CWI

Centrum voor Wiskunde en Informatica

ANNUAL REPORT

'93

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CWI is the National Research Institute for Mathematics and Computer Science. CWI is part of the Stichting Mathematisch Centrum (SMC), the Dutch foundation for promotion of mathematics and computer science and their applications. SMC is sponsored by the Netherlands Organization for Scientific Research (NWO). CWI is a member of ERCIM, the European Research Consortium for Informatics and Mathematics.

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This Annual Report is complementary to the Jaarverslag SMC (in Dutch), which concentrates on SMC's National Activities in Mathematics. A complete overview of CWI's research activities, as well as SMC's Financial and Social Reports (in Dutch), are also available.

INTRODUCTION

Strategy

CWI's core strategic activity in the report year was to act on and realise the principles set down in the 1992 policy document *Towards New Equilibria: MOBILE.* This document deals with CWI's position and policies vis-a-vis both national and international developments. Given the positioning of CWI as a fundamental research institute with a high public profile, applicability of research and knowledge transfer is central to CWI's strategic thinking. Hence, we increasingly seek to conduct our research and related activities in cooperation with other actors in the research and development process, e.g., applied research institutes. In the domestic marketplace we are intensifying acquisition of contract research projects. Here the large technological institutes can play an important role as interface between fundamental research and concrete applications. In the wider arena, back in 1988 CWI co-founded the European Research Consortium for Informatics and Mathematics (ERCIM). Now, ERCIM membership is an increasingly valuable means to benefit from international programmes such as Human Capital and Mobility (EU), the INTAS support programmes for the former Soviet Republics, and - in the near future - Real World Computing (Japan) and ERCIM's own initiative, EDGE (European Distributed Generic Environment). When defining the thrust of CWI research we also anticipate the European Union's Fourth Framework Programme, which is due to start in 1994, with a special eye to its topics of information technology and its greater stress on applications and cluster forming.

The objectives in MOBILE were further detailed in SMC's plan for 1995-1999, which appeared in November 1993. Alongside its research institute CWI, SMC is also in charge of the National Activities in Mathematics programme (LAW) at Dutch universities. LAW is financed by the Netherlands Organisation for Scientific Research (NWO). CWI's research activities are now set out and fine-tuned in close liaison with LAW and, as far as the computer science section is concerned, with the Netherlands Computer Science Research Foundation (SION). The decision to limit and deepen CWI's strategic research areas has led to concentration on the following themes:

- Computer assisted mathematics
- Biomathematics and non-linear dynamics
- HPCN (High Performance Computing & Networking)
- Research at the interface between optimal control and computer science
- Computer intensive methods in stochastics
- Multiple computing agents
- Formal methods in software technology
- Data mining
- Multimedia

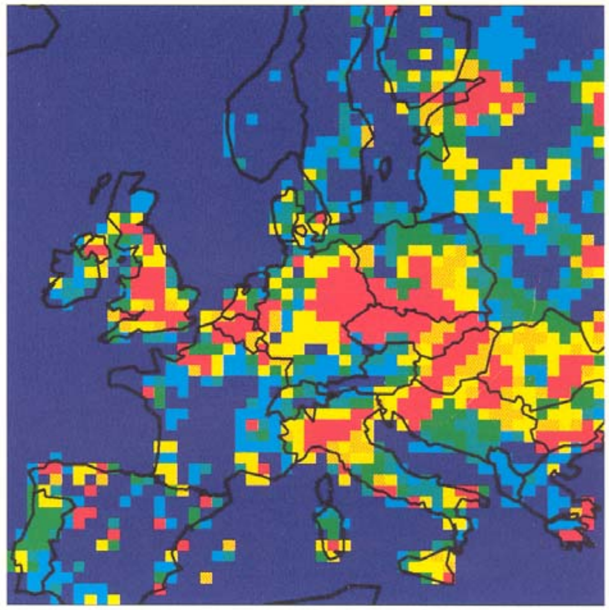
Strategic joint-project alliances with counterpart research institutes were among the visible indicators of CWI's new course during the report year. These included the *Interdisciplinary Centre for Complex Computer Facilities Amsterdam* (IC3A) with Amsterdam University, and the *Research Institute for the Applications of Computer Algebra* (RIACA) with the Netherlands Computer Algebra Foundation (CAN) and the Kurt Gödel School (formerly RISC-Linz, Austria). Similar links were established with a number of national research schools. Lastly, the report year saw the development of several important national initiatives in the fields of HPCN and MPR (Massively Parallel Computing), with CWI being a major contributor. We expect that in 1994 these initiatives will lead to concrete research projects involving CWI.

National and International Programmes

An important part of CWI research is conducted within national and international programmes. More than 70 projects were awarded external financing in 1993. The most striking development related to the SION foundation. Reinforcement of links with SMC went beyond the policy level (SION already proposes three of the present 12

SMC trustees, and CWI computer science research policy is also discussed and agreed with SION); as from 1992, research financed by SION has been open to proposals by CWI. This spectacularly increased CWI's participation in the foundation's projects, from 5 to 18 in 1993. Recent years have also seen NWO launch special programmes whereby research is organised on a larger scale than in the past; CWI is also involved here. Alongside its significant participation in the NWO programme *Non-linear Systems*, started in 1992, in 1993 CWI also commenced research as part of two LAW programmes, *Computer-intensive Methods in Stochastics* and *Algorithms in Algebra*. There was a steady rise in CWI involvement in projects of the Dutch Technical Sciences applications in 1992. Three STW projects were awarded to CWI in 1992, namely *Parameter Identification and Model Analysis for Non-linear Dynamic Systems, Parallel Codes for Circuit Analysis and Control Engineering* and ACELA *(Architecture of a Computer Environment for Lie Algebras)*. New applications were prepared in 1993.

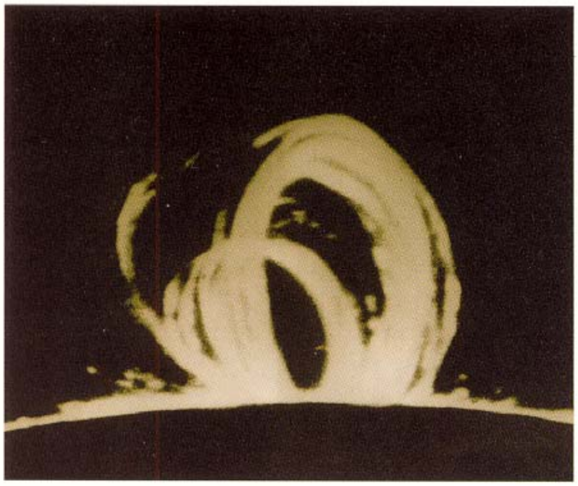
Over the next several years, HPCN/MPR will be an important research area for CWI. This subject melds perfectly with CWI's research profile; there are very many interesting fundamental problems here in both computer science and (numerical) mathematics. Furthermore, the multi-disciplinary angle offers broad potential for cooperative alliances. CWI complements its research activities by helping to build up a meaningful infrastructure; the two aspects of this are a network of researchers and a high-speed network for massive information exchange. In 1993 CWI's active commitment was evidenced by participation in a range of activities such as preparations for the NWO Priority Programme, *Massively Parallel Computing* (due to start in 1994), and the HPCN'93 European Conference, held in Amsterdam in May. Another important milestone in spring 1993, was the set-up of IC3A. This joint initiative by CWI and Amsterdam University has since been formalised in a cooperative agreement between the university and NWO. In a further joint activity, CWI and Utrecht University organised a series of symposia entitled *Massively Parallel Computing & Applications*; the first three were held in the second half of 1993. CWI is also involved in working out the national HPCN programme, which the government is financing with revenues from Holland's natural gas fields.

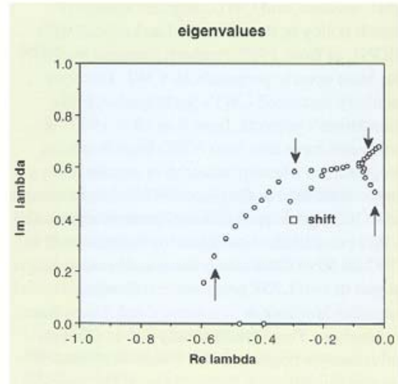


SO_2 air pollution on the European scale, indicated in colour (high-low concentrations correspond to red-blue). In a joint effort with RIVM, CWI's multi-disciplinary Mathematics & the Environment programme is developing new numerical algorithms for a European smog-prediction model.

Further, CWI and a number of industrial partners submitted a research proposal to the Dutch Government, as part of the Innovative Research Programme (IOP) *Distribution, Logistics and Transport.*

CWI's international activities also progressed. The year under review was notable for successes in the fields of mobility and communication. CWI - and in principle the entire Dutch research community - stands to benefit from ERCIM initiatives; these include fellowships part-funded by the European Union's Human Capital & Mobility (HCM) programme. In addition to being a direct recipient of HCM grants for eight Science & Technology Networks, CWI also coordinates two SCIENCE programmes, namely System Identification and Mask (Mathematical Structures in Semantics for Concurrency). The year under review was also notable for the award of five PECO projects, under the European Union's Central and Eastern Europe programme. CWI has a long and broad track record in European research programmes (see page 50), with ESPRIT featuring prominently. In 1992, the start of three new projects, Pythagoras (databases), MADE (multimedia) and CAFE (electronic payment) significantly broadened CWI's previous ESPRIT





(Photo National Solar Observatory, Sacramento Peak; courtesy J.P. Goedbloed, FOM-Institute of Plasmaphysics, Nieuwegein).

A flux loop in the solar corona, escaped from the photosphere. The study of macroscopic waves and instabilities in both thermo-nuclear confinement machines (e.g. tokamaks) and in astrophysical magnetic flux loops requires the large-scale parallel computation of internal eigenvalues of very large, sparse complex matrices. In this research CWI participates in a joint project of NWO's FOM Foundation and Utrecht University. The plot shows part of the internal Alfvén spectrum of magnetohydrodynamic plasma waves. The arrows point at four eigenvalues computed with a new iterative shift method suitable for implementation on massively parallel computers.

research focus on software technology. NeuroCOLT, a fourth new project added toward the end of 1993, involved an ESPRIT Basic Research working group for Neural and Computational Learning. Involvement in programmes like RACE, BRITE and LIBRARIES also contributes to CWI's excellent position in Europe.

Knowledge transfer, central role

Alongside pioneering research in mathematics and computer science, CWI's mission involves the transfer of new knowledge to the community at large and business and industry in particular. In recent years CWI has steadily reinforced the traditional knowledge transfer tools like publications, lectures and courses by making contacts with potential stakeholders, notably in the business community. Building on 1992's success, the second *CWI in the Market-place* presentation day was held in October. Participants heard and saw this year's theme, Technology Transfer, elaborated by players from the software sector, government, research, and the Federation of Netherlands Industry (respectively M.H. Slagmolen of FENIT, P.A.J. Tindemans of the Science and Education ministry, G. van Oortmerssen of CWI, and A.H.G. Rinnooy Kan of VNO). CWI staff also gave papers and demonstrations on their research work. The success and status of this CWI initiative is evidenced by the doubling of participants in 1993 to 120. Building on this good start, we plan a series of gatherings at which representatives of the software industry can present their problems to the scientific team here at CWI. In addition, a special team has been tasked with knowledge transfer in the field of software technology; these activities further improved contact with potential users of research during 1993.

The main ongoing contract projects in 1993 concerned traffic and transport (marshalling rolling stock, queueing problems at intersections and crossings, and control problems on motorways), software verification for chip technology, advanced research into 3D transport models and consultation on miscellaneous statistical subjects.

Obviously, knowledge transfer via conferences, workshops and courses continued as major CWI activity. Our researchers played a prominent role in four conference-type events during summer 1993. The first of these was a symposium to mark the end of the tén year REX programme (Research and Education in Concurrent Systems), appropriately named *REX – a Decade of Concurrency* (J.W. de Bakker). As with the previous six REX workshops, the proceedings were published in Springer Lecture Notes in Computer Science. The other three summer conferences, respectively the 22nd, 4th and 5th editions, were *SPA'93 – Stochastic Processes and their Applications* (A.J. Baddeley), *EMG'93 – European Multigrid Conference* (P.W. Hemker) and *Category Theory and Computer Science* (F.-J. de Vries). All were held in Amsterdam. June 1993 was an undisputed peak period for CWI's activities in stochastics. Hence, as part of LAW's Stochastics Theme Year, the SPA'93 conference on stochastic processes was complemented by a series of lectures on percolation theory at Utrecht University, Delft University of Technology and CWI. That same month, SMC started up special NWO-financed research into computer intensive methods in stochastics. CWI was also involved in the ERCIM course *Partial Differential Equations and Group Theory*, and two more conferences, namely *Typed Lambda Calculi and Applications*, and *The History of ALGOL68*; the latter recalled CWI's leading role in designing this influential programming language, a quarter century ago. One of the very first activities of SMC was the active transferred knowledge to secondary schools through a vacation course for mathematics teachers. The topic chosen for 1993 was *The Real Number*.

Alongside many articles in periodicals and conference reports, CWI researchers also wrote or jointly produced several books, including:

- *Computer Algebra in Industry – Problem Solving in Practice* (A.M. Cohen, editor)
- *Wavelets – an Elementary Treatment of Theory and Applications* (T.H. Koornwinder)
- *An Introduction to Kolmogorov Complexity and its Applications* (P.M.B. Vitányi & M. Li)
- *Morphological Image Operators* (H.J.A.M. Heijmans, to be published in 1994)
- *Topological Dynamics* (J. de Vries).

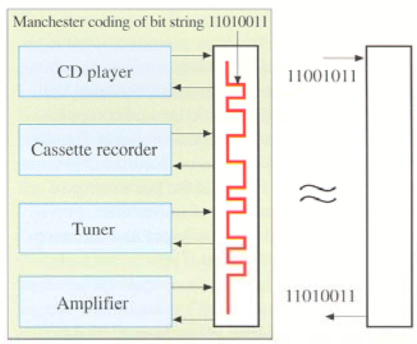
Another important aspect of our knowledge transfer work is the nurturing of a pool of scientific talent for the community at large. LAW projects are one aspect of SMC's close links with the academic community. Further evidence comes from the large numbers of CWI researchers with part-time professorships, and the 21 Ph.D.s granted to younger SMC research staff in 1993, 8 at CWI, and 13 within the framework of LAW.

Other research

Not all CWI research came under the umbrella of the programmes and topics outlined above. The selection below gives a good idea of depth and breadth of our work.

Symbolic manipulation

CWI has five research projects into various aspects of symbolic manipulation:



Fully fledged computer networks are standard features in today's consu-mer electronics, like this Philips 900 audio system. CWI has proved the correctness of part of the Easylink real-time protocol used for the system's intercommunication.

Photo courtesy n.v. Philips Industrial Activities Leuven.

- Uniform ways of manipulation with mathematical and non- mathematical expressions on a computer (SION project MathViews);
- Architecture of a computer environment for Lie algebras (STW project ACELA);
- Interfaces and linkage between computer algebra, automatic proof theory and term rewrite systems (SION/SMC joint project WINST);
- A knowledge package for link and knot invariants based on Hopf algebras (SMC Special Attention Area AIDA – Algorithms in Algebra);
- Interactive versions of large mathematical knowledge packages, e.g., the Encyclopaedia of Mathematics (KAP, 1988-1994) and the Handbook of Algebra (Elsevier, 1994- ...) (Chart & Web of Mathematics).

CWI is also involved in the activities of CAN and RIACA.

Dynamic Systems Laboratory
CWI hosts and runs the Dynamic Systems Laboratory. This melds knowledge and computer facilities into an interdisciplinary centre for services and research focused on non-linear systems. Activities in 1993 included the positioning of workstations at a number of universities, provision of special software packages and the reception of guest researchers at CWI.

Epidemiology
Models developed by CWI were used by the Netherlands Central Veterinary Institute in Lelystad to deal with the spread of disease in pigs. Now this joint effort is to be followed up with similar research into epidemics among the seal population around Holland's North Sea Islands.

Operations research, statistics, system theory
After a short lull, contract and consultation activities grew apace in 1993. The main areas involved were traffic & transportation and statistics. The efforts devoted to the training of young researchers in the past several years produced a crop of three Ph.D.s in 1993 (M.C.J. van Pul: Statistical Analysis of Software Reliability Models; B. Veltman: Multiprocessor Scheduling with Communication Delays; and P. Wartenhorst: Performance Analysis of Repairable Systems). A further six are expected next year, three in the Image Analysis group.

Pan-European numerical research
CWI is active in numerical mathematics research projects across a broad European front. The report year saw the start of research activities as part of four different European programmes: PEPS – Performance Evaluation of Parallel Systems (ESPRIT), AERO II – Solution adaptive Navier-Stokes solvers using multidimensional upwind schemes and multigrid acceleration (BRITE/EURAM), NOWESP – North-West European Shelf Programme (MAST), and Equations of Fluid Mechanics and Related Topics (HCM).

Mathematics and the Environment
This multi-disciplinary project got up full steam in 1993. CWI's involvement is partly on a contract basis. We work jointly with a number of leading Dutch bodies: the Institute of Public Health and Environmental Protection, the Public Works department, the Central Veterinary Institute, the Royal Meteorological Institute, Delft Hydraulics, the Informatics Centre for Infrastructure and the Environment, Utrecht University and Delft University of Technology. The research covers a broad range of disciplines including biomathematics, system theory, statistics, numerical mathematics and algorithmics (high performance computing and computational fluid dynamics in particular).

Programming environments
GIPE came to an end in 1993; the initials stand for Generation of Interactive Programming Environments. CWI and six European partners had been involved in this ESPRIT project for almost ten years. Work is presently underway on detailing the meta-environment for interactive development of programming languages and application languages which arose during the period of GIPE.

Data Mining
Using only the routine management systems, it can be difficult to retrieve strategic information held in modern databases. To this end CWI has commenced research into data mining techniques; this work combines elements of database theory, statistics and learning machines.

Software specification and verification
CWI researchers actively seek meaningful techniques to specify and verify programs for distributed and concurrent computer systems. Most of this work comes under the European Union's

ESPRIT and RACE programmes. The techniques are based on process algebras (an area where CWI has made important theoretical contributions), and also increasingly on program invariants (jointly with MIT). The expansion of these techniques into real-time systems is now bringing industrial applications within reach (audio equipment, process controllers, etc.).

