IIICAD). International projects via ESPRIT (i.e. the MADE project, measuring 2.7 fte for CWI) have helped further internationalising our industrial contacts. Currently the HPCN programme (HPV) and STW as well as SION are supporting our research.

In 1997 and 1998, the percentages of the total costs of INS3 covered by external funding were: 21% and 22%, respectively.

14.5 PhD theses

- J.E.A. van Hintum, *Quality Constraints & Constrained Quality*, Eindhoven University of Technology, 1997, (thesis advisors: D.K. Hammer and S.J. Mullender)
- A.V. Groenink, *Surface Without Structure*, Utrecht University, 1997 (thesis advisors: D.J. van Eijck, W.C.A. Rounds (University of Michigan)
- W.P.M. Meyer Viol, *Instantial Logic*, Utrecht University, 1995 (thesis advisors: D.J. van Eijck, J.K. van Benthem),
- External PhD theses with D.J. van Eijck as advisor: Van Noord (1993), Vermeulen (1994).

14.6 Academic Relations

14.6.1 Secondment of senior staff members at universities

- D.J. van Eijck, full professor at University of Utrecht (0.2 fte)
- D.J. van Eijck, scientific director of Dutch Research School in Logic, University of Amsterdam (0.2 fte)
- D.J. van Eijck, coordinator of Spinoza Logic in Action project 'Dissemination of Logic', University of Amsterdam (0.2 fte).
- Prof.dr. M. Hazewinkel, full professor at University of Utrecht (0.2 fte).

15 Theme INS4: Quantum Computing and Advanced Systems Research

15.1 Short history of the theme and research highlights

The theme continues (since 1997) the former Algorithmics and Complexity Research Group (ACRG) in the former Department of Algorithms and Architecture (one of the six former Scientific Departments). In the last five years of ACRG's existence the major research tracks were machine learning, distributed and parallel algorithmics, and description complexity and computational complexity. In *Quality Assessment of Research: Mathematics and Computer Science at Dutch Universities*, VSNU, Utrecht, 1997, the ACRG part shared with the University of Amsterdam received the highest ranking "excellent" in all categories. New research was started in the novel area of quantum computing. Currently, the group is a leader in the quantum algorithms research.

Quantum Computing and Communication Research in quantum communication complexity was initiated in our group (Harry Buhrman and Richard Cleve). They defined the communication complexity model based on EPR pairs. It was demonstrated that in this setting one can achieve improved performance over classical methods (sometimes even exponentially better). The experimental quantum mechanics groups at Innsbruck (Austria) and Caltech (USA) (Cavity QED) will implement our protocols, serving as an experimental verification and touchstone of quantum computing and quantum mechanics. Another major development initiated by Harry Buhrman and Ronald de Wolf (PhD expected in 2002) is the "black box" complexity analysis of quantum mechanical algorithms leading to general impossibility results and limitations of quantum computation. Barbara Terhal (PhD expected in 1999) is temporarily based at the Quantum Information Research Group at IBM T.J. Watson Research Labs (headed by Charles Bennett). She obtained basic results in quantum information retrieval and quantum communication and in the original motivation of founder Richard Feynman: the simulation of quantum mechanical systems by quantum computers. Wim van Dam (PhD expected in 2000/2001) is temporarily based in the Centre for Quantum Computation at the Clarendon Laboratory of Oxford University (headed by Artur Ekert). He has obtained basic results on universal quantum cellular automata, quantum information extraction, superiority of quantum computers over classical ones in oracle interrogation, and quantum information theory.

Distributed and Network Computing Research in the area of wait-free communication through shared variables was partially initiated by Paul Vitányi. It was continued by John Tromp (PhD 1993) and combined with synchronization and fault-tolerance by Jaap-Henk Hoepman (PhD 1996). Sophisticated and yet practical security methods used for transaction security on internet (making it safe from so-called "active attacks") were constructed by Ronald Cramer (PhD 1997) and led to the highly publicized Cramer-Shoup Cryptosystem to be incorporated by IBM in its new security software. Other highlights include compact routing, a novel search method (mutual search), and renaming methods.

Machine learning A major direction in real-world learning algorithmic methods is the "Minimum Description Length" principle. Research in the area started in our group with description complexity based methods by Paul Vitányi and was continued by Peter Grünwald (PhD 1998). Another area is evolutionary programming with research in theoretical foundations (Paul Vitányi), research in implementation methods for accelerated performance (H. Ehrenburg), and cellular encoding for evolutionary programming in particular for real-world robotics (F. Gruau).

Algorithms and Complexity Our work played a key role in developing and demonstrating the power of Kolmogorov complexity. The book (by Ming Li and Paul Vitányi), *An Introduction to Kolmogorov Complexity and Its Applications*, was the first comprehensive book in this field. It is used to teach graduate seminar courses all over the world; various parts of the book have been translated into Chinese, Japanese and Russian. Work of Harry Buhrman started a new approach to the P vs NP problem by studying structural properties of complete sets. This approach has led to new lower bounds on time/space tradeoffs for the NP-complete problem Satisfiability. He also obtained the first nonrelativizing separation in computational complexity theory. John Tromp was involved in several breakthrough results in bioinformatics.

15.2 Present personnel

15.2.1 Senior staff members

dr. Harry Buhrman (1 fte), Prof.dr.ir. Paul Vitányi, theme leader (0.8 fte).

15.2.2 Total formation

2 senior staff members (1.8 fte), 2 postdocs (2 fte), 5 PhD students (5 fte).

15.3 Selected publications

dr. H.M. Buhrman

- H. Buhrman and R. Cleve and A. Wigderson, Quantum vs. Classical Communication and Computation, *Proc. 30th ACM Symp. Theory Comput.*, 1998, 63–69.
- R. Beals and H Buhrman and R. Cleve and M. Mosca and R. de Wolf, Quantum Lower bounds by polynomials, *Proc. 39th IEEE Symp. Foundations Comput. Sci.* , 1998, 351–362.
- R. Cleve and H. Buhrman, Substituting Quantum Entanglement for Communication Complexity, *Physical Review A*, 56:2(1997), 1201–1204.
- H. Buhrman and L. Fortnow and L. Torenvliet, Using Autoreducibility to Separate Complexity Classes, *Proc. 36th IEEE Symp. Foundations Comput. Sci.*, 1995, 520–528.

prof.dr.ir. P.M.B. Vitányi

- C.H. Bennett, P. Gács, M. Li, P.M.B. Vitányi, and W. Zurek, Information Distance, *IEEE Trans. Information Theory*, IT-44:4(1998) 1407–1423.
- M. Li and P.M.B. Vitányi, *An Introduction to Kolmogorov Complexity and its Applications*, Second Edition, Springer-Verlag, New York, 1997 (xx + 637 pp).
- T. Jiang, J. Seiferas, and P.M.B. Vitányi, Two heads are better than two tapes, *J. Assoc. Comput. Mach.*, 44:2(1997), 237–256.
- M. Li, J. Tromp, and P.M.B. Vitányi, How to share concurrent wait-free variables, *J. Assoc. Comp. Mach.*, 43 (1996), 723-746.
- M. Li and P.M.B. Vitányi, Reversibility and adiabatic computation: trading time and space for energy, *Proc. Royal Society of London, Series A*, 452(1996), 769-789.
- P.M.B. Vitányi and M. Li, Minimum description length induction, Bayesianism, and Kolmogorov complexity, Submitted to *IEEE Trans. Inform. Theory.* (Note: Preliminary notes in: Proc. ISIS: Information, Statistics and Induction in Science, World Scientific, Singapore, 1996, 282-291; 'Computer Science Today', J. van Leeuwen, Ed., *Lecture Notes in Computer Science, Vol. 1000*, Springer Verlag, Heidelberg, 1995, 518-535; Proc. IEEE Intn'l Symp. Inform. Theory, 1998, 346.)