CAFE

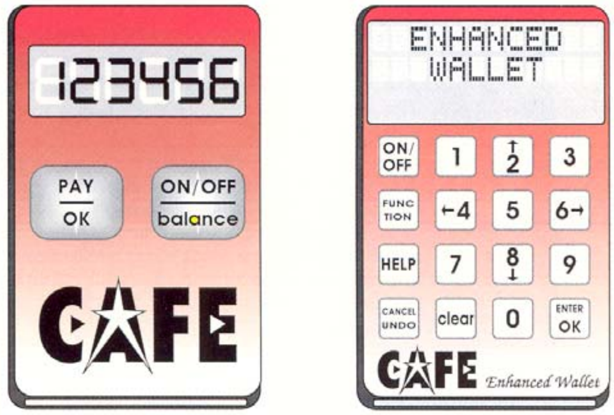
CWI coordinates this ESPRIT project. The objective of CAFE (Conditional Access for Europe) is to give Europe an open and secure electronic payment system, with potential for expansion including the use of personal attributes like passports and house keys. The system will be based on public-key cryptographic techniques. As planned, the first year was mainly devoted to system design and consumer surveys.

FraCaS

The EU's Linguistic Research and Engineering (LRE) programme contributes to the solution of language problems within the European Union via development of a basic language technology for computer applications, with natural language playing an essential role. Starting in 1994, CWI's Logic and Language group will take part in LRE's FraCaS project (a Framework for Computational Semantics).

Multiple Computing Agents

A priority area of CWI research is the study of cooperative parallel processes to describe natural

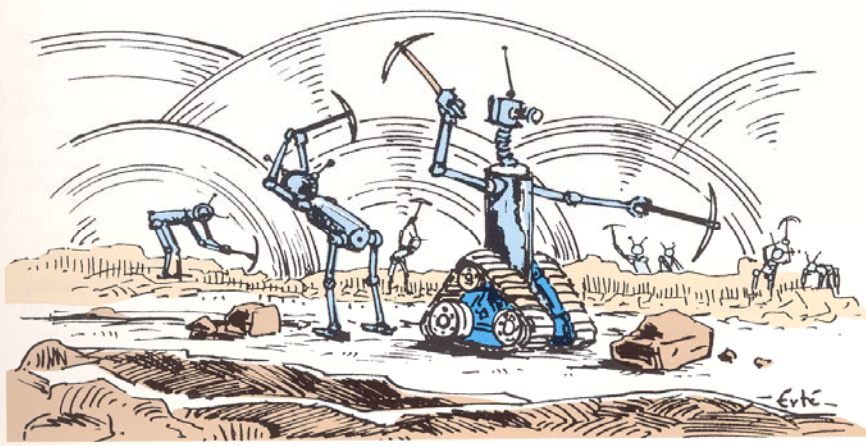


Two possible realisations of the electronic wallet, under development in the ESPRIT project CAFE, coordinated by CWI.

systems with an inherent parallel character, like flow phenomena. Examples of such processes are cellular automata, artificial neural networks, genetic algorithms and autonomous databases. In 1993 this CWI research received a powerful boost with the award of no less than three SION projects, namely Computational Learning Theory, MDL Neuro Computing and Design Theory for Autonomous Databases.

Computational Steering

Visualisation of data is presently the subject of intensive development as an aid to scientific research. The focus at CWI is on 'computational steering', a method which integrates input, simulation and visualisation of output in a single sys-



Data mining.

tem; this makes for fast visibility of the effect on the output of changes in input. A key concept here is 'navigation', the planned realisation of a goal, e.g. finding a local maximum of a function. This is a joint project with the Dutch Energy Research Institute ECN.

MADE

European industry urgently needs a uniform approach to multimedia basis software. MADE stands for Multimedia Application Development Environment; research in this large-scale ESPRIT project is directed towards an object-oriented software basis for multimedia applications and the provision of programming tools for the users. MADE is led by Groupe Bull of France, with CWI as its main partner. Bull and CWI will jointly build the complete software basis and provide the tools and techniques for integrated multimedia objects. CWI is also responsible for developing the basic object model and modelling the database interface.

MAGUS/FERSA

A pair of two-year projects financed by the Dutch Economics ministry as part of its RTD programme PBTS were brought to a close in 1993. These were MAGUS – Management Games Utilities Support (jointly with Lasermedia B.V.), and FERSA – Facial Expression Recognition as a driver for lip-Synchronous Animation (jointly with the Valkieser Groep). FERSA is described in more detail in this annual report.

ERCIM

In 1993 the European Research Consortium for Informatics and Mathematics (ERCIM), could look back with some satisfaction on its first five years in operation. Set up in 1988 by GMD (Germany), INRIA (France) and CWI, membership of the consortium rose to eleven with the admission of AEDIMA (Spain) and VTT (Finland) in 1993. ERCIM presently represents almost 5,000 researchers, making it a player to be reckoned with in the European research scene.

From its inception, ERCIM has promoted greater mobility for researchers in Europe. ERCIM fellowship activities, backed by the EU's Human Capital & Mobility (HCM) programme, grow apace with new members; eleven fellowship places are now available for the 1994/95 round. In addition ECU 0.5 million in HCM grants went to a pair of ERCIM Networks on Computer Graphics and Databases. ERCIM also started up its own internal mobility project.

High Performance Computing & Networking (HPCN) is a priority field for ERCIM, and in 1993 the consortium responded to the European Union's Rubbia report on this subject. Furthermore, the first of a series of annual ERCIM conferences dealt with the theme of Affordable Parallel Processing (the next theme will be Electronic Publishing). This conference led to the set-up of an ERCIM Parallel Processing Network, with participation of small and medium-sized enterprises from across Europe.

Finally, in 1993 ERCIM devoted considerable time and effort to preparation for EDGE, a large-scale initiative to realise a distributed environment leading to Europe-wide availability of generic technologies in the form of IT tools for six sectors: the processing, footwear, electronic parts and automotive industries, and tourism and culture.

Communication

The burgeoning communication factor in research and related activities is spurred by the fast pace of technical advances. CWI's early awareness is evidenced by a range of activities during 1993. Hence, the SMC library made good progress in electronic access. Three achievements by the library were: realisation of world-wide, on-line availability of a catalogue, and other information through Telnet, WWW and Gopher; the enabling of literature research via CD-ROM (alongside the traditional searching of external databases); and use of ftp to obtain and supply scientific reports. In so doing the library responded to - and partly anticipated - recommendations by the governmental Advisory Committee on Mathematics. The SMC library also takes part in the European Union's RIDDLE project (Rapid Information Display and Dissemination in a Library Environment) and has an ongoing involvement in development of electronic periodicals.

Looking ahead over the next two years, CWI has secured almost NLG 6 million in NWO funding for the build-up of a high-speed network (ATM) for massive information exchange. This is becoming essential in more and more scientific research and is particularly significant for CWI's spearhead work on HPCN/MPR.

Whatever the contributions made by technology, communication is still a human activity. In a living, dynamic organisation like CWI this is something none of us can afford to forget. We are fortunate to have a team of people here who are aware of this and who make a deliberate shared contribution to the fine working atmosphere. Indeed, this is a prerequisite for excellent scientific research.

G. van Oortmerssen, Managing Director

P.C. Baayen, Scientific Director

ORGANIZATION

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 operates within the auspices of the Netherlands Organization for Scientific Research (NWO), the main source of funding.

The organizational structure of SMC and CWI is shown on the opposite page. CWI's mission is twofold:
- to perform frontier research in mathematics and computer science;
- to transfer new knowledge in these fields to society in general, and trade and industry in particular.

CWI's research is carried out in six scientific departments. There is considerable interdepartmental collaboration, for example in the ongoing multidisciplinary programmes *Mathematics & the Environment* and *Multimedia*. Researchers at CWI are supported by state-of-the-art computer facilities and a well equipped library of national importance and, hence, ideally prepared to handle the dynamic and interdisciplinary demands of present day research.

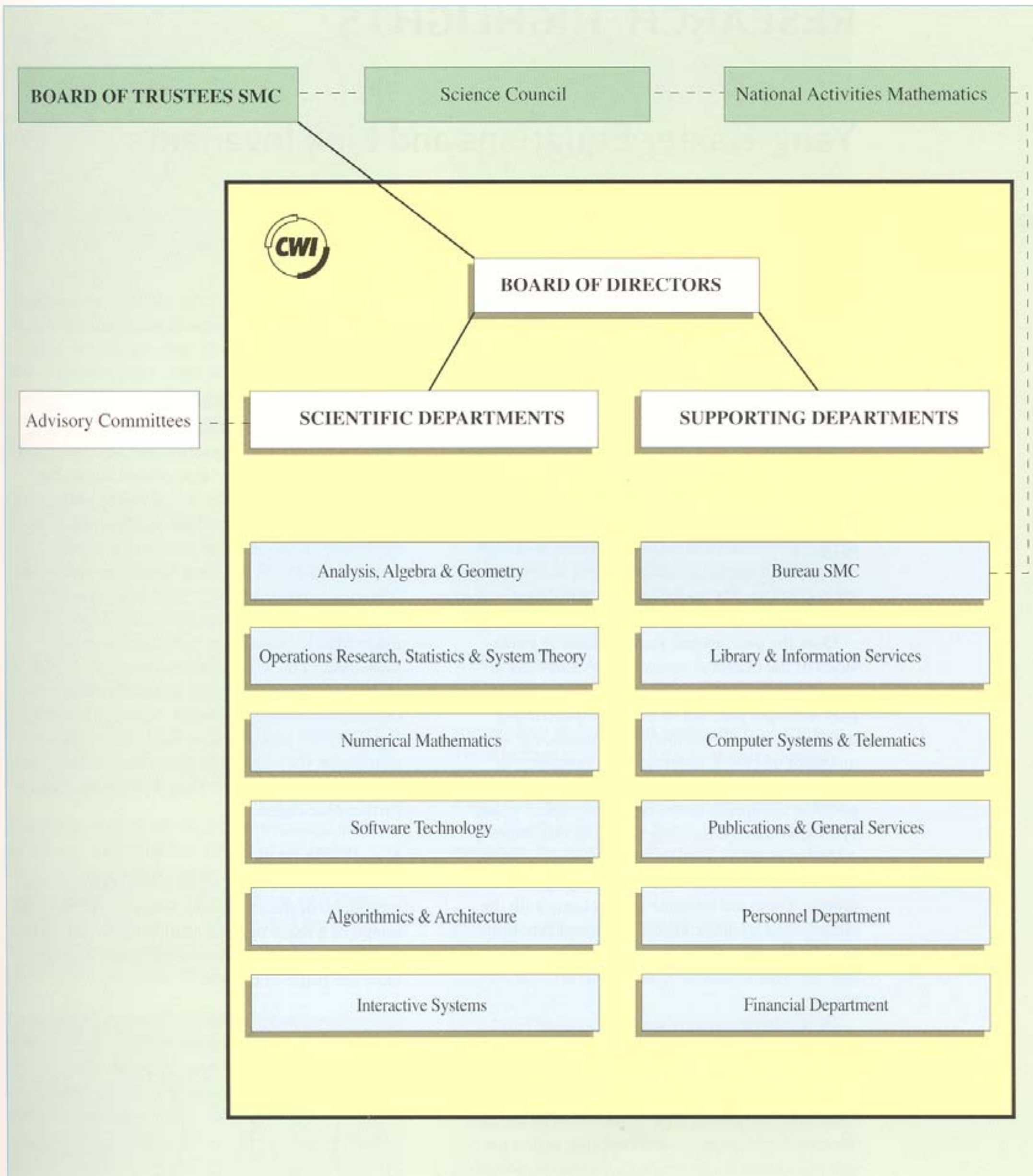
SMC also finances National Activities in Mathematics at Dutch Universities. This research is organized in eight national working parties in the following fields:
- Numerical mathematics
- Stochastic mathematics
- Discrete mathematics
- Operations research and system theory
- Analysis
- Algebra and geometry
- Logic and foundations of mathematics
- Mathematical physics.

In addition, SMC also supports the national working party on History and Social Function of Mathematics.

Anticipating NWO's policy of concentration of financial support on large-scale research programmes, SMC introduced two new types of activity in 1992; these were designated as Special Attention Areas and Special Years. Two new 'Areas' - *Algorithms in Algebra* and *Computationally intensive Methods in Stochastics* - were started during the year under review, and a third, *Algebraic Curves and Riemann Surfaces*, was approved. This now gives SMC a total of five Special Attention Areas. The 1993 Special Year Theme was devoted to *Stochastics*. All these activities, National Working Parties, Special Attention Areas and Special Years, involve a total of almost sixty projects.

SMC is administered by a Board of Trustees. Actual management is delegated to the Board of Directors of SMC, which is also responsible for CWI. The Netherlands Computer Science Research Foundation (SION) has a twofold formal connection with SMC: SION proposes three members of the Board of Trustees and advises SMC about CWI's research programme in computer science. The Dutch mathematics community is, since the end of 1993, structurally represented in the Board of Trustees by three members appointed on the recommendation of the section Mathematics of the Royal Netherlands Academy of Science.

In the year under review NWO implemented a change of policy with respect to the foundations under its umbrella. This related to the foundations' functions of financing projects, reviewing research proposals and acting as a platform. SMC responded by creating a small Science Council, to replace the Science Committee, on which all National Working Parties had been represented. The new Science Council could be much smaller as the National Working Parties are no longer involved in the reviewing process. The Science Council advises the Board of Trustees on matters of research policy and organization involving both the National Research Activities in Mathematics and CWI. The Science Council consists of five researchers from universities and CWI. A number of Advisory Committees make recommendations to CWI scientific departments on implementing research plans.



Organizational chart: the Stichting Mathematisch Centrum SMC and its research institute CWI.

RESEARCH HIGHLIGHTS

Yang-Baxter Equations and Link Invariants

Research Programme	:	Algebra, discrete mathematics and computer algebra
Researcher	:	M. Hazewinkel
E-mail	:	mich@cwi.nl

Introduction

The notion of symmetry is a key concept in mathematics and physics. Traditionally we associate with every symmetry a group of transformations (e.g., reflections, rotations) which leave an object possessing this symmetry invariant. These underlying symmetry groups, of which Lie groups represent an important instance, are of fundamental importance for understanding and describing a wide range of natural phenomena.

Over the past several years interest in extensions of the classical symmetry concept has increased considerably. Such extensions seem to play an important, but as yet very imperfectly understood role in various phenomena, e.g., in quantum inverse scattering. The discovery of quasi crystals exhibiting a symmetry which is impossible according to the crystallographic group symmetry theory, has only added to this interest. A quantum group is such an extension (or deformation) of the Lie algebra belonging to a Lie group. There are intimate connections with the already much earlier known q-special functions as deformations of the special functions associated with the classical equations of mathematical physics.

Of particular interest are the so-called Hopf algebras (of which quantum groups are a special case), related to the q-special functions as Lie algebras are related to the ordinary special functions. Hopf algebras arise from solutions of the Yang-Baxter equations and probably play a pivotal role there as a generalized symmetry group. These braid-like equations arose independently in the context of quantum field theory (C.N. Yang) and soluble Ising-models in statistical mechanics (R.J. Baxter). Since then they gained importance in a multitude of fields in mathematics and physics, including knot and link theory, (quantum) integrable systems and Von Neumann algebras. For example, in quantum integrable systems the integrability is ensured by such a generalized symmetry (Hopf algebra), whereas symmetry in the usual group sense is absent.

All solutions of the Yang-Baxter equations satisfying a certain condition have been described at CWI. In addition, those solutions which are extendible to define link invariants were also identified. The study of these invariants is still underway. Link and braid invariants are of pre-eminent importance in fields including topology (knot theory) and quantum field theory. In the remainder, the relation between link and knot theory and solutions of the Yang-Baxter equations is further elucidated.

Knots and links

A knot is the image of a piece-wise linear diffeomorphism of the circle into 3-space. A link is the image of a finite number of disjoint circles under a piece-wise linear diffeomorphism to 3-space. Here are some examples:

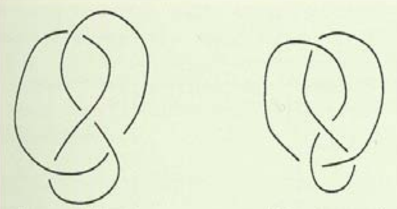
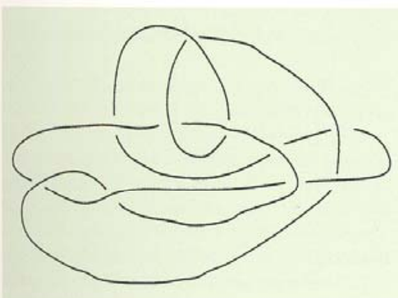


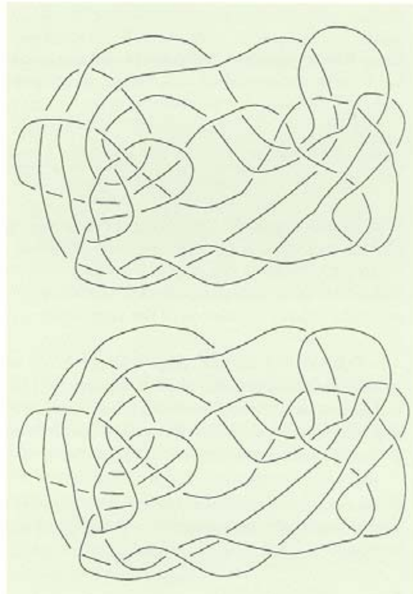
Figure eight knot   Mirror image of Figure eight knot

Two knots or links are considered equivalent, if one can be changed continuously into the other, without cutting and glueing (ambient isotopy). This is precisely the intuitive idea of the equivalence of two knots. For instance, the following knot is equivalent to a simple circle in 3-space (the 'unknot').



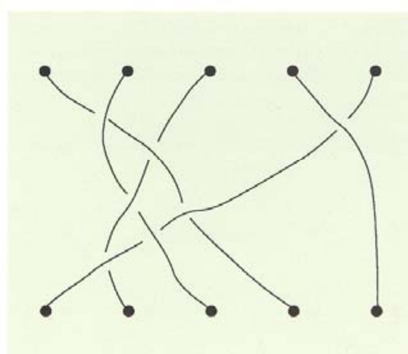
The figure eight knot and its mirror image are equivalent, but the mirror image of the trefoil knot is not equivalent to the trefoil itself. The example below (due to Tietze) shows two knots; one of these is trivial, the other not. They differ in only one spot, where an overcrossing has been changed into an undercrossing.