15.4 External projects and funding

Research in INS4 is primarily based on external funding both through national and international programs.

Nationally, funding has been granted by NFI, SION, NWO, and the University of Amsterdam; internationally by ESPRIT.

- NFI through NWO has funded the project Algorithmic Aspects of Parallel and Distributed Computing (3 PhD students, 2 postdocs, 1 visiting senior expert, each for 4/5 years, finished end 1996);
- SION/NWO has funded the projects
  - Machine Learning (1 PhD student, 4 years, finished 1996),
  - Learning, Cryptography, and Randomness (1 Postdoc, 2 years, finished end 1997);
  - MDL Neurocomputing (1 PhD student, 4 years, finished end 1998), and
  - Quantum Computation (1 PhD student, 1 postdoc, both 4 years, just started). The University of Amsterdam has funded 2 PhD students Quantum Computation and 1 PhD student Quantum Computation/Learning Theory (4 years each, expected to finish in 1999, 2001, 2002).
- International funding by ESPRIT includes

  - the EuroCOLT Working Group, which ended December 31, 1997,
  - the EuroCOLT II Network of Excellence, which started June 1998,
  - COLORET.
- ERCIM has funded 2 postdocs (1995,1996).

Through these projects, the theme collaborates with many academic institutes and partners, both in the Netherlands and abroad.

In 1997 and 1998, the percentages of the total costs of INS4 covered by external funding were: 32% and 17%, respectively.

15.5 PhD theses

- Peter Grünwald, *The Minimum Description Length Principle and Reasoning under Uncertainty*, University of Amsterdam, 1998. (thesis advisor: P.M.B. Vitányi).
- Ronald Cramer, *Modular Design for Secure Yet Practical Cryptographic Protocols*, University of Amsterdam, 1997. (thesis advisor: P.M.B. Vitányi, co-advisor: I. Damgard (U. Aarhus, Denmark)).
- Jaap-Henk Hoepman, *Communication, Synchronization, Fault Tolerance*, University of Amsterdam, 1996. (thesis advisor: P.M.B. Vitányi)
- John Tromp, *Aspects of Algorithms and Complexity*, University of Amsterdam, 1993. (thesis advisor: P.M.B. Vitányi)

15.6 Academic relations

15.6.1 Part-time appointment of senior staff members at universities

- Paul Vitányi, full professor at University of Amsterdam (0.2 fte)

15.6.2 Secondment of university staff at CWI

- Andries Brouwer, full professor at University of Eindhoven (0.1 fte)

15.7 Services to the research community

dr. H.M. Buhrman

- Member of 4 program committees and one steering committee of international conferences.
- Invited speaker at 5 international meetings.
- Referee for many international conferences and journals.

prof.dr.ir. P.M.B. Vitányi

- Guest Editor, 'J. Computer and System Sciences', special issue on Computational Learning Theory.
- Editor 'Distributed Computing', Springer-Verlag. 'Theory of Computing Systems' (formerly: 'Mathematical Systems Theory'), Springer-Verlag. 'Information Processing Letters' North-Holland/Elsevier. 'Parallel Processing Letters', World Scientific Publishers, Singapore. 'Journal of New Generation Computer Systems', Akademie-Verlag, Berlin. 'Frontiers in Computing Systems Research', Plenum Annual Review Book Series, Plenum Press.
- Member of the Scientific Board, 'Encyclopaedia of Mathematics', Reidel (updated and annotated translation of the Soviet 'Mathematical Encyclopaedia'.) since 1987.
- Member of IFIP working group 1.2 descriptional complexity and IFIP working group 1.4 computational learning theory (co-chair).
- Invited plenary keynote speaker at 9 international conferences since 1994 (apart from lecturer at summer schools or tutorial speaker).
- Member of 27 program committees and 3 steering committees (multi years terms) of international conferences (including 2 times chair and 2 times local organizer—different conferences) since 1994.
- Member of 12 PhD committees since 1994.
- Ca 40 invited lectures and seminars abroad since 1994.
- Referee for many international conferences, technical journals, and reviewer of Grant Proposals for Canada's NSERC, USA's NSF, Israel's NSF equivalent, Hong Kong's NSF equivalent.

15.8 Awards and honours

- In 1998 Ronald Cramer received the 1st annual Christiaan Huygens Science Prize (an award for the best Dutch ICT PhD thesis of the preceding three years).
- In 1998 Peter Grünwald received an NWO Talent Award (Fellowship).
- In 1996 Ming Li (for joint work with Paul Vitányi) received from NSERC the E.W.R Steacie Memorial Fellowship (one of Canada's prestigious science and engineering research awards).
- From 1994—1996 John Tromp received an NSERC Canada International Fellowship at the University of Waterloo.

Appendix 4 Supporting Departments

1 Library and Information Services

1.1 Scope and Purpose

Related to the general goal of SMC/CWI, the Library & Information Services Department (henceforth Library in this text) targets its services to two different kinds of user groups: CWI users and users from outside the CWI.

The objective of the Library is:

- to provide scientists (mathematicians, computer scientists and others) with (documentary) scientific information to support the advancement of scientific knowledge.

The Library is *de facto* the central service point in the Netherlands for the supplying of scientific (documentary) information in the field of mathematics and computer science. It is acting as the national library of mathematics and computer science in the Netherlands, which is reflected in its large collection and in its extensive services to the Dutch scientific community. It is an important asset to the CWI scientific infrastructure, thus helping to create an excellent and stimulating working environment for research.

1.2 Developments 1993 - 1998

The *de facto* national status has largely been earned in the past by the extensive collection of the Library, which is one of the largest in Europe at least. Due to yearly price increases of 10–15%, which is a common problem in the library world, it has become increasingly difficult to maintain this collection-based national status within a constant budget level of kf. 590 per annum in the past period. The important journals collection has been affected severely by yearly subscription cancellations, which were necessary to keep costs within the budget; in the past period some 233 subscriptions have been cancelled, leaving a total (ultimo 1997) of $\approx$ 1150 subscriptions. There is also concern about the books collection.