Examples like these indicate the need for algorithmically computable objects (knot and link invariants) which are the same for equivalent knots and links and which, ideally, distinguish between different knots and links. Whether this ideal can be realized is still an open question. However, in the last few years a number of most striking new invariants have been discovered, notably the so-called Jones and Kauffman polynomials. Both of these arise from solutions of the Yang-Baxter equations.



The braid group

A braid on m strings (strands) is formed as follows. Take m points on a line in an upper horizontal plane and m points vertically below it in a lower horizontal plane. Attach strands connecting each upper point to some lower point in such a way that each horizontal plane between the two (including the upper and lower plane themselves) intersects the strands in precisely m points. Here is an example of a braid on five strands:



Yang-Baxter equations, R-matrices and quantum algebras

Let V be an n-dimensional vector space, and R an endomorphism $R : V \otimes V \rightarrow V \otimes V$ i.e. after choosing a basis in V, R is an $n^2 \times n^2$ matrix with coefficients in the base field. For each $i = 1, \ldots, m-1$ let

$$R_i = \underbrace{\mathrm{id}_V \otimes \ldots \otimes \mathrm{id}_V}_{i-1 \text{ factors}} \otimes R \otimes \underbrace{\mathrm{id}_V \otimes \ldots \otimes \mathrm{id}_V}_{m-i-1 \text{ factors}} : V^{\otimes m} \rightarrow V^{\otimes m}$$

With these notations the Yang-Baxter (Y-B) equations are: $R_1 R_2 R_1 = R_2 R_1 R_2$, which written out in terms of the entries of R, $R = \left(r_{cd}^{ab}\right)$, yields n^6 equations in n^4 variables. Hence, apart from trivial ones (all entries identically zero), one does not a priori expect many solutions. Most interest is in invertible solutions, of which there are in fact many; they are virtually all closely related to semi-simple Lie algebras and associated or similar objects. A solution of the Yang-Baxter equations (Y-B solution) is often called an R-matrix.

A bi-algebra (over, say, the complex numbers) is a vector space with an algebra structure (an associative composition structure) and a co-algebra structure (a co-associative decomposition structure) which are compatible in a natural way. Examples are the group algebras of groups and in this way bi-algebras, and in particular Hopf algebras (bi-algebras with an additional structure corresponding to inverses in groups), embody a more general idea of symmetry than can be handled with groups.

Given any $n^2 \times n^2$ matrix R one can associate to it a bi-algebra as follows. Consider the free associative algebra in n^2 indeterminates $k\langle t \rangle = k\langle t_1^1, t_2^1, \cdots, t_n^1; t_1^2, t_2^2, \cdots, t_n^2; \cdots; t_1^n, t_2^n, \cdots, t_n^n \rangle$. Now consider the expression

$$(*) \qquad RT_1T_2 - T_2T_1R$$

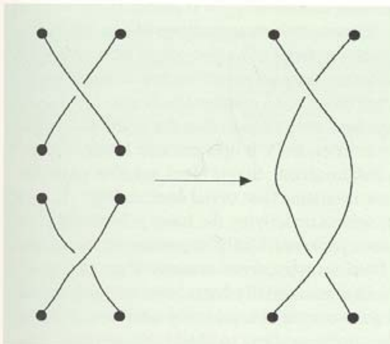
where T is the $n \times n$ matrix of indeterminates

$$\begin{bmatrix} t_1^1 & \cdots & t_n^1 \\ \vdots & & \vdots \\ t_1^n & \cdots & t_n^n \end{bmatrix}, \quad T_1 = T \otimes Id, \ T_2 = Id \otimes T$$

(so that T_1 and T_2 are also $n^2 \times n^2$ matrices). Let $I(R)$ be the ideal in $k\langle t \rangle$ generated by the n^4 entries of (*). Then the quotient algebra $H_n(R) = k\langle t \rangle / I(R)$ always has a natural bi-algebra structure under the standard matrix co-multiplication (the decomposition structure) $t_j^i \mapsto t_\alpha^i \otimes t_j^\alpha$ (where the Einstein summation convention is in force).

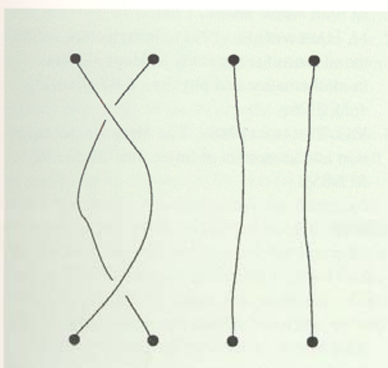
For certain special (and by now relatively well known) R-matrices, which are Y-B solutions, one thus finds quantum groups corresponding to the simple classical Lie algebras. More generally, a Y-B solution tends to yield very nice bi-algebras, including Hopf algebras. In fact it is precisely the relation (*) which makes the so-called quantum inverse scattering method (due to L.D. Faddeev and his school) work. More details on the above issues are given in Ref. 2.

It is easy to compose braids: identify the lower plane of one braid on m strands with the upper plane of another on the same number of strands. This gives a new braid on the same number of strands. The example below shows the composition of two braids.

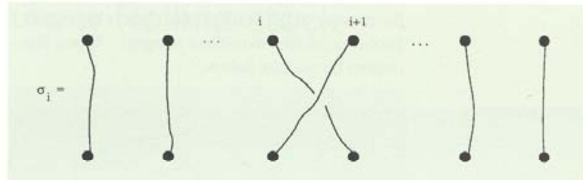


Two braids are equivalent if they can be deformed into each other by an ambient isotopy (as in the case of knots or links) while keeping the end points fixed and without the strands passing out of the area bounded by the horizontal and vertical plane. Non-uniform stretching or shrinking is also allowed, i.e., moving the two bounding planes and/or the endpoints on the upper and lower line further apart or closer together.

The trivial braid on m strands consists of (the equivalence class of) m strands dropping straight down. For instance, the two braids below are equivalent; the right one is the trivial braid.



The braids on m strands form a group, called the Artin braid group B_m. Consider the following elementary braids on m strands:

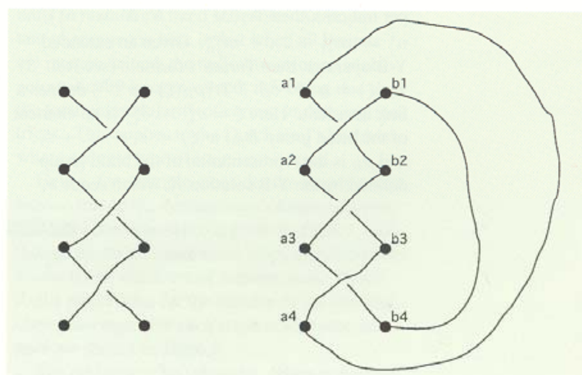


It is now easy to see that each braid on m strands is equivalent to one composed of the elementary braids $\sigma_1, \ldots, \sigma_{m-1}; \sigma_1^{-1}, \ldots, \sigma_{m-1}^{-1}$ where the inverse elementary braids are exactly like the elementary braids above, except that the strand from i to $i+1$ overcrosses the one from $i+1$ to i. Much harder is Artin's theorem: the braid group on m strands is generated (as a group) by the elementary braids $\sigma_1, \ldots, \sigma_{m-1}$ subject to the relations

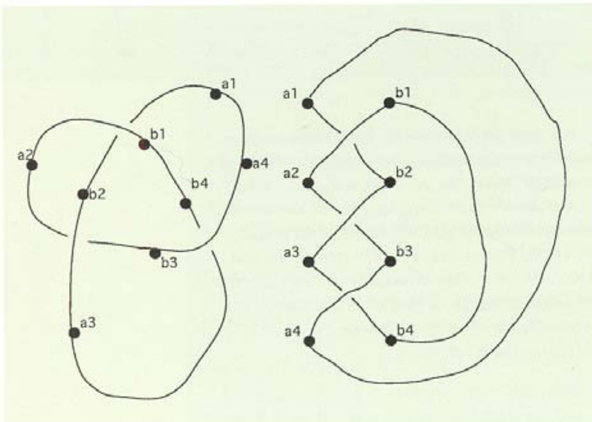
$$\sigma_i\sigma_{i+1}\sigma_i = \sigma_{i+1}\sigma_i\sigma_{i+1}, \quad i = 1, \ldots, m-1$$
$$\sigma_i\sigma_j = \sigma_j\sigma_i, \quad \text{if} \quad |i-j| > 1$$

Links and braids

Given a braid, it is easy to obtain a link or knot from it: simply connect the upper nodes with the lower nodes by non-intersecting curves. It does not matter how these curves go (left or right), as long as they do not intersect. The resulting links will be ambiently isotopic. The following picture illustrates the process.



Every link can be obtained as the closure of a braid (Alexander's theorem). It is not always easy to see whether two knots or links are equivalent, or to see whether the closure of a braid is equivalent to a given knot. As a matter of fact, the closure of the braid on the right is the trefoil knot (one of the two mirror images). To see this, inspect the picture below.



Link invariants from Y-B solutions

An extended Yang-Baxter operator is a quadruple (R, ν, α, β), where R is an invertible Y-B solution, and where ν is an $n \times n$ matrix, and α, β are invertible scalars, such that $\nu \times \nu$ commutes with R and $\mathrm{Tr}_2(R^{\pm 1} \circ (\nu \otimes \nu)) = \alpha^{\pm 1}\beta\nu$. Here, if $M = (m_{kl}^{ij})$ is an $n^2 \times n^2$ matrix (with the usual lexicographic ordering of lower and upper indices), then $\mathrm{Tr}_2(M) = N, N = (n_j^i)$, $n_j^i = m_{j1}^{i1} + \ldots + m_{jn}^{in}$. Given an extended Y-B operator, then Turaev's formula (see Ref. 3) $T_R(\xi) = \alpha^{-w(\xi)}\beta^{-m}\mathrm{Tr}(\rho_R(\xi) \circ \nu^{\otimes m})$ defines a link invariant. Here $\xi = \sigma_{i_1}^{\varepsilon_1} \ldots \sigma_{i_r}^{\varepsilon_r}$ is an element of the braid group B_m, $w(\xi) = \varepsilon_1 + \ldots + \varepsilon_r$, and ρ_R is the representation of the braid group defined by the Y-B solution R, which sends σ_i to R_i. The recent famous new link polynomials, such as the Jones and Kauffman polynomial, can be obtained from this construction.

Multi-parameter R-matrices

In Ref. 1, all solutions of the Y-B equations are described for which the matrix R satisfies the additional condition $r_{cd}^{ab} = 0$ unless $\{a, b\} = \{c, d\}$.

These solutions are built up of two types of blocks, a trivial and a non-trivial type, which can be interconnected in various non-trivial ways. Each block has a number attached to it; if these numbers are all equal, then the solution extends to an extended Y-B operator and, hence, defines a link invariant. Single block solution yields no new invariants (just trivial ones and the 'A_n-type' invariants underlying the Jones polynomial). However, non-trivially interconnected solutions of various types promise more. Even two trivial blocks, non-trivially interconnected, give interesting invariants. It is probably feasible to weaken the condition above to obtain similar results concerning 'B, C, D-type' solutions. Work in this direction is underway.

The single block non-trivial solutions (by the construction discussed in the Box) give precisely rise to the multi-parameter quantum groups of type A_n which have been constructed by several groups of authors in the last few years (see Ref. 1 for details).

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Minimum Circulation of Railway Rolling-stock

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Introduction

Nederlandse Spoorwegen N.V. (Dutch Rail) seeks to determine the minimum number of train-units they need to purchase in order to perform their time-table, whereby lower bounds are prescribed for the number of 1st and 2nd class seats per scheduled train. A train is taken to mean one or more coupled units, with the potential for a change of composition at certain intermediate stops. This can be described as a minimum-cost circulation problem, which is a special case of an integer linear programming problem. Classical network flow techniques can be used where there is just one type of rolling-stock, but the problem becomes more complicated with mixed configuration trains. To this end we apply techniques of *polyhedral combinatorics*.

Development of the field

The field of network flows and circulations goes back to a classic 1927 paper by K. Menger in which he characterizes a certain bifurcation number in topological spaces. In modern terms one can call this a formula for the maximum number of paths found in a network between two fixed points, where any of the two paths are disjoint (with the exception of the end points). This theorem acquired the status of a fundamental result in graph theory. In the 1950s, driven by the increasing interest in computations for transportation and other logistic problems, researchers at the RAND Corporation (the U.S. Air Force think tank in Santa Monica, California) focused on the following related *maximum flow* problem: 'Consider a rail network connecting two cities by way of a number of intermediate cities, where each link of the network has a number assigned to it representing its capacity. Assuming a steady state condition, find a maximal flow from one given city to the other.' It was observed that this question is a special case of a *linear programming* problem, and can hence be solved with the famous *simplex method* designed by G.B. Dantzig which forms the basis for the field of *operations research*.

At RAND, Ford and Fulkerson developed a direct method for the maximum flow problem and derived the *max-flow min-cut* theorem. This theorem states that the maximum amount of flow which can be transmitted is equal to the minimum capacity of any cut separating the source and the sink. It transpired that the theorem was equivalent to Menger's theorem. A similar technique can be used where there are lower bounds (demands) instead of upper bounds (capacities) and one seeks to *minimize* the total amount of flow. In 1957, Bartlett showed that this gives an algorithm for the minimum number of transport units to maintain a fixed schedule. An important phenomenon here is that when all bounds are integer-valued, the optimum solution is also automatically integer-valued; this being due to the total unimodularity of certain underlying matrices. This applies to the Dutch Rail's problem where a single type of train-unit is used.

Hence, for example, consider the hourly train service run on the Amsterdam-Vlissingen route. The weekday time-table is given in Table 1. Although the trains make more stops, the chart only shows those which are of interest to us. Dutch Rail's projections for the number of 1st and 2nd class passengers for each stage of any scheduled train are shown in Table 2.

The problem to be solved is: What is the min-

ride number		2123	2127	2131	2135	2139	2143	2147	2151	2155	2159	2163	2167	2171	2175	2179	2183	2187	2191
Amsterdam	V		6.48	7.55	8.56	9.56	10.56	11.56	12.56	13.56	14.56	15.56	16.56	17.56	18.56	19.56	20.56	21.56	22.56
Rotterdam	A		7.55	8.58	9.58	10.58	11.58	12.58	13.58	14.58	15.58	16.58	17.58	18.58	19.58	20.58	21.58	22.58	23.58
Rotterdam	V	7.00	8.01	9.02	10.03	11.02	12.03	13.02	14.02	15.02	16.00	17.01	18.01	19.02	20.02	21.02	22.02	23.02	
Roosendaal	A	7.40	8.41	9.41	10.43	11.41	12.41	13.41	14.41	15.41	16.43	17.43	18.42	19.41	20.41	21.41	22.41	23.54	
Roosendaal	V	7.43	8.43	9.43	10.45	11.43	12.43	13.43	14.43	15.43	16.45	17.45	18.44	19.43	20.43	21.43			
Vlissingen	A	8.38	9.38	10.38	11.38	12.38	13.38	14.38	15.38	16.38	17.40	18.40	19.39	20.38	21.38	22.38			

ride number		2108	2112	2116	2120	2124	2128	2132	2136	2140	2144	2148	2152	2156	2160	2164	2168	2172	2176
Vlissingen	V			5.30	6.54	7.56	8.56	9.56	10.56	11.56	12.56	13.56	14.56	15.56	16.56	17.56	18.56	19.55	
Roosendaal	A			6.35	7.48	8.50	9.50	10.50	11.50	12.50	13.50	14.50	15.50	16.50	17.50	18.50	19.50	20.49	
Roosendaal	V		5.29	6.43	7.52	8.53	9.53	10.53	11.53	12.53	13.53	14.53	15.53	16.53	17.53	18.53	19.53	20.52	21.53
Rotterdam	A		6.28	7.26	8.32	9.32	10.32	11.32	12.32	13.32	14.32	15.32	16.32	17.33	18.32	19.32	20.32	21.30	22.32
Rotterdam	V	5.31	6.29	7.32	8.35	9.34	10.34	11.34	12.34	13.35	14.35	15.34	16.34	17.35	18.34	19.34	20.35	21.32	22.34
Amsterdam	A	6.39	7.38	8.38	9.40	10.38	11.38	12.38	13.38	14.38	15.38	16.40	17.38	18.38	19.38	20.38	21.38	22.38	23.38

Table 1

Photo: NV Nederlandse Spoorwegen

Table 2

train number	2123	2127	2131	2135	2139	2143	2147	2151	2155	2159	2163	2167	2171	2175	2179	2183	2187	2191
Amsterdam-Rotterdam		47 340	100 616	61 407	41 336	31 282	46 287	42 297	33 292	39 378	84 527	109 616	78 563	44 320	28 184	21 161	28 190	10 123
Rotterdam-Roosendaal	4 58	35 272	52 396	41 364	26 240	25 221	27 252	27 267	28 287	52 497	113 749	98 594	51 395	29 254	22 165	13 130	8 77	
Roosendaal-Vlissingen	14 328	19 181	27 270	26 237	24 208	32 188	15 180	21 195	23 290	41 388	76 504	67 381	43 276	20 187	15 136			

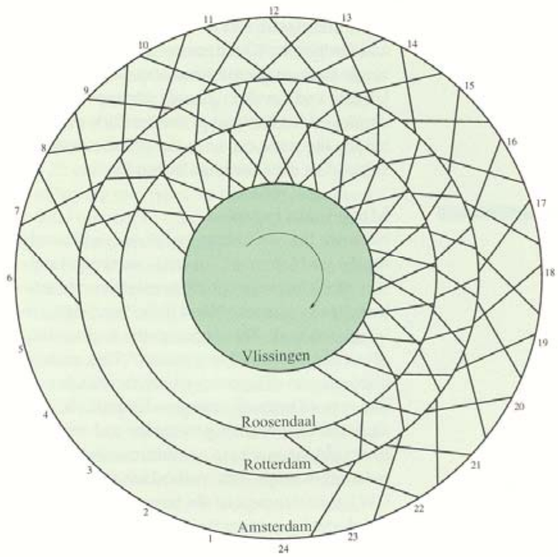
train number	2108	2112	2116	2120	2124	2128	2132	2136	2140	2144	2148	2152	2156	2160	2164	2168	2172	2176
Vlissingen-Roosendaal			28 138	100 448	48 449	57 436	24 224	19 177	19 184	17 181	19 165	22 225	39 332	30 309	19 164	15 142	11 121	
Roosendaal-Rotterdam		16 167	88 449	134 628	57 397	71 521	34 281	26 214	22 218	21 174	25 206	35 298	51 422	32 313	20 156	14 155	14 130	7 64
Rotterdam-Amsterdam	7 61	26 230	106 586	105 545	56 427	75 512	47 344	36 303	32 283	34 330	39 338	67 518	74 606	37 327	23 169	18 157	17 154	11 143

imum amount of rolling-stock needed to perform the service so that there are sufficient seats at each stage? In a first variant of the problem considered, the rolling-stock comprises a single type of two-way train-units, with three carriages each and 38 1st class and 163 2nd class seats per unit. There is a driver's cab at each end of the unit, and units can be coupled together, up to a maximum of 5 units. The train length can be changed by coupling or uncoupling units at the termini, i.e. Amsterdam and Vlissingen stations, and *en route* at two intermediate stations, Rotterdam and Roosendaal. Any train-unit uncoupled from a train arriving at location X at time t can be linked up to any other train departing from X at any time later than t. (The Amsterdam-Vlissingen schedule is such that in practice this gives enough time to make the necessary switches.) A last condition set is that logistical factors require that for each location $X \in \{$Amsterdam, Rotterdam, Roosendaal, Vlissingen$\}$, the number of train-units staying overnight at X must be constant during the week (but may vary for different locations). Only the number of units is important here and there is no need for the same train-unit after sojourning overnight at a given location, to return there at the end of the day.