It is obvious that electronic tools and automation play a role of growing importance in the library community. Due to the tremendous increase of interest in Internet the debate on the future of libraries in an "electronic age" has been intensified. New concepts like the "digital library", the "networked library", the "library without walls" etc. are common terms by now. Despite the new technologies however, the traditional library processes will not disappear all of a sudden, but will coexist and interact with the new approaches. This perfectly illustrates the dilemma the Library is in: the national status is still largely based on its (diminishing) collection, where new technologies cannot yet fully take over this role. The Library is clearly in a phase of transition, and is trying to cope with both "worlds".
It has however embarked on a course to maintain the national status by shifting activities towards coordination, cooperation and digitization, thus creating a different "national visibility". Like most libraries, the Library has actively taken up the challenge of the electronic age; activities related to WWW and electronic journals, but also projects like RIDDLE (EC Libraries Programme), EULER (EC Libraries Programme), NCSTRL, the VOGIN Information Retrieval Tools (IRT) project, ERCIM Digital Libraries initiative, CWI Digital Libraries research group INS3.2 (e.g. project with ABN-AMRO bank), CAPCAS, TechRom and active participation in the Dublin Core metadata development are examples in this context.

Cooperation with other libraries is another important involvement of the Library, where it takes an active and sometimes leading role. The Library is leading the coordination activities of the mathematics and computer science libraries in the Netherlands ("LOBBI") and is participating actively in the development of plans for future library services of the Kenniscentrum Amsterdam (Knowledge Center Amsterdam, KCA) ("β-cluster") as well as in the Amsterdam library network ADAMnet. Special cooperation activities with the University of Amsterdam WINS Library are under way to remove redundancies in the collection overlap and coordinate the collection development. An external consultant made recommendations to this end in 1997.

Cooperation is not only compulsory from a financial point of view, but also focuses attention on the important role libraries play in the knowledge infrastructure.

As outlined, the Library is in an interesting and challenging transition phase. This situation is a complex one, due not only to the transition itself, but also due to an as yet unstable electronic alternative, of which nobody knows to which direction it develops. What actually is clear, is that electronic information

will to a large extent not be available for free, but will be charged for as with the paper copy versions. For solving budget problems, electronic information does not seem very helpful.
For the library staff (8.1 fte in total including the head librarian) the situation of the Library demands extraordinary efforts and also strains the total available human resources. The Library is very happy however, that it can profit from the Digital Libraries research in Research Group INS3.2.

WWW pages: `http://www.cwi.nl/cwi/departments/BIBL.html`

2 Computer Systems and Telematics

2.1 Organization

The CWI IT department (Computer Systems and Telematics, CST) has been the central IT facilitating department, since 1986. Its focal point has mainly been supporting researchers at the forefront of mathematics and computer science research. The organizational changes in 1992 (integration with part of the STO staff) and 1995 (spin-off of multi-media group to research department) have had a severe impact. From a mainly research-oriented department, CST has evolved to a support and facility department, with dedicated attention to the rapid changing needs of CWI's researchers and supporting staff. To ease information flow and to better facilitate the research community, CST has a longstanding open and thorough relationship with the OCV (Overleg Computervoorzieningen, CWI's deliberative body on computer facilities) and ever since the 'restructuring' in 1997 also with theme-leaders, allowing for direct input and comments of ongoing work.

2.2 Policies

CST has implemented several policies to enable the proliferation of a stable IT infrastructure, while at the same time allowing for quick adaptation to the needs of our researchers. Started in the late 1980's and effectively continuing today, the first policy is based on the vision *to realize a desktop infrastructure several years ahead of the commodity market*. This translates into an investment policy to incrementally supply every researcher with sufficient desktop compute power, whereby a differentiation has been made between 'high end' users on the one hand and commodity users on the other. The first category receives new and latest models more frequently, but also share the risks involved in using leading-edge technology. The systems being replaced are then used by a second group of researchers. This process continues until the oldest equipment can be removed from CWI, or returned to the supplier. With this policy every researcher receives better equipment approximately every other year.

A second policy established a central control over investment funds, *to economically facilitate large resources*, such as file, compute, and database servers. Combined with the desktop setting, this creates a communication riche environment, requiring an adequate network facility and tailor-made services. CST has taken a national lead position in deploying high-bandwidth interconnects to the desktops.

A policy which is possibly reaching the end of its effectiveness, is the restriction on the number of computing equipment suppliers. For more than a decade, Silicon Graphics and Sun Microsystems have been the only (Unix) vendors. The reasoning for this is based on efficient support, as well as at the same time allowing for a high degree of support, avoiding fragmentation. For personal use, Apple Macintoshes were used. Although our Financial Department has been using Wintel-based equipment ever since the early 1990's, for our researchers Windows-NT has only been introduced (in larger numbers) as short ago as the summer of 1998. Institute-wide, PC-hardware comes in principle only from one vendor and an effort is made to limit the number of different versions and models, again aiming at better utilization and more efficient support. This latter policy development is based on the so-called 'Vision' document (December 1997), and targets for industry standards at the desktop, aiming at both lower cost of ownership as well as being able to more easily communicate and collaborate with partners outside CWI.

Time and time again, CWI has played a prominent role as (beta-) tester, early adapter and integrator of leading-edge technologies. This has always been triggered by the distinct need by researchers for new techniques and features, creating an atmosphere of boundary-breaking research at the frontier of technical possibilities.

2.3 Architecture

The foundation for the current IT-environment was laid in 1987, with the implementation of an institute-wide (coaxial) Ethernet network. On this network a workstation has long been available on every desk,

for both researchers and supporting staff. This decentralized model is balanced by relatively large central facilities, ranging from pure compute power, to visualization and multi-media support, to downright disk-space and backup facilities, and supplemented by central services for e-mail, news, printing, databases, etc. Network-wise, a major impact has been the proliferation of ATM connected workstations, starting as early as 1993. In 1996 glass fibres were put in place allowing for two connections per end-user, effectively resulting in connecting over 100 desktop systems and over a dozen servers to three ATM-switches. It was anticipated at that time, that ATM would succeed Ethernet as main carrier. But so-called Fast Ethernet (100Mb/sec) has evolved quicker and pricing of ATM has not dropped as quick as expected. We therefore are now faced with the need to invest in a high performing switched 100Mb/sec Ethernet environment, connecting effectively and efficiently with the already in-place ATM infrastructure.

This builds on the long-standing evolvement from CWI to networking in general, starting with being the incubator as well as the co-founder of both the Dutch and European Internet, leading to housing (until recently) the Dutch primary Domain Name Server and for about ten years being the Dutch domain name registrar. This involvement and tradition continues in partnerships and cooperations with for instance Telematics Institute (the virtual organization network and MESH, both ATM based), ERCIM (alphaten155 managed bandwidth project) and SURFnet (ATM connectivity, Snelnet, inter alia).

On the server side, the trends over recent years largely deal with a change in the type of use and workloads. It used to be that computing equipment was less a research tool and more a research subject. This has changed dramatically by the way basic and standard facilities (wordprocessing, communication and web-browsing) have become commonplace. This calls for extensive availability (preferably 24 hours per day, seven days per week) and a high degree of robustness with short repair times. This changeover cannot be done overnight, given the type of equipment currently available at CWI and the way it is currently used. This can only be put in place when dedicated equipment is introduced. This has been partially done, creating a distinct difference between core servers and services on the one hand and research triggered ones on the other.

For the desktops (and an increasing number of laptops) the differences in type of use have become even more elaborate. Both changes in the way researchers do their work, as well as organizational changes play a large role in this. The average researcher is no longer satisfied with an editor, a mailer and a compiler. The need for an increasingly growing palette of user applications is eminent, based both on 'what the rest of the world is using' and as plain but highly dedicated tools for day-to-day work. In future, each workstation will have to be tailored explicitly to the specific and ever-changing needs of the researcher. This calls for personalized environments and (again) a tight integration with central core facilities and services at the 'back office', while at the same time allowing for 'stand alone' working.

Appendix 5 CWI Alumni

Former PhD student	Current affiliation
Akker, J. van den	CMG Finance
Berg, C.A. van den	IBM Networks
Boender, H.	Origin
Bonsangue, M.M.	CWI
Borst, S.C.	CWI and Eindhoven University of Technology
Bosscher, D.J.B.	University of Amsterdam
Breugel, F. van	York University, Toronto
Cabo, A.J.	Nederlands Kamerorkest
Coelho de Pina, J.	University of Sao Paulo
Combé, M.B.	N.V. Bank Nederlandse Gemeenten
Cong, Nguyen huu	University of Hanoi
Cramer, R.	ETH Zürich
Deursen, A. van	CWI
Diepen, N.W.P. van	Catholic University of Nijmegen
Dijke, M.I.J. van	Heriot-Watt University, Edinburgh
Dijkhuizen, M.S.	Kobe University
Does, J. de	Baltzer
Elbers, H.J.	Central Statistics Agency for the Netherlands (CBS)
Elkenbracht-Huizing, M.	ABN-AMRO
Etalle, S.	University of Maastricht
Fokkink, W.J.	University of Wales
Groenink, A.V.	Eidetica
Grünwald, P.	Stanford University
Hardman, H.L.	CWI
Hintum, J.E.A. van	National Aerospace Laboratory (NLR)
Hoepman, J.-H.	University of Twente
Hof, J.M. van den	Central Statistics Agency for the Netherlands (CBS)
Holst, H. van der	Hebrew University of Jerusalem
Horita, E.	NTT Laboratories, Japan
Janssen, R.H.P.	Monastery of Berne
Jeuring, J.T.	University of Utrecht
Kamperman, J.F.Th.	Reasoning, Palo Alto, USA
Klusener, A.S.	Techforce (Emendo)
Korver, H.P.	IDresearch
Kuijk, A.A.M.	CWI
Lieshout, M.N.M. van	CWI
Loon, M. van	TNO Institute for Environment, Energy and Process Innovation
Maarel, H.T.M. van der	MARIN

Meulen, E.A. van der	MeesPierson
Meyer Viol, W.P.M.	Imperial College
Mulder, J.D.	CWI
Nacken, P.F.M.	Shell International Exploration and Production
Olde Daalhuis, A.B.	University of Edinburgh
Overkamp, A.A.F.	ORTEC Consultants B.V.
Peletier, M.A.	CWI
Pellenkoft, J.	CWI
Pul, M.C.J. van	Shell Research and Technology Center
Raamsdonk, F. van	Free University of Amsterdam
Schotting, R.J.	Delft University of Technology
Spee, E.J.	Royal Netherlands Meteorological Institute
Stortelder, W.J.H.	Berger Financial Research, Israel
Swart, J.J.B. de	CWI and Paragon
Teusink, F.	Origin
Thieme, C.	Syllogic
Tip, F.	IBM Thomas J. Watson Research Center
Tromp, J.	CWI
Trompert, R.	Origin
Turi, D.	University of Edinburgh
Veen, W.A. van der	MacNeal-Schwendler
Veltman, B.	ORTEC Consultants B.V.
Voort, M.H. van der	Charm
Wartenhorst, P.	McKinsey
Zeeuw, P.M. de	CWI

Appendix 6 Evaluation of University Research Groups

Research group	University	Professor(s) from CWI	Quality	Productivity	Relevance	Viability
Logic programming and theorem proving	UvA	K.R. Apt	Excellent	Excellent	Excellent	Excellent
Algorithmics and complexity	UvA	P.M.B. Vitányi	Excellent	Excellent	Excellent	Excellent
Discrete mathemtics	UvA	A. Schrijver	Excellent	Excellent	Good	Good
Theoretical computer science	VU	J.W. de Bakker, J.W. Klop	Excellent	Excellent	Good	Good
Numerical algorithms	UvA	P.W. Hemker, P.J. van der Houwen	Good	Excellent	Good	Excellent
Programming environments	UvA	P. Klint	Good	Excellent	Good	Good
Application of analysis in technical sciences	TUD	C.J. van Duijn	Good	Good	Good	Good
Intelligent sensory information systems	UvA	M.L. Kersten	Good	Good	Good	Good
Software technology	UU	L.G.L.T. Meertens	Good	Satisfactory	Unsatisfactory	Satisfactory

TABLE 8. Evaluation of University Research Groups

Appendix 7 ERCIM

The European Consortium for Informatics and Mathematics (ERCIM) was officially founded on April 13, 1989, when an Agreement on Scientific Cooperation was signed by three directors of European research institutions in informatics and (applied) mathematics: A. Bensoussan (INRIA – Institut National de Recherche en Informatique et en Automatique, France), G. Seegmüller (GMD – Forschungszentrum Informationstechnik (previously Gesellschaft für Mathematik und Datenverarbeitung), Germany), and P.C. Baayen (CWI – Centrum voor Wiskunde en Informatica, The Netherlands).

Membership rapidly increased and now comprises leading research organizations in informatics and applied mathematics in 14 European countries, representing some 7000 researchers all over Europe (see Table 1). During the 1990s several actions envisaged in the 1989 Cooperation Agreement were put into operation. A series of joint workshops, seminars and advanced courses on frontier research topics gradually developed into the creation of regular ERCIM Working Groups on a variety of subjects. At present there are 14 such Working Groups (see Table 2), three of them coordinated by CWI staff members. Another core activity is the definition and implementation of joint projects and cooperation frameworks with several ERCIM members as participants. Recent examples are the Digital Libraries Initiative, the EU project Aquarelle, and activities in the framework of the World Wide Web Consortium W3C (of which ERCIM as a whole as well as a number of member institutes separately are a member, CWI hosts for example the national W3C office). A relatively new phenomenon, actively pursued by CWI, is the conclusion of bilateral cooperation agreements with ERCIM partners. Such a cooperation already existed between CWI and INRIA prior to the creation of ERCIM, and has recently been extended to similar agreements with GMD and SZTAKI. Furthermore ERCIM produced several strategic documents related to developments in ICT research and their implications for Europe, for example in connection with the EU Fifth Framework Programme, and is now considered as an important party in discussions on future ICT research at the European level.

The very successful Fellowship Programme, started in 1990, and supported by the EU, gave until now almost 80 promising young scientists from all over the world the opportunity to work for a period of (usually) 18 months at one or two ERCIM institutes (CWI hosted almost 30). As a stimulus for young scientists within ERCIM the annual Cor Baayen Award for outstanding research achievements was established in 1995, in honour of the first ERCIM President. In 1992 ERCIM acquired the legal status of a European Economic Interest Grouping (EEIG) and an office was established (hosted by INRIA at its headquarters in Rocquencourt near Paris).