Given these problem data and characteristics, the problem is to find the minimum number of train-units needed to perform the required daily cycle of train rides. The amount of reserve stock is not taken into account here, as this generally only amounts to a fixed percentual addition on top of the net minimum. To apply the network flow methods, a network N is constructed as follows. For each location $X \in \{$Amsterdam, Rotterdam, Roosendaal, Vlissingen$\}$ and for each time t at which any train leaves or arrives at X, we make a point (X, t). For any stage of any train journey, leaving place X at time t and arriving at place Y at time t', we make an arc directed from (X, t) to (Y, t'). For instance, there is an arc from (Roosendaal, 7.43) to (Vlissingen, 8.38). Moreover, for any location X and any two successive times t, t' at which any train leaves or arrives at X, we make an arc from (X, t) to (X, t'). Thus in our example there will be arcs, e.g., from (Rotterdam, 8.01) to (Rotterdam, 8.32), from (Rotterdam, 8.32) to (Rotterdam, 8.35), from (Vlissingen, 8.38) to (Vlissingen, 8.56), and from (Vlissingen, 8.56) to (Vlissingen, 9.38).

Finally, for each place X there will be an arc from (X, t) to (X, t'), where t is the last time of the day at which any train leaves or arrives at X and where t' is the first time of the day at which any train leaves or arrives at X. So there is an arc from (Roosendaal, 23.54) to (Roosendaal, 5.29).

We can now describe any possible routing of train stock as an integer-valued circulation that obeys, for any arc, a given lower bound (and an upper bound of 5). The number of units deployed is given by the the total flow on the four 'overnight' arcs, and this is the number that needs to be minimized. Having this model, we can now apply standard flow algorithms. Implementation gives solutions of the problem (for the above data) in about 0.05 CPUseconds on an SGI R4400. It turns out that 22 units are required for the Amsterdam-Vlissingen route. It is possible to modify and extend the model quite directly in order to contain several other problems. Instead of minimizing the number of train-units one can minimize the amount of carriage-kilometres to be travelled daily, or any linear combination of both quantities. One can also put an upper bound on the number of units that can be stored at any of the stations. Instead of considering just one line on its own, one can more generally consider *networks* of lines sharing the same railway rolling-stock, including trains which are scheduled for



Directed network (all arcs oriented clockwise) describing traffic flow on the Amsterdam - Vlissingen route.

splitting or combination. (Dutch Rail has trains from The Hague and Rotterdam to Leeuwarden and Groningen which are combined into one single train on the common trajectory between Utrecht and Zwolle.) If only one type of unit is employed for that part of the network, each unit having the same capacity, the problem can be solved fast even for large networks.

More train types

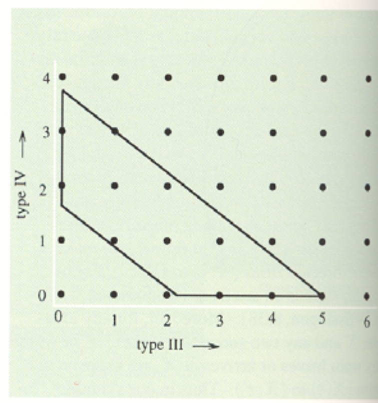
Network flow techniques work very efficiently for the problem of circulating one type of railway stock because optimum solutions are automatically integer-valued if the input data are integer-valued. This is due to the *total unimodularity* of the underlying matrix. This attractive phenomenon disappears where there is more than one type of mutually couple-able unit. In this situation the problem gets harder and we need to extend the model to a 'multi-commodity circulation' model. The method we developed at CWI uses elements of the powerful technique of *polyhedral combinatorics*. U.S. researchers have recently employed this technique to solve very large scale *traveling salesman* problems.

To return to the case Amsterdam-Vlissingen again, here we can now deploy two types of two-way train-units, which can be coupled together; these are type III, with each unit made up of three carriages, and type IV, with each unit comprising four carriages. Type III capacity is 38 1st class and 163 2nd class seats, and 65 and 218 respectively in type IV. Once again, there is a maximum of 15 carriages per train. Hence, if a train consists of x units of type III and y units of type IV, then $3x + 4y \leq 15$ should hold. It is quite easy to extend the above model to the present case. Again we consider the network N as above. We should now find *two* circulations f and g which together obey a given lower bound and which minimize a given cost function. Note that in contrast to the case of one type of unit, here there is no minimum number of units required for any train stage. In fact, there are now two dimensions, so that minimum train compositions need not be unique. The cost function depends on the cost of purchasing units of types III and IV. Although train-units of type IV are dearer than type III, they are cheaper per carriage, because of the relatively costly driver's compartment.

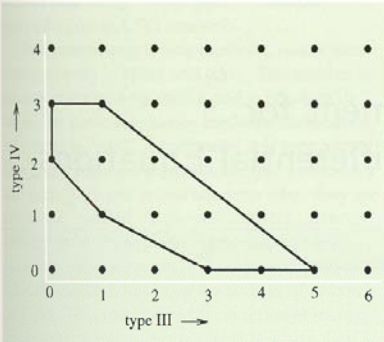
When solving this as a linear programming problem, we lose the pleasant phenomenon observed above whereby we would automatically obtain optimum circulations with *integer* values only. In fact, the problem is an integer linear programming problem, with 198 integer variables. Looking at the Amsterdam-Vlissingen case, solving the problem in this form with the integer programming package CPLEX would give a running time of several hours. This long running time is caused by the fact that, despite a fractional optimum solution being found quickly, a large number of possibilities has to be checked in a branching tree (corresponding to rounding fractional values up or down) before one finds an integer-valued optimum solution. However, there are ways of speeding up the process by sharpening the constraints and by exploiting more facilities offered by CPLEX. The lower bound conditions can be sharpened as follows. For each arc representing a stage, consider the set of integer-valued vectors (x, y) with the property that using x units of type III and y units of type IV yields sufficient seats for the corresponding train stage and does not mean a train with more than 15 carriages. For instance, the trajectory Rotterdam-Amsterdam of train 2132 gives the polygon

(1) $P = \{(x, y) | x \geq 0, y \geq 0, 3x + 4y \leq 15,$
$38x + 65y \geq 47, 163x + 218y \geq 344\}.$

In a picture:



In a sense, the inequalities are too wide. The constraints given in (1) could be tightened so as to describe exactly the convex hull of the integer vectors in the polygon P (the 'integer hull'), as in:



Thus for train 2132 on the segment Rotterdam-Amsterdam the constraints (1) can be sharpened to:

(2) $x \geq 0, y \geq 0, x + y \geq 2, x + 2y \geq 3,$
$y \leq 3, 3x + 4y \leq 5.$

Doing this for each of the polygons representing one of the 99 stages gives a sharper set of inequalities. This helps to obtain more easily an integer optimum solution from a fractional solution. (This is a weak form of application of the technique of *polyhedral combinatorics*.) Finding all these inequalities can be done in a pre-processing phase, and takes about 0.04 CPUseconds. Another ingredient that improves the performance of CPLEX when applied to this problem is to give it an order whereby the branch-and-bound procedure should select variables. In particular, one can give higher priority to variables that correspond to peak hours (as one may expect that they form the bottleneck in obtaining a minimum circulation), and lower priority to those corresponding to off-peak periods. Implementation of these techniques ensures that CPLEX gives a solution to the Amsterdam-Vlissingen problem in 1.58 CPUseconds. In total, one needs 7 units of type III and 12 units of type IV. So, comparing this solution with the solution for one type only (where 22 units of type III are needed), the possibility of having two types means both a decrease in the total number of train-units and in the total number of carriages needed.

As part of our research for Dutch Rail we also considered more extended problems requiring more complicated models and techniques. One requirement is that in any train journey between Amsterdam and Vlissingen, at least one unit should make the whole trip. A further requirement is the ability to couple or uncouple units from a train - but not both simultaneously - at any of the four stations involved, i.e., Amsterdam, Rotterdam, Roosendaal and Vlissingen. Moreover, fresh units may only be coupled onto the front of the train, and laid-off units may only be uncoupled from the rear. All this makes the order of the different units in a train a significant factor, and gives the conditions a more global impact: the order of the units on a given morning train can still influence the order of a given train that evening. This does not fit directly in the circulation model described above, and requires an extension. The method we have developed for Dutch Rail to date is based on introducing extra variables, extending the network described above and utilizing some heuristic arguments, which yields a running time (with CPLEX) of about 30 CPUseconds for the Amsterdam-Vlissingen problem.

Local Uniform Grid Refinement for Time-Dependent Partial Differential Equations

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Introduction

Numerous processes in nature are described by models containing time-dependent partial differential equations. One can simulate these processes by solving these equations. However, the complexity of the equations often demands that they are solved numerically. A numerical solution can be obtained by approximating the partial differential equations in some way on a set of discrete points in space and time, called a space-time grid. The accuracy of such an approximation is determined by the distances between the neighbouring grid points and the variation of the solution from point to point. The necessary computational effort to obtain the numerical solution depends on the number of points used. The local uniform grid refinement (LUGR) method is an adaptive grid method which aims to distribute grid points in such a way that an accurate approximation of the solution is obtained with the fewest possible points.

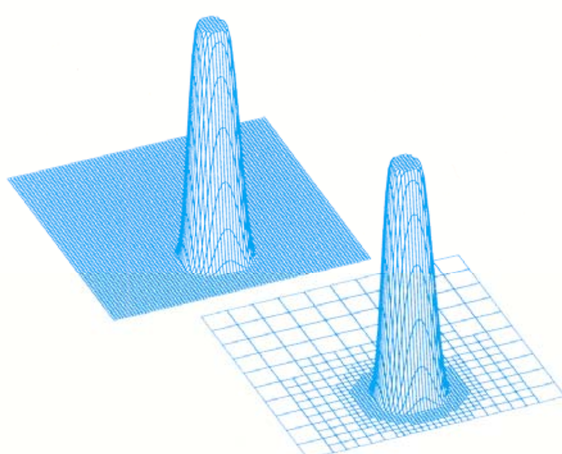

Figure 1. *The solution computed with a uniform grid (left) and an adaptive grid (right).*

Adaptive grid methods

Many time-dependent partial differential equations have solutions which vary rapidly in space and time. Partial differential equations arising from models describing shock hydrodynamics, transport in porous media, combustion processes and plasma physics and so on, can serve as an example in this respect. The accuracy of the approximate solution depends on the variation of the true solution from point to point. Loosely speaking, the larger the variations, the smaller the distances needed between neighbouring points to obtain accurate results. This means that when the variations get larger the grid needs to be finer.

When the variations of the solution in space are only locally large but small anywhere else, adaptive grid methods prove to be greatly beneficial; the reason being that in this type of situation, these methods seek accurate results with minimal computational effort, by using the fewest possible grid points. These methods adapt the distances between grid points to the local variations of the solution. Over the years, a large number of adaptive grid methods has been proposed for time-dependent problems. Two main categories of adaptive grid methods can be distinguished, namely, moving-grid or dynamic-regridding methods and static-regridding methods. There are also hybrid methods combining static and dynamic regridding. Both types of methods have played a part in CWI research.

In dynamic-regridding methods, points move continuously in space and time. The number of points contained by such a grid is constant in time. In static-regridding methods the location of points is fixed. A method of this type adapts the grid by adding points to the grid where they are necessary and removing them when they are no longer needed. This type includes methods which embed new points in the existing grid. Another method of the static-regridding type, the LUGR method, has been the subject of research at CWI. This method creates a series of increasingly finer local uniform subgrids where they are needed. To advance the solution in time from one time point to the next, the partial differential equations are solved separately for this time step at each grid. Instead of being embedded in the coarser grid, these finer grids overlay it.

The main advantage of static-regridding methods over moving-grid methods is that the former are more reliable than the latter. The main problem with moving grid methods is the lack of control over the grid movement which leads to the phenomenon of 'grid point crossing' in one space dimension and 'grid distortion' or 'grid skewness' in two or three space dimensions. This can considerably reduce the accuracy of the computations. A problem of this kind may be overcome by applying penalty functions which limit the grid motion. However, these penalty functions contain parameters which have to be chosen by the user, and the choice of the parameters, which may be critical, depends on the partial differential equations at hand. Static-regridding methods do not have this type of problem. Moreover, they only need a few user-defined parameters such as error tolerances, and in general the choice of such parameters is not critical. However, in contrast to static-regridding methods, moving-grid methods attempt to smooth the variations of the solution in the time direction; this allows larger time steps when the grid motion is sufficiently smooth. Finally, when working properly, moving-grid methods use fewer points than static-regridding methods for a given accuracy.

The LUGR method

CWI has researched this method for the past five years. The particular type of adaptive grid method emerged in the early 1980s. The idea behind LUGR is simple. Starting from a coarse base grid covering the whole region where the partial differential equations are defined, successively finer uniform subgrids are recursively created locally in a nested manner in regions where the variations are large, i.e. where the solution is steep. For each time step the partial differential equations are solved at each grid separately in a consecutive order, from coarse to fine. Hence, rather than being patched into the coarser grids, the local subgrids actually overlay them. A finer grid uses a time step which is smaller or equal to the coarser-grid time step. When a grid of a certain level of refinement has reached the same time level as a coarser grid, then the solution at the coarser grid is, in some way, updated by the more accurate solution at the finer grid, leading to a more accurate solution at the coarser grid. The location, shape and size of these subgrids are adjusted at discrete times to follow the movement of the region where the solution is steep. The generation of subgrids is continued until sufficient accuracy is reached at the finest subgrid.

The construction of these local subgrids is controlled by a refinement strategy which can be based on heuristic criteria like the slope or the curvature of the solution or error estimates. In general, a refinement strategy based on heuristic criteria is computationally cheaper than a strategy based on error estimates. However, a strategy based on error estimates can give more accurate results than a strategy based on heuristic error monitors. This is due to the fact that heuristic error monitors bear no relationship to the true numerical error. Because of this, the situation can arise whereby a strategy based on heuristics does not refine a grid cell which should be refined in view of the numerical error and vice versa. Therefore, a strategy based on error estimates can

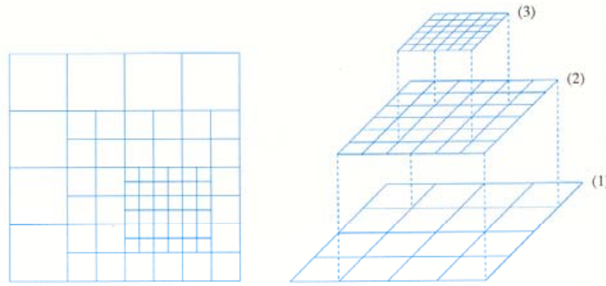

Figure 2. *The composite grid used in the LUGR method (left), and its component local uniform subgrids (right). During a single given time step the solution is computed first on (1), then on (2) and finally on (3).*

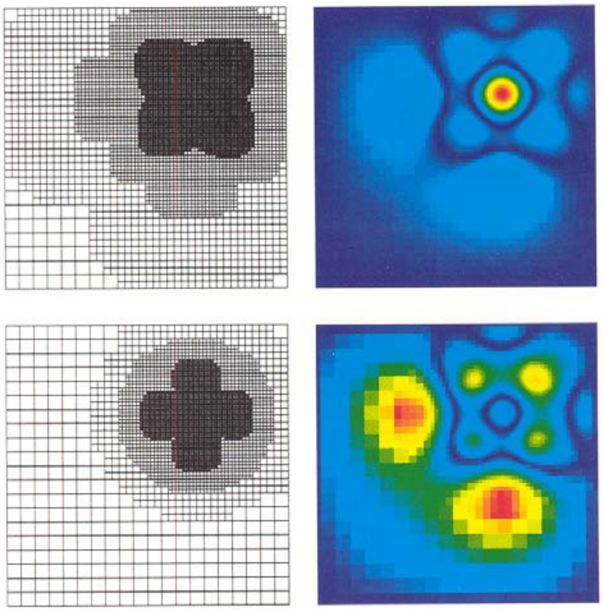

Figure 3. *The LUGR method applied to the description of a steep pulse rotating clockwise around the centre of the domain. The pictures above and below show the composite grid (left) and spatial error (right) for a refinement strategy based on error estimates (A) and error-monitor computations (B) respectively. Error size is indicated in colour (large errors red, small errors blue). In this case strategy A yields far better results, and smaller errors, than strategy B; moreover, with strategy A the largest errors occur in the region covered by the finest subgrid, contrary to the error-monitor case.*

generate better subgrids than a heuristic strategy. The research at CWI focused on the development of a LUGR method, together with a refinement strategy based on error estimates.

An error-estimate-based refinement strategy requires an error analysis. Error analyses were carried out for different kinds of partial differential equations and different time stepping schemes. In these analyses we were able to split the error up into its spatial and temporal parts; the reason being that certain kinds of partial differential equations were considered and that the 'method-of-lines' was used whereby the spatial approximation of the partial differential equations is carried out before the temporal approximation.