A Board of Directors and an Executive Committee take care of the general development policy of ERCIM and its translation into concrete actions, respectively. All members are represented in these two bodies. From the Board of Directors a President is elected, who chairs its meetings and formally represents ERCIM externally. CWI provided the first and the third (present) President: P.C. Baayen (1992–1994) and G. van Oortmerssen (1998– ...), respectively. Another body with regular meetings is the Editorial Board, consisting of representatives from most members and a central editor at the ERCIM Office. The Board is responsible for all ERCIM documentation, in particular ERCIM News – a quarterly newsletter (7000 copies in 70 countries) informing the ERCIM research community and interested outside parties on issues such as joint ERCIM actions and current research – , and the ERCIM Website (maintained by the central editor). The staff of several ERCIM members includes a European Liaison Officer monitoring international and national research programmes and maintaining contacts with Brussels. These Officers also meet whenever it is felt useful, mainly for the exchange of information. Finally, in November 1999 ERCIM will celebrate its 10th anniversary with a 2-day event to be organized at CWI.

At present CWI is represented in ERCIM as follows:

Board of Directors and President	G. van Oortmerssen
Executive Committee and European Liaison Officers Grouping	F.A.M. Snijders
Editorial Board	H.M. Nieland
Chairman/coordinator Working Group *Constraints*	K.R. Apt
Chairman/coordinator Working Group *Control and Systems Theory*	J.H. van Schuppen
Chairman/coordinator Working Group *Parallel Processing Network*	H.J.J. te Riele

Organization	Country	Research staff	Member since
CWI (Centrum voor Wiskunde en Informatica)	The Netherlands	185	1989
GMD (Forschungszentrum Informationstechnik)	Germany	1250	1989
INRIA (Institut National de Recherche en Informatique et en Automatique)	France	2100	1989
CLRC (Central Laboratory of the Research Councils)	United Kingdom	290	1990
CNR (Cosiglio Nazionale delle Ricerche)	Italy	600	1991
SINTEF (Stiftelsen for Industriell og Teknisk Forskning ved Norges Tekniske Hogskole (SINTEF Telecom and Informatics))	Norway	350	1992
FORTH (Foundation of Research and Technology – Hellas (Institute of Computer Science))	Greece	160	1992
SICS (Swedish Institute of Computer Science)	Sweden	80	1992
VTT (Technical Research Centre of Finland (VTT Information Technology))	Finland	200	1993
SZTAKI (Magyar Tudományos Akadémia – Számítástechnikai és Automatizálási Kutató Intézete)	Hungary	350	1994
SARIT (Swiss Association for Research in Information Technology)	Switzerland	800	1994
CRCIM (Czech Research Consortium for Informatics and Mathematics)	Czech Republic	250	1996
DANIT (Danish Consortium for Information Technology)	Denmark	80	1996
SRCIM (Slovak Research Consortium for Informatics and Mathematics)	Slovakia	145	1998

TABLE 9. Present ERCIM Membership

Working Group	Chairperson/Coordinator
Computer Graphics	D. Duce (CLRC)
Constraints	K.R. Apt (CWI)
Control and System Theory	J.H. van Schuppen (CWI)
Database Research Group	K.G. Jeffery (CLRC)
Digital Library Initiative	C. Thanos (CNR)
Electronic Commerce	C. Vanoirbeek (SARIT)
Environmental Modelling	A. Sydow (GMD)
Fluid Mechanics	U. Becker-Lemgau (GMD)
Formal Methods for Industrial Critical Systems	D. Latella (CNR)
Health and Information Technology	V. Pakarinen (VTT)
Parallel Processing Network	H.J.J. te Riele (CWI)
Programming Language Technologies	N. Jones (DANIT)
User Interfaces for All	C. Stephanidis (FORTH)
W4G - World Wide Web Working Group	S. Robinson (CLRC)

TABLE 10. Present ERCIM Working Groups

Appendix 8 Financial Overviews

INCOME/YEAR	1993	1994	1995	1996	1997	1998 [7])
NWO basic funding	15322	15848	17331	16190	16381	16724
NWO projects [1])	549	477	269	420	465	397
National programs[2])	0	0	0	439	939	843
International competition [3])	3038	2791	1679	958	1021	1049
Additional funding [4])	1630	1813	1871	1621	1971	2869
Final payments completed projects	85	0	146	39	1230	115
Other income [5])	1053	1063	1273	888	751	669
Capital investments:	2502	4975	3397	1268	791	1948
Allowance for depreciation [6])				1992	1825	1580
Total Income:	24179	26967	25966	23815	25374	26194
Total cost:	23669	26274	25832	22989	24111	26988
Result:	510	693	134	826	1263	-794
Equity at year end	1243	1936	2070	2896	4159	3365

TABLE 11. Summary of income, institute-level; overall result; equity

[1]) The vast majority of NWO projects is not visible here, because the researchers involved are employed by NWO. On average, this concerns 30 fte paid by NWO.

[2]) ICES projects (Thus, the national programs do not reflect funding from, e.g., SION, SWON, STW, NCF, and NFI.)

[3]) EU projects

[4]) Contract research and Telematics Institute

[5]) E.g. interest, software, reproduction

[6]) From 1996 on (due to a change in NWO consolidation-guidelines) cost of depreciation is calculated; to correct for corresponding differences in result, allowance for depreciation is added to income

[7]) Projected figures, based on financial report third quarter 1998

INCOME per RESEARCHLINE/YEAR	1993	1994	1995	1996
National competition:				
- AM	–	–	–	0
- BS	–	–	–	0
- NW	–	–	–	200
- AP	–	–	–	0
- AA	–	–	–	8
- IS	–	–	–	231
total CWI	–	–	–	**439**
International competition:				
- AM	0	0	4	6
- BS	70	100	49	14
- NW	125	113	113	8
- AP	1273	899	307	15
- AA	819	815	650	905
- IS	705	820	556	10
- supporting departments	46	44	0	0
total CWI	**3038**	**2791**	**1679**	**958**
Additional funding:				
- AM	79	79	68	156
- BS	462	446	239	246
- NW	95	200	200	150
- AP	3	59	353	529
- AA	13	40	46	1
- IS	57	4	20	31
- supporting departments	851	972	945	473
- other	70	13	0	35
total CWI	**1630**	**1813**	**1871**	**1621**

INCOME per RESEARCHLINE/YEAR	1997	1998 [1])
National competition:		
- MAS	200	200
- INS	318	401
- PNA	0	0
- SEN	420	242
total CWI	**938**	**843**
International competition:		
- MAS	0	0
- INS	881	952
- PNA	26	76
- SEN	114	21
total CWI	**1021**	**1049**
Additional funding:		
- MAS	394	282
- INS	244	371
- PNA	205	237
- SEN	730	1212
- supporting departments	398	222
- other		545
total CWI	**1971**	**2869**

[1]) Projected figures, based on financial report third quarter 1998

TABLE 12. Specification of income, researchline-level

COST/YEAR	1993	1994	1995	1996	1997	1998 [3])
Personnel expenses [1])	16807	16581	17128	15792	16464	18573
Material expenses	4733	4849	5208	3336	3781	4712
Depreciation [2])				1992	1825	1580
Investments:						
- building-infrastructure	0	1236	163	20	99	148
- computer-infrastructure	2004	1327	3234	1678	619	1975
- reservations	125	2281	99	171	1323	0
total investments	2129	4844	3496	1869	2041	2123
Total Cost:	23669	26274	25832	22989	24111	26988