The LUGR method and the two different refinement strategies developed at CWI, aimed at the control of the spatial part of the error by the spatial refinement of the grid. The strategies are based on the control of the local space error and global space error respectively. The global space error is the spatial component of the error and the local space error is the local contribution to the global space error corresponding with one time step. Both strategies aim to control the global space error in some way. The most important difference between the two is that the global-space-error strategy is less restrictive than the local-space-error strategy, because it creates smaller local subgrids than the latter; this in turn makes it computationally cheaper. However, the local-error-based strategy is 'safer' and this strategy enabled theoretical results to be obtained which would not have been feasible via the global-error-based strategy.

A basic demand to be met by a refinement strategy is that the largest global space error must be in the region overlapped by the finest subgrid. If this is not the case then this finest subgrid becomes redundant in that it does not improve the accuracy of the solution, and the computational effort to compute the solution on this grid is wasted. Both strategies appear to fulfil this demand. Moreover, the results obtained indicated that when the number of subgrids is fixed in time, the obtained accuracy is approximately equal to the accuracy obtained with a single comparable uniform grid. This property could be proved for some model situations when the local-space-error refinement strategy is used.

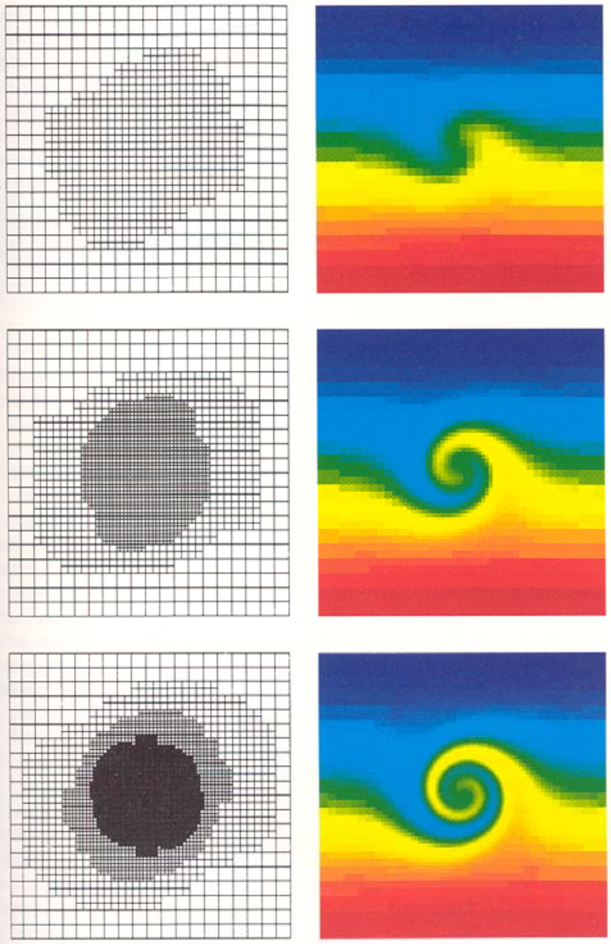

Figure 4. *The LUGR method applied to a simple model used in meteorology to describe the mixing of hot and cold air. The composite grid (left) and the temperature distribution (right) are shown at three successive times. Temperature is indicated in colour (hot-cold ≈ red-blue). The initially horizontal boundary layer separating cold and hot air is twisted by a steady rotational wind field resembling the cyclonic air motion at low pressure systems, as seen on the daily weather maps. As time proceeds the transitions from hot to cold become steeper and steeper and increasingly finer local subgrids are needed.*

Defining Formal Languages

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Introduction
During the past ten years, considerable progress has been made in solving the problems of automatic generation of interactive programming/development environments, given a formal definition of some programming language or specification language. In most cases, research has focused on the functionality and efficiency of the generated environments; indeed, these are the aspects which will ultimately determine the acceptance of environment generators. Even so, only marginal attention has been devoted to the actual development process of formal language definitions. Assuming that the quality of automatically generated environments will be satisfactory within a few years, the development costs of formal language definitions will then become the next limiting factor determining ultimate success and acceptance of environment generators. We will briefly sketch the design and implementation of a *meta-environment* (a development environment for formal language definitions) based on the formalism ASF+SDF and show some of its applications.

Background – CENTAUR **system**
A programming environment is a coherent set of interactive tools such as syntax-directed editors, debuggers, interpreters, code generators, and prettyprinters to be used during the construction of texts in the desired language. Automatic generation of programming environments has been used to generate environments for languages in different application areas including programming, formal specification, proof construction, text formatting, process control, and statistical analysis. All projects in this area are based on the assumption that major parts of the generated environment are language independent and that all language-dependent parts can be derived from a suitable language definition.

An example of such a general architecture is the CENTAUR system developed in the ESPRIT GIPE project in which CWI has participated. This is a set of generic components for building environment generators. The kernel provides a number of useful data types but does not make many assumptions about, for instance, the language definition formalism itself. It has been extended with compilers for various language definition subformalisms, as well as several interactive tools. CENTAUR thus resembles an extendible toolkit rather than a closed system.

Research at CWI – ASF+SDF **Meta-environment**
Our own contributions to the GIPE project are focused around the idea of constructing a development environment for formal language definitions. Our research went through three phases:
- Design of an integrated language definition formalism (ASF+SDF).
- Implementation of a generator which generates interactive programming/development environments given a language definition.
- Design and implementation of an interactive development environment for the ASF+SDF formalism itself.

The result is the *Meta-environment* mentioned in the introduction, in which language definitions can be edited, checked and compiled in precisely the same way that programs can be manipulated in a *generated environment*, i.e., an environment obtained by compiling a language definition; observe that 'compiling a language definition' and 'generating an environment' are synonymous in our terminology. Both the generator itself and the Meta-environment have been implemented on top of the CENTAUR system.

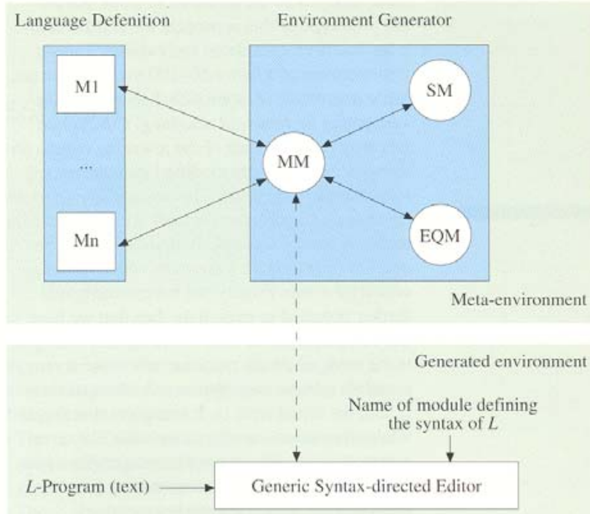
Figure 1 shows the overall organization of our system. First of all, we make a distinction between the *Meta-environment* and a *generated environment*. In the Meta-environment we distinguish:

- A language definition (in ASF+SDF) consisting of a set of modules $M_1, \ldots, M_n$.
- The environment generator itself, which consists of three components: a Module Manager (MM) controlling the overall processing of the modules in the language definition, the Syntax Manager (SM) controlling all syntactic aspects, and the Equation Manager (EQM), taking care of all semantic aspects

The output of the environment generator is used in conjunction with GSE (Generic Syntax-directed Editor), a generic building block which we use in generated environments. GSE not only supports text-oriented and syntax-oriented editing operations on programs but can also be extended by attaching 'external tools' which perform operations on the edited program, including checking and evaluation. The main inputs to the Generic Syntax-directed Editor are:

- A program text P
- The modules defining the syntax of P
- Connections with external tools.

As both the syntax description of P and the definition of external tools may be distributed over several modules, we are faced with the problem of managing several sets of syntax rules and equations simultaneously. One of the major contributions of the ASF+SDF Meta-environment is that the system is so interactive and responsive that users are completely unaware of the fact that each modification they make to their language definition has major impacts on the generated environment. So, for instance, the presence of a parser generator is completely invisible to the user. As a result, the system is also accessible to 'naive' users, who have no previous experience of using tools like scanner and parser generators. Important factors are: (1) an internal syntax tree representation ('term', see next section) and a prettyprinter for the language are derived automatically from the language definition; (2) after parsing, syntax trees are built automatically; (3)



GLOBAL ORGANIZATION

the generated scanner, parser, tree constructor and rewrite system are interfaced automatically. To summarize, several parts of the generated implementation are derived from the language definition, and the system takes care of the interfacing of *all* components of the generated environment.

Current research

Central to our approach is that we represent everything (i.e., programs and specifications being edited) as uniform tree structures which we call *terms*. All operations on programs - like checking and compiling - are expressed as operations on their underlying term representation. These operations have to be defined in the language definition and their execution is based on *term rewriting*. Given some initial term t_0, an attempt is made to apply a rule in the specification and transform the initial term into a new term t_1. This process is repeated until a term t_n is obtained, to which no further rule is applicable. This is the *normal form* that corresponds to the initial term t_0. Clearly, efficient term rewriting is essential to us; hence, we approach this problem from several angles. Firstly, by investigating how rewrite rules can be translated directly to C programs; this would enable elimination of much of the overhead of term rewriting (in particular the search for matching rules) by performing an extensive static analysis of the given set of rules. An initial prototype of this approach, the ASF2C compiler, has been completed and exhibits a speed improvement of a factor 50–100 over our current, more interpretative, approach. Secondly, by investigating *incremental rewriting*, a technique whereby previous runs of the rewriting engine on the same, or a slightly modified term are reused to avoid rewriting steps. This method is important for speeding up interactive tools which operate on terms. A typical example is an interactive type-checker operating on a program which is being edited by a user. Finally, we have investigated further potential to exploit the fact that we base our computations on term rewriting. An example is the work on *origin tracking*, where we try to establish reverse links between the normal form t_n and the initial term t_0. It transpires that this is vital information for interactive tools like error reporters (associate an error message with a part of the source program) and animators (visualize the statement we are currently executing).

Other work underway involves *extending* the ASF+SDF formalism (higher-order algebraic specifications, parameterized sorts) and re-engineering the current implementation of the Meta-environment (connection with Emacs, re-implementation of the user-interface manager).

Applications

Although originally designed as a generator for *programming* environments, it transpires that there are many other areas where our Meta-environment can be applied with success. These range from general system design and the specification of environments for various languages, to specific areas like query optimization, hydraulic simulation, and application generators. We sketch four applications in some detail:

- We participate in the ESPRIT project COMPARE which aims at the construction of optimizing compilers for parallel architectures. In this context, we have designed a specification formalism fSDL to define the intermediate data representations in compilers. We have also constructed (using ASF+SDF) a generator which compiles these specifications into C.
- In cooperation with a Dutch bank, we designed a specification language for financial products. Given such a product definition, appropriate (Cobol) code can be generated to include the information related to the product instance in the company's information system. This enables the time needed to construct software for new products to be reduced from several months to several days.
- In cooperation with IBM (Yorktown Heights) work is underway on highly optimizing compilers. The essential idea is to translate the source language, e.g. C, into a high-level, intermediate level called PIM. All further optimizations can be expressed as symbolic manipulations on the intermediate PIM representation of the program. All these manipulations have been defined using ASF+SDF.
- In close cooperation with Peter Mosses (Aarhus, Denmark), we have constructed an interactive system to support development of specifications written in *Action Semantics*, a formalism for defining the semantics of (programming) languages. It is currently used for defining the semantics of ANDF (Architecture Neutral Definition Format), an exchange format for compiled programs.

Software Performance Assessment

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Introduction

Performance evaluation is an art in which right tools are indispensable. Could Rembrandt ever have created his 'Nightwatch' without good brushes and an easel? By the same token, many of today's computer system users are involved in the art of performance evaluation and thus require tools to support assessment and analysis of measurements taken. Here we discuss a system which greatly simplifies performance assessment of advanced database management systems (DBMSs).

Database technology for single processor architectures has matured from file processing by a large number of individual programs to sound data models and data manipulation schemes applicable in many environments. The DBMSs are delivered as portable, single processor implementations with many techniques to obtain good performance. However, new (prototype) systems often exhibit low quality and low performance due to lack of extensive field tests in the application areas they intend to support. Inclusion of new techniques into existing architectures also suffers from unpredictable side effects on system performance and stability. Yet, from an economic angle it is essential to predict their performance and to assess their stability, long before installation of the hardware and software. This was the underlying reason for setting up the ESPRIT project Pythagoras.

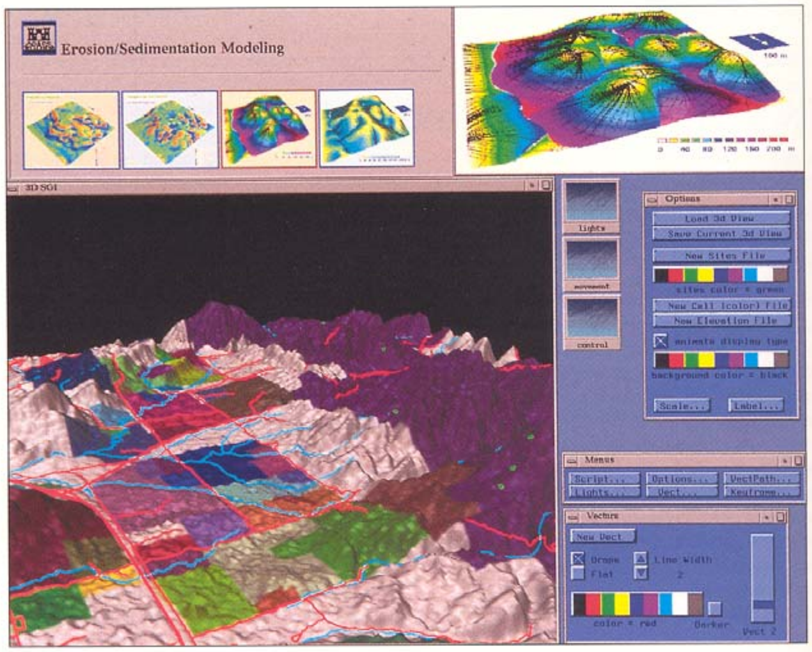
The project's objectives are to develop the means of predicting, assessing and tuning the performance of Advanced Information Servers (AIS). To achieve this, the project seeks to develop a tool-kit and methodology for performance quality evaluation and prediction of the parallel database servers which are intended to support an AIS. Furthermore, the Pythagoras project targets buyers and designers alike. It has three principal facets:

- The project delivers a performance suite aimed at quantifying the effectiveness of AIS in geographic, case, and business applications.
- These exemplars are complemented by in-depth studies to improve the knowledge of the key software technology required, and to assess the impact of hardware technology on the software choices, e.g., its architecture, logical query optimization and data placement.
- The Pythagoras project delivers several engineering tools for designers and users of a parallel database server:
  - The Adaptive Performance Evaluator provides the compiler designers with detailed application behaviour when designing query optimizers;
  - The SMART performance predictor provides users with a means to analyze application specific performance;
  - A prototype generalized DBMS simulator provides system designers with a means to assess the performance impact of new hardware architectures;
  - The SOFTWARE TESTPILOT developed at CWI assists both database designers and users to assess the robustness and the performance of applications running on a prototype system.

An overview of the development of the SOFTWARE TESTPILOT provides the main topic in the rest of this contribution.

DBMS benchmarking

The common approach to obtaining performance characteristics of a DBMS is to run a set of carefully chosen queries and then to observe its be-



Geographical information, stored in a database, is used, e.g., to model terrain erosion and sedimentation. Here efficiency and reliability of the database management system are of crucial importance. CWI coordinates the ESPRIT project PYTHAGORAS, which is developing a Software Test Pilot to assess the quality of new database management systems.

haviour. Database benchmarks like Wisconsin and AS3AP are primarily designed as tools for DBMS developers. Their aim is to expose the internal strengths and weaknesses of a system implementation. A recent developers-benchmark for Object Oriented DBMS is the OO7 benchmark; this is designed to provide a useful workload for evaluating new techniques and algorithms for OODBMS implementation. The TPC-A and TPC-B benchmarks have the advantage of being based on a real application (a bank teller network), but have become divorced from the real applications requirements. They can only be used to provide a simple comparative measure of a small part of the system being tested. Current TPC work is directed towards providing benchmarks for more complex traditional application domains (e.g., Order-Entry, Decision Support) with an emphasis towards conventional systems.

The role of benchmarking is primarily to compare performance of two or more systems. Indeed, it is of limited value as a means to improve software quality. Moreover, the known benchmarks do not directly aid users in determining the DBMS effectiveness for a particular domain. Domain-specific benchmarks are a response to this diversity of computer system use. They specify a synthetic workload characterizing a typical application problem domain. The OO1 benchmark is a step in this direction, which addresses the perceived performance critical aspects of a Computer-Aided Design (CAD) application.

The benchmarks are complemented by test-suites geared at exposure of weaknesses in specific system implementations. Together they provide the basis for technical quality assessment. Extension with software quality assessment techniques, like ISO-9000, further improve the organization of software production. Finally, the alpha- and beta- test sites represent the last barrier before systems reach the market.

A major drawback of the benchmarks and test-suites, addressed in the SOFTWARE TESTPILOT project, is that they only represent a few points in the workload search space. Hence, a DBMS engineer or user with a workload characteristic which is slightly off those measured, may find his system performing badly. Moreover, system implementors may be inclined to provide good performance on the published benchmarks.

In particular, attaining good performance on the notorious complex operations may ignore the workload characteristics of the application domain. Likewise, test-suites may be biased by isolated implementation challenges, e.g., novel data structures or query optimization techniques, and neglect possible side-effects.

From these observations we conclude that DBMS engineers and users require a performance assessment method which goes beyond benchmarking. What they need are intelligent tools to explore a large workload search space, quickly seeking out the slope, top, and knees of performance figures.

Automation of the performance assessment process

The predominant pragmatic approach in exploring a workload search space is to use shell scripts to capture the repetitive nature of the test runs or to rely on a small test space explored manually. The major drawback here is that this often results in a brute force approach, running the script over night to obtain a few points of the performance function without intermittent adjustment or error recovery. Another drawback is that shell scripts are difficult to port and maintain due to their operating system dependent nature.

Using our approach the performance assessment support system (PASS) experimenter specifies an abstract workload search space, a small interface library with the target system, and a description of the expected behaviour in a test-suite. Thereafter, it is up to the PASS to select the actual workload parameter values and to execute the corresponding target system transactions, such that the performance characteristics and quality weaknesses are determined at minimal cost (=time). A novel aspect of this approach lies in using a behavioral model of the target system to drive the process. The experiments selected by the SOFTWARE TESTPILOT are based on the incremental list of results (i.e. the experimentation history) and the mathematical properties of the hypothesis function constituting the behavioral model. The requirements on a PASS are derived using the user's interaction and the target system demands shown in Figure 1. A user describes an abstract experimental space using a test-suite specification language. This search space encompasses all legal parameter values for experimental control and results. Thereafter, the user interacts with a PASS to guide the execution of the experiments. Using visualization and summarization of the measurements, the user is informed about the performance behaviour of the system under test.

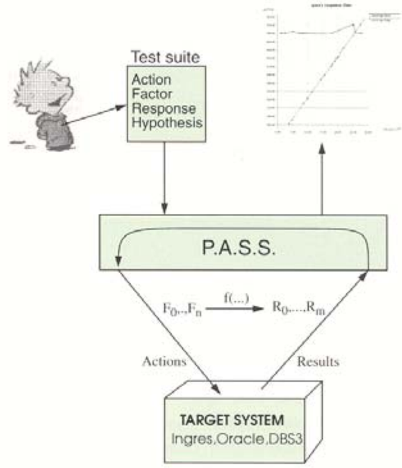
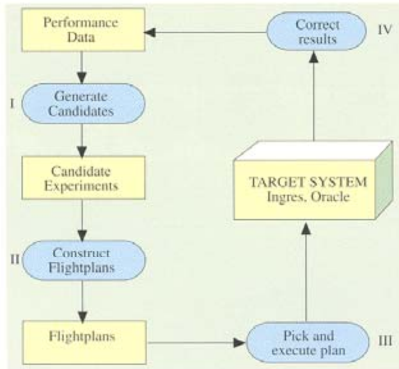


Figure 1. *The PASS environment.*

We derived the following list of requirements for a PASS system from the perspective of user interaction. A PASS system should provide:

- a flexible language for experimental space specification, including test space definitions in terms of factor- and response variables, a target system interface description with re-usable components, and a mechanism for hypothesis specification to guide the exploration of the test space;
- an extendible module to encapsulate algorithms to explore a large workload search space and quickly find the slope, top, and knees of performance figures of the target system;
- a graphical user interface enabling the user to control and direct execution of the experiments. Furthermore, measurement, summary and hypothesis visualization by means of a hybrid graphical monitor;
- statistical validation and fitting of user supplied and system generated hypotheses to adapt the behavioral model to the target system;
- persistent storage of measurement data for post-session analysis by domain specific tools (e.g. statistical packages and AI machine learning applications);
- documentation of experiments. Performance results are non-interpretable without exact information on the experimental environment, e.g.

Figure 2. *The software testpilot architecture.*



its design assumptions. A short narrative description of the objectives and boundary conditions of the experiment helps to interpret results.

The following requirements apply to the target system under test:

- Isolation of the target system from its environment should be possible in order to provide full control over the system by PASS. The target system state should be deterministic.
- Target system crash recovery and state inspection. A PASS may stretch the target system to and across its limits. This can result in a system crash. Hence, the target system should be crash recoverable. Target system state inspection is required to assess the system state after a crash and to verify assumptions implied in a performance test-suite.
- The target system should be machine controllable; i.e., the target should provide an interface enabling a separate application (e.g. a PASS) to control the system's actions and assess performance results, for example an SQL interface for DBMSs with additional commands to retrieve performance figures.

Although testing and benchmarking have been the subject of considerable attention over the past ten years, we are not aware of similar attempts to automate performance quality assessment at this level.

Test environments mostly focus on test-data generation and path coverage testing, or they explore the programming language properties to proof (type) assertions. Performance monitors, built into the DBMS or operating system environment, are passive. They merely provide measurement data, statistical analysis, and visualization tools. Instead, the SOFTWARE TESTPILOT provides a mechanism for partial automation of the interpretation of the results to prepare for and to perform the next test-run.

Conclusions

We have described the requirements for a performance assessment support system and a novel environment, the SOFTWARE TESTPILOT, which implements them. The tool is being used on a daily basis both to assess performance of parallel DBMS and to tune database cost models. The approach taken is to provide a declarative language, called TSL, to specify a large performance test space. Finding an efficient exploration is left to the SOFTWARE TESTPILOT. The result is a highly flexible language where the user's prime responsibility is to define actions objects, their relationships, and their interface with the DBMS. A clear separation between test space exploration and target system interaction ensures a highly generalizable tool applicable to a broad application domain.

FERSA: Lip-Sync Animation

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Introduction

Procedures to create lip-synchronous facial animations have been time consuming, costly and non-automatic. The central goal of the FERSA project (Facial Expression Recognition as a driver for real-time lip-synchronous Speech Animation) is to develop a means to automate this procedure for use in a television post-production environment. The FERSA project is partially funded by a PBTS grant from the Dutch Ministry of Economic Affairs. We are faced with two problems: (1) automatically determining the correct sequence of mouth shapes needed for animating a given text, and (2) synthesis or reconstruction of a talking face (or object) using a small set of mouth shapes (on the order of 25 shapes). Much work is being done in the area of facial animation, i.e., creating synthetic actors. We do not investigate the area of synthesis. Our main concern is with area number one. We would like to 'drive' or 'puppeteer' synthetic talking faces and use simple forms of reconstruction, i.e., 2D flipbook and 3D computer generated animation, mainly to demonstrate the power of our approach. We employ Computer Vision techniques to automatically process and analyze video images of a narrator and to identify the necessary mouth positions needed to reconstruct a lip synchronous animation using the narrator's original sound track. The project as a whole has links with the topics of Intelligent User Interfaces, Computer Graphics, Image Analysis and Multimedia, all of which are studied at CWI. After a period of experimentation and software prototyping, and the production of our first animations we are now in the process of completing a first production version of the system for delivery to our industrial partner (Valkieser BV) by April '94. Possible further developments and applications of the system will be discussed at the end of this contribution.

Background

To place this project into a context let us examine some approaches to the problem of speech animation.

Synthetic speech-to-image or text-to-visual speech

A phonetic score is generated from a text script and a mapping between phoneme and corresponding facial movement generates the animation. The problems associated with this approach include:

- the mapping used in the construction is language dependent;
- the set of synthetic sounds does not span that of human speech leading to a lack of 'naturalness';
- absence of rhythm and voice inflection.

Audio speech recognition to image

With an eye to remedying some of the problems associated with Synthetic Speech to Image, efforts are underway in the scientific community to perform speech recognition via analysis of the human voice. Among the problems encountered with this approach are that, given its inherent complexity, it is difficult to realize speech recognition for a large range of speakers/voices, and that one cannot detect non-audible mouth movements or gestures.

Visual speech recognition to image

An alternative approach uses Computer Vision/ Image Processing techniques and anatomical analysis for purposes of full speech recognition.

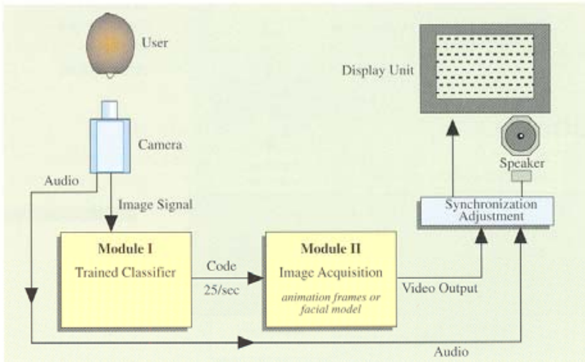


Figure 1. *Sketch of the FERSA system.*

Problems associated with this approach include:
- user independence is difficult for a large vocabulary;
- the processing requirements hinder real-time implementation.

Our approach has affinity with this last strategy. Because we neither attempt nor need to perform full speech recognition, we can avoid its main problems. However, we draw from this work along with fundamental work in speech analysis, which provides us with knowledge about mouth shape/movement during speech production. We have relied on this body of research to guide us in choosing relevant mouth shape features, texts for system training, and in determining an adequate set of visual speech elements.

The FERSA system

FERSA is composed of two main modules (see Figure 1):

(1) a training/classification module which has to recognize the mouth shapes exhibited by a narrator who uses the system. In order to do its work, this module processes video (recorded or real-time) of the narrator speaking;
(2) a reconstruction module which produces the animation, using the recognition results.

Trained classification/recognition

Since our goal is to drive a lip-synchronous facial speech animation, we do not intend to recognize speech but rather the mouth gestures and mouth shapes of the speaker during speech production. Thus, our limited recognition task is simpler than that of Visual Speech Recognition. Our recognition module (Module I) will simultaneously analyze video frames and classify the mouth shapes per frame (see Figure 1). The output of this classifier is a string of identifiers that serve as input to a Module II for the creation of the animation.

Module I is trained by having the narrator read a phonetically rich text in front of the camera. The images are analyzed and the narrator's characteristics are extracted for later classification of any general text input. If the training script is chosen correctly the system can be used for different languages.

Previous research suggests that a small set of some twenty mouth shapes suffices to represent the basic set of mouth shapes necessary to reconstruct a convincing speech animation (French and English). However, this holds for reconstruction at unequal intervals. We will be sampling at an equal interval rate of 25/sec. Thus, we may need additional mouth shapes in the reconstruction to accommodate for in-between mouth positions. At present, our recognition module operates off-line on recorded video. The software involved can perform its task real-time however.

Reconstruction

As stated, the reconstruction module is presented with a string of identifiers, analogous to a musical score, each identifier specifying a recognized mouth shape, one for every analyzed video frame. These identifiers are used by the reconstruction module in basically one out of two ways: the flipbook approach and the facial model approach. In the flipbook approach, images (animation frames) are flipped to screen to form an animation. These animation frames are selected from a prestored set of images of the mouth shapes to be used in the animation. The selection is determined by a mapping from the set of recognizable mouth classes to the set of animation mouth shapes. Depending on the type of realization, e.g., 3D wire frame, 2D claymation, line drawing or photo stills (see Figure 4, left), the mapping of mouth class to animation mouth shape is one-to-one or many-to-one (see Figure 2). The number of animation mouth shapes is maximal, i.e., equal to the number of mouth shape classes, for purposes of full realism, although in a simple line drawing or a 3D implementation using an off-line keyframe method, it may only be necessary to animate with a small number of shapes. For the flipbook animation one only has to fetch images from some storage medium and to display them, which can be done real-time.

In the facial model approach a parametrized model of some speaking entity (maybe a human face, maybe a dinosaur) is used. In this case, every recognized mouth shape is mapped to parameter settings for the facial model which then uses them to produce an image corresponding to the mouth shape. For simple models, this process can run real-time, the use of complicated models and/or complicated rendering (e.g. texture mapping) of the images generated by them will be off-line. It should be noted that the facial model easily adapts itself to synthetic 'talking heads'.

Initial experiments and software prototypes

Image acquisition

Our first investigation was to compare two very different approaches to the acquisition of the narrator's facial features. In the first approach, the narrator is marked up with reflective dots, in the second approach a B/W video recording is used. To explore the reflective dots approach we were allowed to use the PRIMAS motion analysis system developed at Delft University of Technology. For the exploration of the second approach, we made recordings in our own office environment, where one of us assumed the role of narrator, with make-up applied to enhance the facial features.The recorded video approach turned out to be well suited to image analysis techniques and was relatively easy to apply as far as recording is concerned. We chose for the latter approach.

Analysis, training and recognition

In order to facilitate our analysis of training- and test-data and to prototype our software, we first used the general purpose image processing package SCILIMAGE, developed by the University of Amsterdam and TNO. During the analysis of the training data, our first test system performed four simple measurements on each mouth image. After normalization and scaling, the ratios of these measurements gave us points in a 2D feature space. Scatterplots convinced us that these two numbers were fairly independent. In this space, we performed a straightforward cluster analysis, using a hierarchical clustering procedure, with the number of clusters to be generated limited to thirty. As a final step, in each of these clusters a central point was chosen, figuring as the mouth

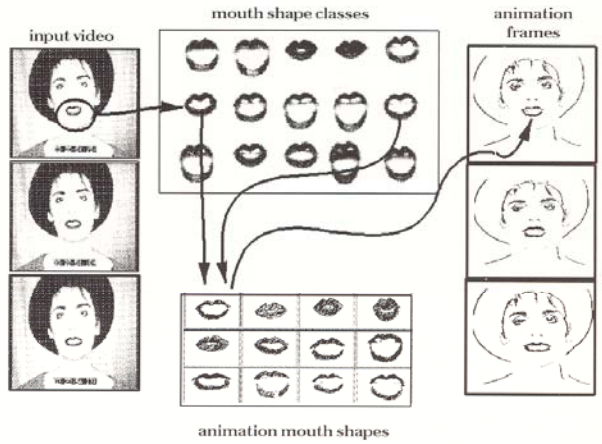


Figure 2. Analysis and reconstruction.

Figure 3. Talking bottles.

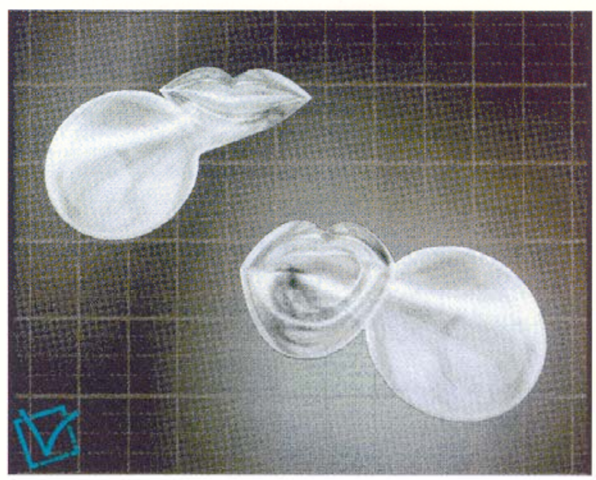


Figure 4.
Left:: whitened face and blackened lips for recording. Right: line drawing as a keyframe for reconstruction.

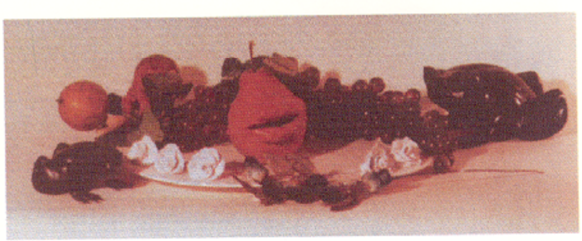
shape characteristic of that cluster. This way, the set of mouth shape classes was formed.

Recognition proceeded as follows. The same four measurements were made on every image as had been made during analysis of the training set. These measurements defined a point in feature space. Next, the cluster centre nearest to this point (using Euclidean distance) was selected and so the representational mouth shape for that image was determined.

Reconstruction

For the display of flipbook animations we wrote a program running on Silicon Graphics workstations using SGI's graphics library and audio tools to display reconstructed animations in real-time. Real-time performance can be achieved with this setup because of the small number of images to be flipped (at most it equals the number of mouth shapes), so they can be loaded into main memory before the animation starts. All there is to do is to move them to screen at the rate of 25 per second. In the facial model approach, we adapted a version of Parke's facial model available in the public domain. For every animation mouth shape, a set of model parameters giving the desired shape was determined beforehand. So, showing an animation is done by selecting one of these parameter sets and having the model generate the corresponding image 25 times a second.

Figure 5.
Animation frame using clay model of pear (claymation).



With this facial model (and without texture mapping) this was just possible real-time on an IRIS Indigo.

Some animations

With the test system we constructed some very short animations using the audio tracks 'Casablanca', 'Smakelijk eten', 'My name is Pat' and 'Good morning ladies and gentlemen'. These were reconstructed using line drawings (Figure 4, left), photo stills from a clay model of a pear (Figure 5) and Parke's facial model. In collaboration with our industrial partner, Valkieser BV, we constructed some more professional animations, using about two minutes of text and featuring items including speaking bottles (Figure 3).

A production system

Our first system actually destined for production purposes will be delivered to Valkieser before April '94. It consists of C^{++} software, running under UNIX on SGI workstations, using SGI's graphics library. Broadly speaking the central element of this software, the recognition system, consists of five parts: initialization, nostril tracking, image processing, feature extraction and classification.

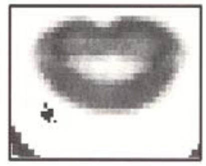
Because lighting conditions and anatomical details (e.g. mouth position, contrasts) may vary from registration to registration, operation of the system begins by interactively indicating positions (nostrils and mouth corners) and threshold levels through mouse-clicks on pixels of stationary images. The parameters thus set determine which grey values within which image area are taken to denote the narrator's lips, as well as the site of the nostrils. When looking more or less straight into the camera, most people's nostrils show up as two distinct grey spots in the image. Moreover, nostrils are the only facial features whose position is almost fixed with respect to the underlying bone structure. To compensate for (not too violent) head movement during image registration, the nostrils are tracked from image to image. In every image, the mouth region is then found in a window located at a fixed offset below the nostrils.

In spite of the use of make-up on the narrator's face, segmenting out the lips from the mouth region is still a complicated matter due to noise, light reflections (on moist lips) and the fact that the oral cavity can look both darker or lighter than the surrounding lips and even partly lighter and partly darker in one and the same image; this last effect is due to the tongue and teeth. We perform a number of problem specific preprocessing steps; these have in common that they exploit the fact that we are looking for a closed ring (open mouth) or a disc (closed mouth). A few stages are shown in Figure 6. Once the lips have been located, measurements are performed, e.g., mouth height, mouth width, outer perimeter, total area, perimeter of cavity and cavity area, position of highest and lowest point, of mouth corners and of centre of mass. Ratios of quantities of the same dimension formed from these measurements then serve as features. (One of the advantages of ratios is that they are independent of camera distance.)

The classification part of the software is still the least crystallized. As said, during our initial experiments, we used clustering to separate the feature space. In the current software we are experimenting with dividing the feature space in a fixed number of rectangular cells. Although this approach is easier to implement and far more robust, it still remains to be seen whether it can sufficiently cope with differences between speakers and language.

Future developments and conclusions

To date the project has resulted in a tool which can greatly simplify the production of lip-synchronous animations. Possible further extensions are feature detection under varying lighting conditions without using make-up, and recognition of basic facial emotion expressions. These tasks will demand further research into the applicability of aspects including active contours, neural nets and optical flow analysis. This could lead to the construction of a tool for 'performer driven' animations, or a tool for teleconferencing on relatively cheap systems with low-bandwidth communication channels through image analysis at the sending side and image reconstruction at the receiving side.