TABLE 13. Summary of cost, institute-level

[1]) For details: table 14
[2]) From 1996 on (due to a change in NWO consolidation-guidelines) cost of depreciation is calculated
[3]) Projected figures, based on financial report third quarter 1998

Personnel expenses per researchline/YEAR	1993	1994	1995	1996
- AM	1038	1120	1123	1272
- BS	2382	2224	2301	2131
- NW	1977	1900	2107	1955
- AP	2212	2132	1965	1341
- AA	1528	1629	2226	2158
- IS	1899	1821	1913	2010
- Research related	2418	2542	2036	1823
- Other (incl. management)	3353	3212	3457	3101
total CWI	16807	16580	17128	15791

Personnel expenses per researchline/YEAR	1997	1998 [1])
- MAS	2917	3007
- INS	3465	4259
- PNA	2500	3045
- SEN	2622	2995
- Research related	1966	2094
- Other (incl. management)	2994	3173
total CWI	16464	18573

TABLE 14. Personnel expenses, researchline-level

[1]) Projected figures, based on financial report third quarter 1998

Appendix 9 Diagrams

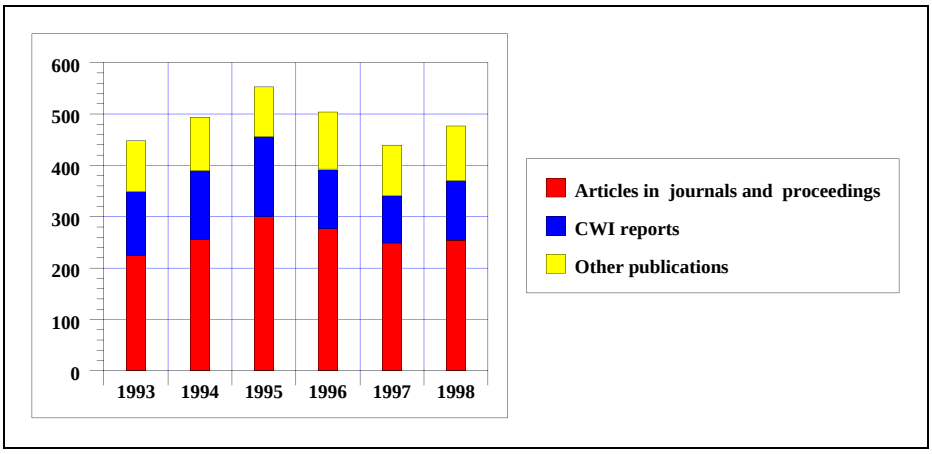

FIGURE 3. Numbers of papers

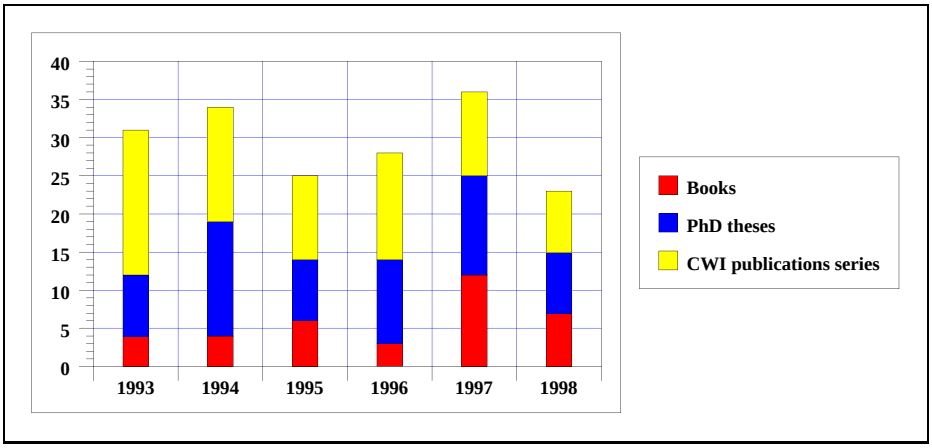

FIGURE 4. Numbers of monographs

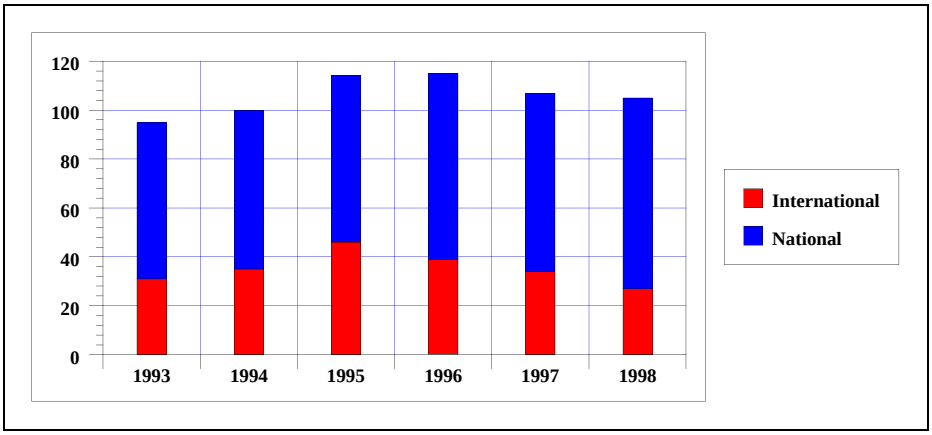

FIGURE 5. Externally funded projects

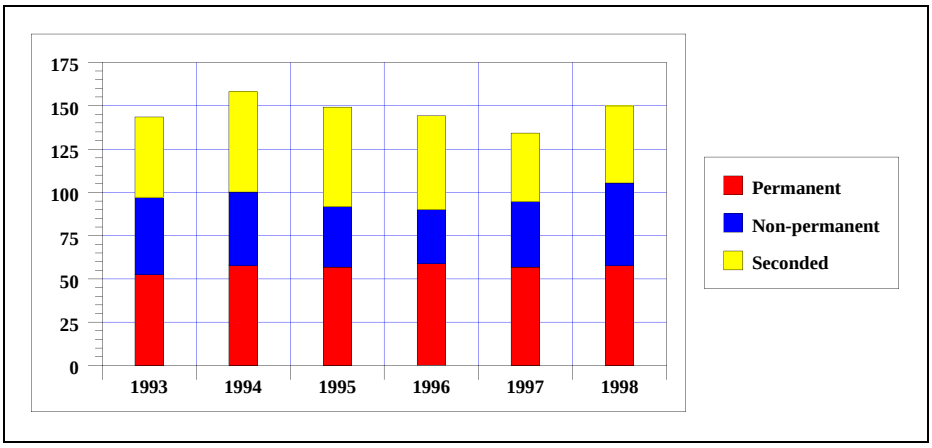

FIGURE 6. Gross scientific staff at CWI (fte)