A.
Mouth area extracted from image of narrator's face.

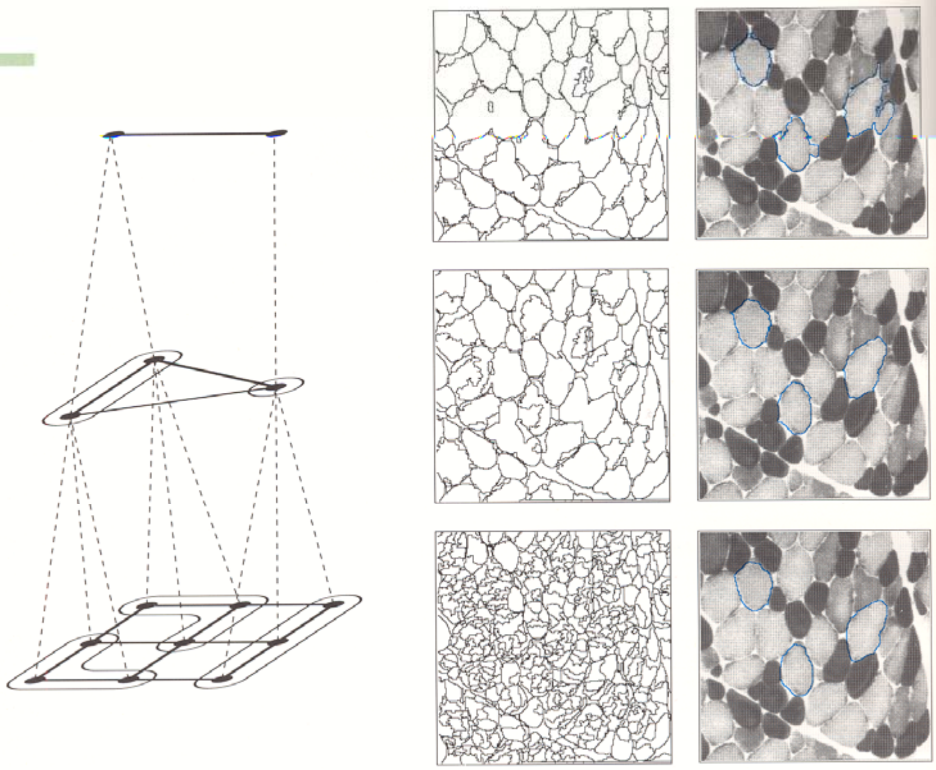
B.
Pixels averaged over small neigbourhood.

C.
Triple threshold:
Skin removed and cavity determined from dark- and light area's.

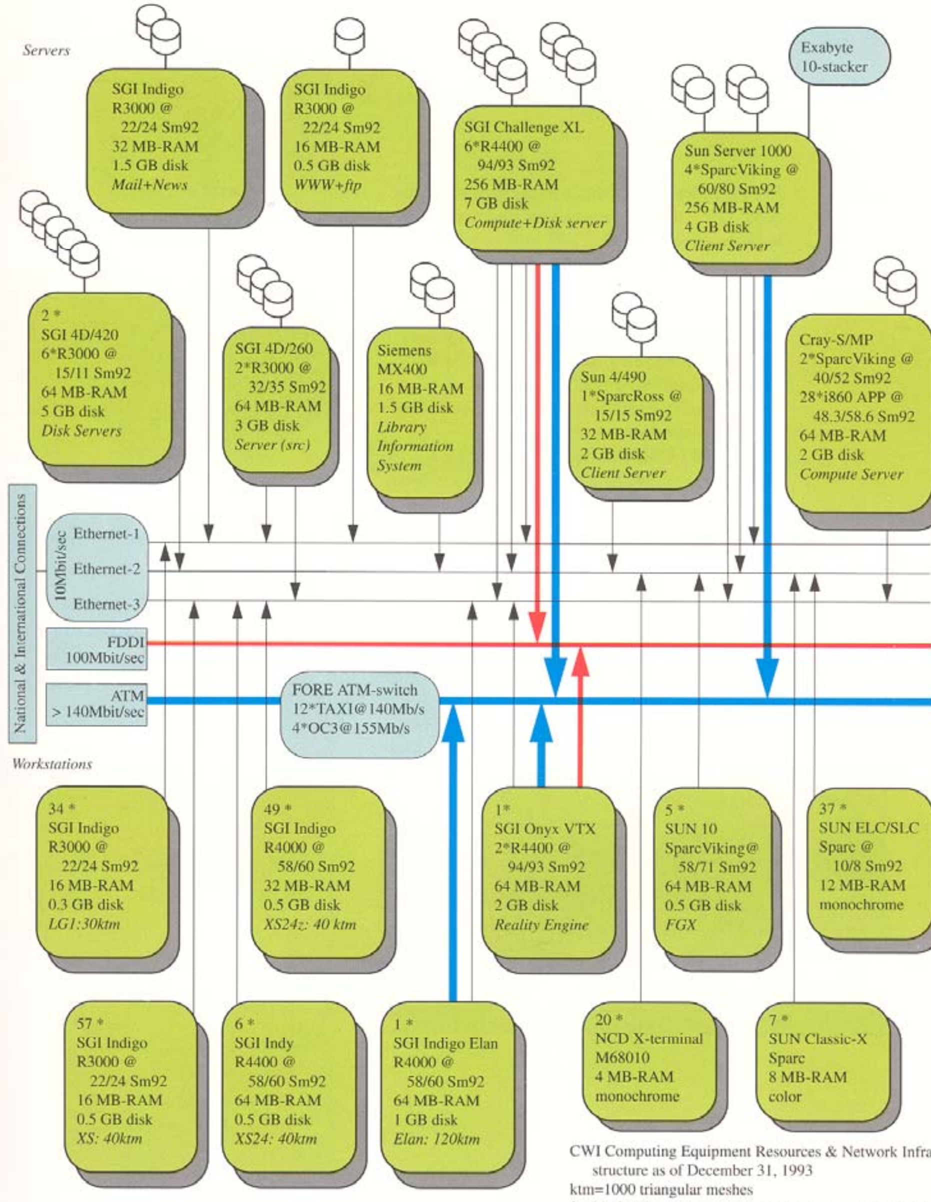
D.
Final image:
Remaining noise removed.
Edges smoothed.

Figure 6. *Some stages in image segmentation and preprocessing.*

COMPUTING EQUIPMENT RESOURCES



Current image analysis research at CWI involves the application of a *hierarchy of graphs*. This special data structure represents a stack of image segmentations, from a coarse segmentation at the top, to fine segmentations at the bottom. Each segmentation is represented by a *region adjacency graph*, in which each region is represented by a vertex, and vertices representing adjacent regions are connected by an edge. The figure shows (to the left) a representation of the data structure and (middle and right) its application to the detection of muscle fibre boundaries. An initial coarse guess is produced in the top level of the hierarchy, and is subsequently refined in the lower levels. CWI's C^{++} GRAPHLIB package enables fast development of several methods using hierarchies of graphs. The data structure can include a large number of vertices, even in excess of 100,000. Other features to be represented include edges in the region adjacency graphs and links between vertices at differing levels, as well as additional information on image grey levels. Although application of these data structures requires large amounts of memory, they can be run conveniently on CWI's Silicon Graphics Indigo machines.

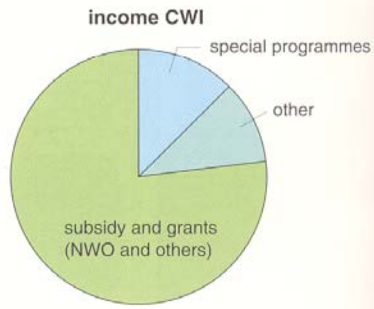


CWI Computing Equipment Resources & Network Infrastructure as of December 31, 1993
ktm=1000 triangular meshes
Sm92=SPECmark92 integer&floating point performance

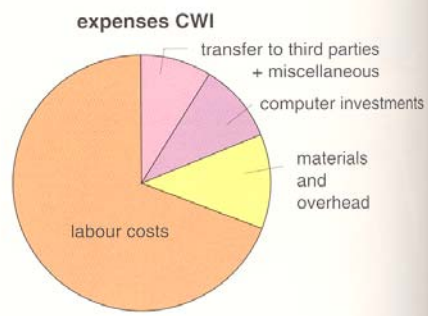
FINANCIAL AND OTHER DATA

FINANCES 1993

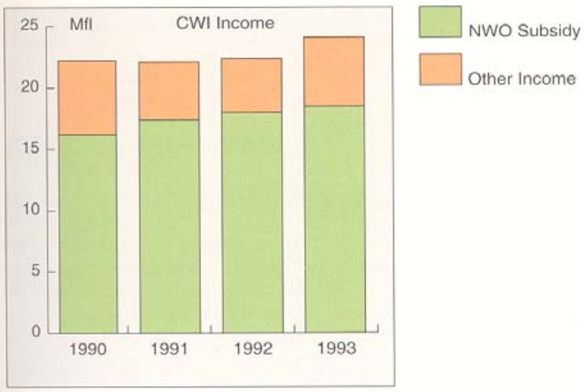
In 1993, SMC spent Dfl. 26.41 million, of which about Dfl. 2.94 million was allocated to university based research and Dfl. 23.47 million to CWI. The expenses were covered by a subsidy from NWO (Dfl. 21.42 million), other subsidies and grants (Dfl. 0.22 million), and from the international programmes (mainly EC programmes, e.g. BRITE, ESPRIT, SCIENCE and RACE) (Dfl. 3.04 million). Finally, an amount of Dfl. 2.48 million was obtained as revenues out of third-party-services and other sources.
During 1993 CWI also hosted over sixty researchers in externally financed positions. These are not included in the adjacent financial summary.

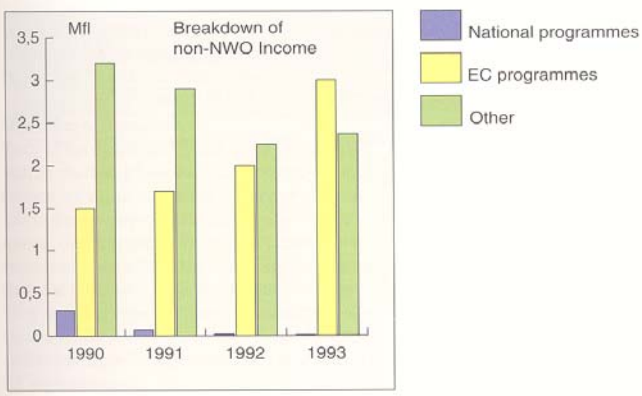


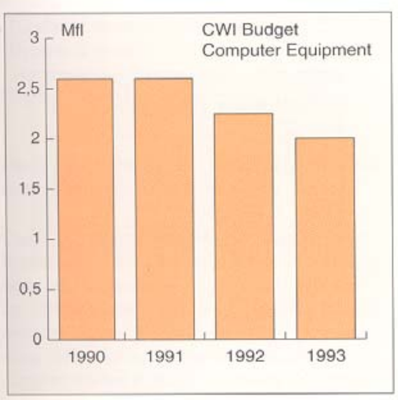
	university based	CWI	SMC
	* Dfl. 1000		
INCOME			
subsidy and grants			
- NWO	3134	18281	21415
- other	-	216	216
national programmes	-	-	-
international programmes	-	3037	3037
other revenues	35	2445	2480
total income	3169	23979	27148
EXPENSES			
labour costs	2423	16513	18936
materials and overhead	27	2742	2769
computer investments	200	2004	2204
transfer to third parties	291	1991	2282
miscellaneous	-	219	219
total expenses	2941	23469	26410



FINANCES 1990 - 1993







CWI Ph.D. THESES

Author	Title	Thesis advisor(s)+)
A.B. Olde Daalhuis	Uniform, Hyper- and q-Asymptotics	T.H. Koornwinder (UvA) F.W.J. Olver (UMa)
M.C.J. van Pul	Statistical Analysis of Software Reliability Methods	R.D. Gill (RUU)
H.T.M. van der Maarel	A Local Grid Refinement Method for the Euler Equations	P.W. Hemker
J.T. Jeuring	Theories for Algorithm Calculation	L.G.L.T. Meertens
B. Veltman	Multiprocessor Scheduling with Communication Delays	J.K. Lenstra (TUE) E.H.L. Aarts (TUE)
P. Wartenhorst	Performance Analysis of Repairable Systems	F.A. van der Duyn Schouten (KUB)
A.S. Klusener	Models and Axioms for a Fragment of Real Time Process Algebra	J.A. Bergstra (RUU) J.C.M. Baeten (TUE)
J.T. Tromp	Aspects of Algorithms and Complexity	P.M.B. Vitányi

+) For external advisors the university's acronym is added:

UvA = University of Amsterdam

UMa = University of Maryland (USA)

RUU = State University of Utrecht

TUE = Technical University Eindhoven

KUB = Catholic University Brabant

Library (ultimo 1993)

41 000	books
1450	subscriptions on journals
110 000	reports

Publications 1993

223	papers in journals and proceedings
128	CWI Reports
79	Other publications

CWI RESEARCH PROGRAMMES

Algebra, Analysis & Geometry

Algebra, discrete mathematical structures and computer algebra
Research in and implementation of algorithms in algebra and combinatorics; making such algorithms and other mathematical knowledge available through integrated coherent computing systems. Symbolic manipulation packages (computer algebra) are an essential part here.
Subjects:
- Algorithmic algebra and discrete mathematics
- Computer assisted mathematics
- Quantum groups and q-special functions

Programme leader: M. Hazewinkel

Modelling and analysis
Study of the dynamics of biological populations with an internal, physiological, structure through balance laws relating the life history of individuals to the development of the population as a whole. Construction of an infinite dimensional dynamical system from the model specification; theory of functional differential equations; stability analysis; ergodic theory; development of a Dynamical Systems Laboratory. Research into uniform asymptotic expansions and their numerical implementation.
Subjects:
- Population dynamics and epidemiology
- Dynamical systems
- Asymptotics

Programme leader: O. Diekmann

Operations Research, Statistics & System Theory

Combinatorial optimization and algorithmics
Fundamental and applied research, with an orientation towards mathematics (discrete mathematics, geometry, number theory, probability theory), operations research (linear and integer programming, optimization, sequencing, scheduling), computer science (complexity theory, computational geometry) and applications (VLSI-layout, robotics, pattern recognition, railway and airplane routing, scheduling, and time-tabling).
Subjects:
- Design and analysis of algorithms
- Polyhedral methods and polynomial-time algorithms
- Multicommodity flows and VSLI-layout
- Discrete mathematics and geometry
- Applications (routing, scheduling, time-tabling)

Programme leader: A. Schrijver

Analysis and control of information flows in networks
Fundamental and application-oriented research concerning the behaviour of stochastic systems: mathematical analysis of queueing models; performance analysis of computer and communication networks; integration of queueing and reliability theory in order to assess the behaviour of systems subject to breakdown, replacement and repair; stochastic phenomena in lattice-type networks, including applications in mathematical physics and communications.
Subjects:
- Analysis of mathematical queueing models
- Stochastic processes on networks
- Reliability and availability of networks
- Performance analysis and control of computer and communication

Programme leader: O.J. Boxma

System and control theory
Formulation and analysis of dynamical systems as models for phenomena which evolve in space and time, and the solution of control and prediction problems.
Subjects:
- Deterministic system theory
- Stochastic system theory
- Control of discrete-event systems
- System identification for compartmental models
- Control computations for element models
- Control of distributed computer systems

Programme leader: J.H. van Schuppen

Image analysis
Research on the analysis of digital images and spatial data: fundamental study of stochastic models,statistical procedures, and stochastic and geometric algorithms; applications to consulting problems in spatial statistics and image analysis; software implementation.
Subjects:
- Stochastic geometry
- Applied spatial statistics and stereology
- Bayesian and likelihood-based image analysis
- Mathematical morphology and discrete image transforms
- Software development

Programme leader: A.J. Baddeley

Numerical Mathematics

Discretization of evolution problems
Fundamental and applied research into numerical methods for evolutionary differential equations. Both ordinary and partial differential equations are covered. In many cases of practical interest, these two problem classes can be linked numerically via the Method of Lines. Attention is given to theoretical analysis on stability and convergence issues and to applying specific algorithms to important problems from actual practice.
Subjects:
- Adaptive grid methods
- Three-dimensional transport problems
- Parallel initial-value-problem algorithms
- Algorithms for atmospheric flow problems

Programme leaders: P.J. van der Houwen, J.G. Verwer

Boundary-value problems, multigrid and defect correction
The design, analysis and implementation of methods for the numerical approximation of solutions of problems described by ordinary or (elliptic and hyperbolic) partial differential equations, as arise in, e.g., structural mechanics, fluid dynamics and chemistry. The research focuses on defect correction and multigrid techniques. Applications include: optimization problems; and the compressible Navier-Stokes equations, in particular in relation with aerodynamics.
Subjects:
- The analysis of defect correction and adaptive techniques for convection-diffusion problems
- Application of multigrid techniques to fluid dynamics problems
- Singular perturbation problems
- Parameter identification in ordinary differential equations

Programme leader: P.W. Hemker

Large-scale computing
Research into general aspects of implementation of mathematical and numerical algorithms for modern (massively) parallel architectures. In particular, iterative methods for extremal eigenvalues of large sparse matrices (with applications in magnetohydrodynamics) and algorithms for number-theoretical problems with a numerical component (with applications in data protection) are investigated.
Subjects:
- Parallel numerical algorithms and tools for their implementation on parallel systems
- Computational number theory

Programme leader: H.J.J. te Riele

Software Technology

Semantics
Investigation of theory and applications of programming language semantics, in particular: the study of a category-theoretic perspective on the various domains employed in semantic modelling, with extensions of the metric methodology as developed by the Amsterdam Concurrency Group over the past decade; applications to concurrent programming, emphasizing imperative, logic and object-oriented programming; program refinement, state and predicate transformer semantics.
Subjects:
- Research and Education in Concurrent Systems (REX)
- Non-well-founded sets and semantics of programming languages
- Mathematical structures in concurrency semantics (Science-MASK)
- Foundations and applications of semantics
- Program refinement, predicate transformer and state transformer semantics

Programme leader: J.W. de Bakker

Concurrency and real-time systems
Research into software engineering, in particular the discovery of technically sound methods of specification , design and verification of

distributed and concurrent computer systems. The emphasis is on the theory of concurrent processes, process algebras, structural operational semantics, temporal and modal logics, and correctness of real-time and distributed systems.
Subjects:
- Specification and Programming Environment for Communications Software (RACE-SPECS)
- Broadband Object-Oriented Service Technology (RACE-BOOST)
- Calculi and Algebras of Concurrency: Extensions, Tools and Applications (ESPRIT BRA-CONCUR II)
- Real-time specification and programming