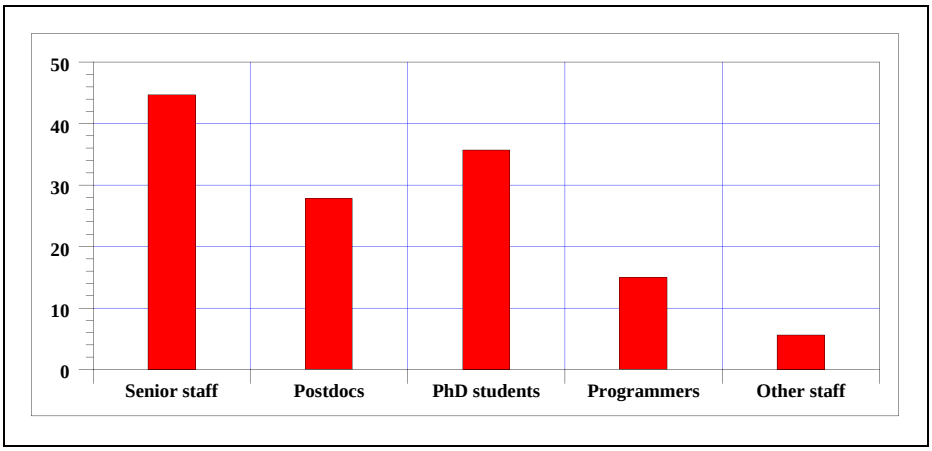

FIGURE 7. Present nett scientific staff (fte)

Appendix 10 Abbreviations

Abbreviation	Meaning
AACE	Association for the Advancement of Computing in Education
ABN-AMRO	Algemene Bank Nederland-Amsterdam Rotterdam Bank
ACELA	Architecture of a Computer Environment for Lie Algebras
ACM	Association for Computing Machinery
ACMP	Advanced Multimedia Content Processing
ACP	Algebra of Communicating Processes
ADAMnet	Network of Amsterdam Mathematics and Computer Science Libraries
Aeritalia	Italian aircraft manufacturer
AKZO	Multinational chemical concern
ALW	NWO Council for Earth and Life Sciences
AMAST	Algebraic Methodology and Software Technology
ARCOBEL	Software concern
ARW	Akademie Raad voor de Wiskunde
ASCI	Advanced School for Computing and Imaging
ASF	Algebraic Specification Formalism
ATM	Asynchronous Transfer Mode
BRA	Basic Research Action
BRIMS	Basic Research Institute in the Mathematical Sciences
BRITE	Basic Research for Industrial Technology in Europe
BS	Former CWI department
CADANS	PNA project for Dutch Railways
CAPCAS	Project of Library
CBS	Centraal Bureau voor de Statistiek (Statistics Netherlands)
CCSOM	Centre for Computer Science in Organization and Management
CFD	Computational Fluid Dynamics
CHI97	ACM Special Interest Group on Computer Human Interaction
CIMS	Computing-Intensive Methods in Stochastics
CMG	Computer Management Group
CMIF	CWI Multimedia Interchange Format
CMIFed	CMIF editing
CNRS	Centre National de Recherche Scientifique
CNT	Computational Number Theory
CNUCE	Italian ERCIM-partner
CoLa	Formal methods and refinement for coordination languages
COLORET	European HCM Project in the area of Computation, Logic and Recursion Theory
COMPASS'95	Conference on Computer Assurance
COMPULOG	Computational Logic
CONCUR'95	Calculi and Algebras of Concurrency: Extensions, Tools and Applications
COORDINA	EU project for coordination models

COQ	French project on machine-checked formal mathematics
COTIC	Concurrent Constraint Programming for time-critical applications
CRL	Common Representation Language
CRREL	Cold Regions Research and Engineering Laboratory – USA
CS	Circulation Simulation
CSIRO	Commonwealth Scientific and Industrial Research Organization – Australian Scientific research agency
CSLI	Centre for the Study of Language and Information (Stanford University)
CSS	Cascading Style Sheets
CST	Computer Systems and Telematics
CWI	Centrum voor Wiskunde en Informatica (Centre for Mathematics and Computer Science)
DACCORD	EU project for control of a motorway network
DAE	Differential-Algebraic Equations
DBMS	Data Base Management System
DBRG	Data Base Research Group
DELOS	EU Library Project
DIKU	Department of Computer Science, Univ. of Copenhagen
DIMACS	Center for Discrete Mathematics and Theoretical Computer Science (A collaborative project of Rutgers University, Princeton University, Bell Labs, AT&T Labs-Research, Bellcore, and NEC Research Institute)
DLO	Dienst Landbouwkundig Onderzoek (Agricultural Research Agency)
DSL	Dynamical Systems Laboratory
DSLs	Domain Specific Languages
DSM	Chemical concern
dtp	Desk Top Publishing
DYNA	A Dynamic Traffic Model for Real-Time Applications
EC	Commission of the European Union
ECAI	European Conference on Artificial Intelligence
ECN	Energie Centrum Nederland (Netherlands Energy Research Foundation)
EEC	European Economic Community
EIDMA	Euler Institute for Discrete Mathematics and Applications
EPR	Einstein-Podolsky-Rosen
EPSRC	Engineering and Physical Sciences Research Council
ERCIM	European Research Consortium for Informatics and Mathematics
ERO	European Research Office of the USA
ESF	European Science Foundation
ETAPS	European Joint Conferences on Theory and Practice of Software
ETH	Eidgenössische Technische Hochschule
EU	European Union
EURANDOM	European Unit for Research and Analysis of Non-Deterministic Operational Models
EuroCOLT	European Conference on Computational Learning Theory
EUROFOCS	EU HCM Network
EZ	Ministry of Economic Affairs
FASE	Facial Animation System with emotional Expression
FOM	Fundamenteel Onderzoek der Materie (Foundation for Fundamental Research on Matter)
fSDL	formal Structural Definition Language
Fte	Full time equivalent
GBE	Gebiedsbestuur Exacte Wetenschappen (Physical Sciences Council)
GI	Gesellschaft für Informatik, General Independent (term used in queuing theory)
GIPE	Generation of Interactive Programming Environments

GMD	Gesellschaft für Mathematik und Datenverarbeitung
GRiNS	Graphical Interface for SMIL
HCI	Human-Computer Interface
HCM	Human Capital and Mobility
HPCN	High Performance Computing and Networking
HPL	Hewlett Packard Laboratory
HPV	High Performance Visualization
HRM	Human Resource Management
HTML	Hypertext Markup Language
HTTP	Hypertext Transfer Protocol
IC	Integrated Circuit
ICALP'97	International Colloquium on Automata, Languages, and Programming
ICDE	International Conference on Data Engineering
ICDT	International Conference on Database Theory
ICES	Interdepartementale Commissie Economische Structuurversterkingen (Dutch agency for infrastructural investments)
ICT	Information and Communications Technology
IEC	International Electrotechnical Commission
IEE	Institution of Electrical Engineering
IFAC	International Federation of Automatic Control
IGPL	Interest Group in Pure and Applied Logics
IIICAD	Intelligent Integrated and Interactive Computer Aided Design
IMAU	Institute for Marine and Atmospheric Research Utrecht
INESC	Portugese Institute for Engineering and Science (ERCIM partner)
ING	Internationale Nederlanden Groep (Multinational banks and insurance companies group)
INRIA	Institut National de la Recherche en Informatique et en Automatique
INS	Information Systems
INTAS	International Association for promotion of cooperation with Scientists from the former Sowjet Union
IPA	Institute for Programming Science and Algorithmics
IPG	Interaction and Parallelism Group
IRT	Internet/Information Retrieval Tools
ISI	International Statistical Institute
ISSN	International Standard Series Number
IVP	Initial Value Problem
IWIM	Idealized Worker - Idealized Manager
JCSS	Journal of Computer and System Sciences
JTC1	Joint Technical Committee 1 of ISO/IEC
KCA	Knowledge Centre Amsterdam (Kenniscentrum Amsterdam)
KESO	EU Data mining project Knowledge Extraction for Statistical Offices
KIS	Kennis Infrastructuur (Knowledge infrastructure)
KNAW	Koninklijke Nederlandse Academie van Wetenschappen (Royal Netherlands Academy of Arts and Sciences)
KNMI	Koninklijke Nederlands Meteorologisch Instituut (Royal Netherlands Meterological Institute)
KONI	Dutch industry (shock absorber manufacturer)
KPN	Koninklijke PTT Nederland (Royal Netherlands Post, Telegraph and Telephone company)
LARIS	Language for Railway Interlocking Specifications
LICS	Logic in Computer Science
LNCS	Lecture Notes on Computer Science
LOTOS	Long Term Ozon Simulation

LPC	National Project Concurrency
LPO	Linear Process Operators
LTR	Long Term Research
LUW	Landbouw Universiteit (Agricultural University) Wageningen
MAS	Modelling, Analysis and Simulation
MDL	Minimum Description Length
MFl	One million Dutch Guilders (≈ 0.45 million Euros)
MIT-LCS	MIT Laboratory for Computer Science
MM'98	Multimedia conference
Monet	A novel main memory database kernel
MPEG2	A multimedia compression standard
MRI	Mathematics Research Institute Utrecht
NAIC	Netherlands Conference on Artificial Intelligence
NAM	Nederlandse Aardolie Maatschappij (Dutch oil company)
NCF	NWO Foundation (National Computing Facilities Foundation)
NCSTRL	Networked Computer Science Technical Report Library
NFI	Nationale Faciliteiten Informatica (National Facilities Informatics)
NIH	Nederlands Instituut voor Hersenonderzoek (Netherlands Institute for Brain Research)
NOBIS	Business partner of MAS1
NSERC	National Science and Engineering Research Council of Canada
NT	Network Technology
NVTI	Nederlandse Vereniging voor Theoretische Informatica (Dutch Society for Theoretical Computer Science)
NWO	Nederlandse Organisatie voor Wetenschappelijk Onderzoek (Netherlands Organization for Scientific Research)
OCIAM	Oxford Centre for Industrial and Applied Mathematics
OC&W	Ministry of Education Culture and Sciences
ODE	Ordinary Differential Equation
Oratrix	CWI Spin-off on Multimedia
OTKA	Hungarian research foundation
PD	Personnel Department
PDE	Partial Differential Equation
PHACT	Philips Automated Conformance Tester
PIM	Logic for program analysis and optimization of imperative programs
PNA	Probability, Networks and Algorithms
ProMACS	Probabilistic Methods for the Analysis of Continuous Systems
PSIDE	Parallel Software for Implicit Differential Equations
PVS	Formal specification and verification system
QMIPS	Quantitative Modelling in Parallel Systems
RAL	Rutherford-Appleton Laboratory
RISLA	Specification language for financial products (Rente Informatiesystemen Language)
RIVM	Dutch National Institute for Public Health and Environmental Protection
RKC	Runge Kutta Chebyshev
ROCCADE	Large Dutch software company. Business partner of SEN1
RS	Remote Sensing
RSA	Public key encryption method (Rivest, Shamir and Adleman)
RWS	Rijkswaterstaat (Dutch State Agency for Water Management)
SARA	Stichting Academisch Rekencentrum Amsterdam (Academic Computer Services Amsterdam)
SC24	ISO/IEC subcommittee responsible for Computer Graphics and Image processing standards

SCAI	GMD-Institut für Algorithmen und Wissenschaftliches Rechnen (Institute for Algorithms and Scientific Computing)
SciCADE	International Conference on Scientific Computation and Differential Equations
SDF	Syntactic Definition Formalism
SEN	Software Engineering
SENTER	Funding agency of Dutch Ministry of Economic Affairs
SI	System Identification
SIAM	Society for Industrial and Applied Mathematics
SIGCHI	Special Interest Group Computer-Human Interface
SIGGRAPH	Special Interest Group Computer Graphics
SION	Stichting Informatica Onderzoek Nederland (former NWO Foundation for Computer Science Research in the Netherlands)
SMC	Stichting Mathematisch Centrum (Foundation Mathematical Centre)
SMIL	Synchronized Multimedia Integration Language
STO	Sector Technische Ondersteuning (Sector technical support)
STW	Stichting Technische Wetenschappen (Dutch Technology Foundation)
SURFnet	Network of University Computing Centres
SWON	Stichting Wiskunde Onderzoek Nederland (former NWO Foundation for Mathematics Research in the Netherlands)
SWOT	Strengths, Weaknesses, Opportunities, and Threats
SZTAKI	Hungarian ERCIM partner of CWI
SYMM	W3C Synchronized Multimedia Working Group
TACAS	Tools and Algorithms for the Construction and Analysis of Systems
TASC	Transport Applications and Scientific Computing
TCS	Theoretical Computer Science
TGV	Train à Grande Vitesse (French high-speed train)
TI	Telematics Institute
TMR	Transport and Mobility of Researchers
TNO	Toegepast Natuurwetenschappelijk Onderzoek (Organisation for Applied Scientific Research)
TU	Technical University
TUD	Technische Universiteit Delft (Delft University of Technology)
TUE	Technische Universiteit Eindhoven (Eindhoven University of Technology)
UvA	Universiteit van Amsterdam (University of Amsterdam)
UU	Universiteit Utrecht (University of Utrecht)
VHDL	VHSIC Hardware Description Language
VHS	Verification and control of Hybrid Systems
VHSIC	Very High Speed Integrated Circuit
VLDB	Very Large Data Base
VOGIN	Vereniging van Online Gebruikers In Nederland (Union of online users in The Netherlands)
VSNU	Vereniging van Samenwerkende Nederlandse Universiteiten (Society of cooperating Dutch universities)
VU	Vrije Universiteit Amsterdam (Free University of Amsterdam)
W3C	World Wide Web Consortium
WIAS	Weierstraß Institute for Applied Analysis and Stochastics
WL	Waterloopkundig Laboratorium (Delft Hydraulics)
WINST	Wiskunde en informatica: Samenwerkingsthema's (Cooperation themes on mathematics and computer science)
WTCW	Wetenschappelijk Technologie Centrum Watergraafsmeer (Science and Technology centre in which CWI is located)
WWW	World Wide Web
XELION	Delft Software Agency selling CWI software (GKS)
XML	Extended Markup Language
ZAMM	Zeitschrift für Angewandte Mathematik und Mechanik
ZAMP	Zeitschrift für Angewandte Mathematik und Physik