Programme leader: F.W. Vaandrager

Extensible programming environments
Incremental generation of type checkers and evaluators from formal static and dynamic semantics definitions. Generation of incremental programming environments from formal language definitions. Generation of compilers for parallel computers.
Subjects:
- Incremental program generation
- Generation of interactive programming environments
- Compiler generation for parallel machines (ESPRIT-COMPARE)

Programme leader: P. Klint

Algebraic and syntactic methods
Foundational research directed primarily, but not exclusively to term rewriting systems. The emphasis is on the study of oriented equational axiom systems, enabling rigorous consistency proofs and - in principle - executability of concurrent calculi, and on term graph rewriting.
Subjects:
- CONcurrency and Functions: Evaluation and Reduction (ESPRIT BRA-CONFER)
- Extensions of orthogonal rewrite systems – syntactic properties
- SEMAntics and pragmatics of generalised GRAPH rewriting (ESPRIT BRA working group SEMAGRAPH)

Programme leader: J.W. Klop

Logic and language
The study of various correctness properties of logic programming and PROLOG, and the relation between logic programming and non-monotonic reasoning, addressing both proof theoretical and semantic issues. Furthermore, the study of topics in natural language analysis from a formal point of view, inspired by the analysis of programming languages.
Subjects:
- Logic programming and non-monotonic reasoning
- Formal aspects of PROLOG and logic programming (ESPRIT BRA-COMPULOG II)
- Structural and semantic parallels in natural languages and programming languages
- Non-monotonic reasoning and semantics of natural language

Programme leader: K.R. Apt

Algorithmics & Architecture

Algorithms and complexity
Study and design of algorithms for non-conventional computer networks and distributed information systems, covering the design, construction and use of hardware, as well as applications. In particular, realistic models for multicomputers, design and analysis of algorithms suitable for distributed computations, and fundamental research in computational complexity theory and Kolmogorov complexity. Computational Learning theory and applications to artificial neural networks and genetic algorithms – Computing by Multiple Agents.
Subjects:
- Distributed algorithms
- Machine learning

Programme leader: P.M.B. Vitányi

Cryptography
The research concerns all aspects of cryptology related to information security. This involves the construction and analysis of cryptographic protocols and their underlying algorithms, and the mathematical proofs of their soundness and reliability. Emphasis is placed on protection of individual privacy in protocols for the transmission of messages, payment systems, and their treatment of personal data by various organizations.
Subjects:
- Public-key cryptography
- Specification of cryptographic protocols
- Conditional Access For Europe (ESPRIT-CAFE)

Programme leader: R.A. Hirschfeld

Constructive algorithmics

Development of concepts, notations, formalisms and methods for deriving algorithms from a specification. The issues investigated include the unification of specification formalisms and formalisms for denoting algorithms, and the development of specialized theories for aspects of interoperable systems.

Subjects:

- A generic editor based on the TAXATA user model
- Interoperable systems

Programme leader: L.G.L.T. Meertens

Databases

Research on database design theory and effective architectures for advanced database management systems. In particular, those issues stemming from requirements posed by information systems - found in, e.g., office, (financial) trading and scientific environments - which are distributed over time and location, where the data organization and the applications change frequently, and where the content of the database is only guaranteed to be locally consistent. The focus is on novel architectures to exploit the potential parallelism of database management in large-scale processor systems and the theory for active database systems.

Subjects:

- Object-oriented database platforms
- Design theory for active databases
- A performance assessment toolkit (ESPRIT-Pythagoras)

Programme leader: M.L. Kersten

Interactive Systems

Computer graphics

Research on computer graphics, visualization and image processing with a strong commitment to approaching these areas from a Human-Computer Interaction point of view. The research covers application-driven exploitation of fundamental techniques. Solutions range from developing new algorithms to specifying new architectures including custom VLSI systems. The research on visualization involves a study of novel techniques, by means of which an end user can incrementally build a graphical interface to an ongoing simulation for interactive control of numerical simulations.

Subjects:

- Scene analysis (priorities, quality factors and collision detection)
- Adaptive image synthesis (quality-speed trade-off)
- Multi-resolution image coding based on wavelets
- Computational Steering (navigation, logging, monitoring, presentation and constraint specification)

Programme leader: A.A.M. Kuijk

Interaction and parallelism

On the basis of a previously developed powerful parallel programming facility (MANIFOLD), various experiments are underway, including visual programming, complex user interfaces, parallel control structures and parallel object bases. Further points of attention include the maintainance, extension and distribution of the experimental bases, and the development of software engineering methods for parallel software.

Subjects:

- MANIFOLD – language and systems
- MANIFOLD – cases

Programme leader: F. Arbab

Interaction and multimedia

Development of the object-oriented bases for multimedia software engineering methods, with inclusion of object parallelism, constraints and a time dimension. Further research topics concern interaction handling, time-based constraints, uniform image manipulation and multimedia compound composition.

Subjects:

- Multimedia fundamentals (ESPRIT-MADE)
- Multimedia systems (ESPRIT-MADE)
- FERSA (Facial Expression Recognition as a driver for lip-Synchronous Animation)

Programme leaders: P.J.W. ten Hagen, I. Herman, P.A. Griffin

Computer Systems & Telematics

Multimedia kernel systems

Study of a small number of fundamental problems associated with the systems-level support for multimedia data manipulation, viz. distributed multimedia. It concerns the definition, manipulation and support of multimedia data across collections of computers in a cooperative

manner. Research issues include: the specification of multimedia presentations in a transportable, multi-machine environment; the definition of hyper-information links into data; protocol rules for machine-machine and interpersonal multimedia communication; distributed resource allocation algorithms.
Subjects:
- Transportable multimedia document specifications
- CWI Multimedia Interchange Format (CMIF)
- Dynamic, hyper-structured multimedia document generation
- MAnagement Games Utilities Support (MAGUS)
- Multimedia distributed operating systems
- Multimedia CoProcessor (MmCP)

Programme leader: D.C.A. Bulterman

Multidisciplinary Programmes

Mathematics & the Environment
This programme combines all CWI research groups with applications to the environmental sciences.
Subjects:
- Mathematical techniques for the study of the population biology of infections
- System identification of compartmental systems - a mathematical tool in public health and environmental protection
- Analysis of bootstrap resampling schemes, with applications to environmental data sets
- Statistics and oil pollution in the North Sea
- Mathematical modelling of global transport and chemistry of trace constituents in the troposphere
- Algorithms for air pollution models used in smog-prediction
- Parallel solution techniques for a 3D coupled shallow-water/transport model

Programme leader: J.G. Verwer

Multimedia
Study of the coordinated use of various information streams within a computing system, seeking ways to support the capture, transfer and storage of potentially vast amounts of information across appropriate user, system and device interfaces.The goal is to share results obtained from complementary research activities, which span a wide range of interests from user interface systems to operating system support, from database models to network protocols, and from data models for images to data models for sound.
Subjects:
- Aspects of the definition
- Manipulation
- Presentation of multimedia data

Programme leader: D.C.A. Bulterman

INTERNATIONAL AND NATIONAL PROGRAMMES

This chapter summarizes the major national and international projects in which CWI participates. While participation in European research projects (e.g. ESPRIT) remained on the same level in 1993, participation in European research networks and national projects increased substantially.

The following data are given for each project:
- title,
- period,
- cooperation with other institutes,
- special role of CWI (if any),
- CWI project leader(s).

European Programmes

ESPRIT

GIPE II (2177): Generation of Interactive Programming Environments
January 1989 - January 1994
SEMA METRA Group SA, Bull SA, INRIA, Technische Hochschule Darmstadt, PTT Research, Planet SA, GIPSI SA, Univ. Amsterdam, PELAB
P. Klint

COMPARE (5399): Compiler Generation for Parallel Machines
January 1991 - January 1995
Ace BV, STERIA, GMD, INRIA, Harlequin Ltd, Univ. Saarland
P. Klint

MADE (6307): Multimedia Application Development Environment
May 1992 - June 1995
Bull SA, SNI, Iselqui, British Aerospace, INESC, Gipsi SA, ESI, Barclays Bank, NR, FhG-IAO, INRIA
P.J.W. ten Hagen

PEPS (6942): Performance Evaluation of Parallel Systems
July 1992 - July 1995
Thomson Sintra, Intecs Sistemi, Simulog, Univ. of Warwick, NPL (UK), AFNOR (France), CNR (Italy), PTB (Germany)
J. Kok

CAFE (7023): Conditional Access for Europe
December 1992 - December 1995
Digicash, PTT, Cardware, Gemplus, SEPT, Ingenico, SINTEF-Delab, Institut für Sozialforschung Frankfurt, Institut für Informatik Hildesheim, Siemens, Universities of Leuven and Aarhus
Coordinator
R.A. Hirschfeld

PYTHAGORAS (7091): Performance Quality Assessment of Advanced Database Systems
May 1992 - May 1995
ICL, Bull SA, Heriot-Watt Univ., CCIP, Infosys, IFATEC
Coordinator
M.L. Kersten

ESPRIT Basic Research

SEMAGRAPH II (6345)
October 1992 - October 1995
Univ. East Anglia, ECRC GmbH, Univ. Rennes, Univ. Nijmegen, Imperial College
J.W. Klop

CONFER (6454): Concurrency and Functions: Evaluation and Reduction
September 1992 - September 1995
INRIA Rocquencourt, ECRC GmbH, Univ. Edinburgh, CNRS-ENS, Imperial College, INRIA Sophia Antipolis, Univ. Pisa, SICS
J.W. Klop

COMPULOG II (6810): Formal Aspects of Prolog and Logic Programming
August 1992 - August 1995
Univ. Leuven, ECRC GmbH, RWTH Aachen,

Univ. Saarland, Univ. Pisa, Univ. Rome (La Sapienza), Univ. Rome (Tor Vergata), UNINOVA Lisbon, Univ. Uppsala, Imperial College, Universities of Bristol, Edinburgh and Aix-Marseille II
Coordinator
K.R. Apt

CONCUR 2 (7166): Calculi and Algebras of Concurrency: Extensions, Tools and Applications
September 1992 - September 1995
Universities of Eindhoven, Aalborg, Edinburgh, Sussex and Oxford, INRIA, SICS, INPG, Sharp, Chalmers Univ., ECRC
F.W. Vaandrager

QMIPS (7269): Quantitative Modelling In Parallel Systems
October 1992 - October 1995
Univ. René Descartes LAA, Univ. Erlangen-Nürnberg, Univ. Torino, Imperial College, Univ. Newcastle, INRIA Sophia Antipolis
O.J. Boxma

NeuroCOLT (8556): Neural and Computational Learning
Royal Holloway and Bedford New College, Univ. Mons, Rheinisch-Westfälische Tech. Hochschule, Univ. Pompeu Fabra, Techn. Univ. Graz, London School of Economics, Helsingin Yuopisto, Lab. de l'Informatique du Parallelisme, Univ. Milan
P.M.B. Vitányi

BRITE/EURAM

AERO II (AER2-CT92-0040): Solution adaptive Navier-Stokes solvers using multidimensional upwind schemes and multigrid acceleration
January 1993 - January 1996
Von Karman Institute for Fluid Dynamics, Free Univ. Brussels, Politecnico di Bari, Technical Univ. Denmark, Royal Institute of Technology, Dornier Deutsche Aerospace, Fokker Aircraft B.V., Aerospatiale, British Aerospace, Dassault Aviation
P.W. Hemker

DRIVE

DYNA (V2036): A Dynamic traffic model for real-time applications
January 1992 - January 1995
Hague Consulting Group, CSST, Univ. Naples, Elasis, RWS, Univ. Lancaster, Univ. Libre Bruxelles, Univ. Delft
J.H. van Schuppen

MAST Marine Science and Technology

NOWESP: North-West European Shelf Programme
September 1993 - September 1996
RWS, Institut für Meereskunde, Univ. Leuven, NIOZ, Proudman Oceanographic Laboratory Bridston, Sir Allister Hardy Foundation for Ocean Science, Institute of Marine Research, Inst. für Ostseeforschung, Delft Hydraulics, BSH, IfBM, IFREMER, MUMM, Univ. Delft, Trinity College, Universities of Bordeaux and Liverpool
P.J. van der Houwen

RACE

BOOST (2076): Broadband Object-Oriented Service Technology
January 1992 - January 1995
MARI Computer Systems Ltd, IPSYS Software Plc, Bull S.A., Société Français de Genie Logiciel S.A., GIE Emeraude, Detecon Technisches Zentrum, Intrasoft S.A., Telefonica, Intecs Sistemi Spa, Standard Elektrik Lorenz AG, Alcatel SEL, Centro de Estudos de Telecomunicaçoes, Univ. College of Wales, Universities of Athens and Aveiro
F.W. Vaandrager

Libraries Programme

RIDDLE(1038): Rapid Information Display and Dissemination in a Library Environment
February 1993 - October 1994
Longman Cartermill Ltd, Rutherford Appleton Laboratory
F.A. Roos

Evolutionary Systems: Deterministic and Stochastic Evolution Equations, Control Theory, and Mathematical Biology (CT90-0464)
March 1990 - March 1993
Universities of Tübingen, Besançon, Graz, Mons and Zurich, Scuola Normale Superiore Pisa
O. Diekmann

Algorithmic Approaches to Large and Complex Combinatorial Optimization Problems (CT91-0620)
October 1990 - October 1993
Universities of Leuven, Augsburg, Grenoble (Univ. Joseph Fourier) and Valencia, CNR Rome
A. Schrijver

MASK: Mathematical Structures in Semantics for Concurrency (CT92-0776)
September 1, 1992 - September 1, 1995
Univ. Pisa, CNRS/INRIA, Universities of Udine, Mannheim and Koblenz
Coordinator
J.J.M.M. Rutten/J.W. de Bakker

System Identification: Modeling, Realization and Parameter Estimation for Problems of Engineering, Economics and Environmental Science
July 1992 - June 1995
Univ. Groningen, Technical Univ. Wien, Univ. Leuven, INRIA, Univ. Rennes I, Univ. Cambridge, LADSEB-CNR, Linköping Univ.
CWI participates through the Systems & Control Theory Network of Univ. Groningen, seat of the coordinator
J.H. van Schuppen

Human Capital and Mobility Networks

EXPRESS: Expressivenes of languages for concurrency (CT93-0406)
1994-1997
Free Univ. Amsterdam, SICS, Univ. Genova, Univ. Rome (La Sapienza), Univ. Hildesheim, Univ. Amsterdam, INRIA, GMD, Univ. Sussex
Coordinator
F.W. Vaandrager

Statistical inference for stochastic processes (CT92-0078)
1993 - 1996
Universities of Paris VI, Berlin, Aarhus and Freiburg, INRIA
K.O. Dzhaparidze

EUROFOCS: European institute in the logical foundations of computer science (CT93-0081)
1994-1996
Univ. Edinburgh, INRIA, Universities of Pisa and Cambridge, ENS
J.W. de Bakker

The equations of fluid mechanics and related topics (CT93-0407)
1994-1996
CMAP, Univ. Paris VI, IX, XIII, Univ. Pisa, Univ. Ferrara, Univ. Nantes, IST (Lisbon), Universities of Trento, Pavia, Grenoble, Coimbra, London and Valladolid
J.G. Verwer

Algebraic combinatorics (CT93-0400)
1993-1996
Univ. Magdeburg, KTH Stockholm, Univ. Perugia, Univ. Cagliari, Univ. Bielefeld, Univ. Strasbourg, Univ. Bayreuth, Univ. Vienna, Univ. Paris VI, Univ. College of Wales, Universities of Copenhagen, Erlangen and Bordeaux I, Konrad Zuse Inst.
M.A.A. van Leeuwen

DONET: Discrete optimization and applications (CT93-0090)
1993-1996
Univ. Joseph Fourier, ZOR Bonn, Univ. Oxford
A. Schrijver

ERCIM computer graphics network (CT93-0085)
1993-1996
P.J.W. ten Hagen

ERCIM advanced databases technology network
1994-1997
M.L. Kersten

European Science Foundation Networks

Dynamics of complex systems in biosciences
O. Diekmann

Highly structured stochastic systems
A.J. Baddeley

National Programmes

SION (Netherlands Foundation for Computer Science)

Incremental program generators
1990-1995
P. Klint

Mathematical morphology in hierarchical graph representations of images
1990-1994
Inst. voor Zintuigfysiologie TNO, Univ. Amsterdam
H.J.A.M. Heijmans

Design implementation and application of a transparant distributed computing system
1990-1994
Univ. Twente
M.L. Kersten

Nonwellfounded sets and semantics of programming languages
1991-1995
J.J.M.M. Rutten

Extensions of orthogonal rewrite systems - syntactic properties
1992-1995
J.W. Klop

Computational Learning Theory
1992-1996
P.M.B. Vitányi

MathViews - Functional and architectural aspects of mathematical objects in an Integrated System
1992-1996
A.M. Cohen

Logic programming and non-monotonic reasoning
1992-1996
K.R. Apt

Specification of cryptographic protocols
1993-1997
R.A. Hirschfeld

Themes for collaboration in mathematics and computer science
1993-1997
Universities of Nijmegen and Eindhoven
H.P. Barendregt, J.W. Klop, M. Hazewinkel, A.M. Cohen

Design theory for autonomous databases
1993-1997
A.P.J.M. Siebes

Incremental parser generation and disambiguation in context
1993-1997
Univ. Amsterdam
D.J.N. van Eijck

MDL Neurocomputing
1993-1998
P.M.B. Vitányi

Equational term graph rewriting
1994-1996
J.W. Klop

Generic tools for program analysis and optimization
1994-1998
P. Klint

Checking verification of concurrent systems with type theory tools
1994-1996
Univ. Utrecht
F.W. Vaandrager

Constraints in object-oriented interactive graphics
1994-1998
Univ. Eindhoven
P.J.W. ten Hagen

Higher-order and object-oriented processes (HOOP)
1994-1999
Universities of Eindhoven and Leiden
J.W. de Bakker

MAGNUM, Database technology for multimedia information systems
1994-1998
Universities of Twente and Amsterdam
M.L. Kersten

1993-1996
Univ. Eindhoven
A.M. Cohen, L.G.L.T. Meertens

PBTS (Programmatische Bedrijfsgerichte Technologie Stimulering)

MAGUS: Management Games Utilities Support
January 1992 - December 1993
Lasermedia B.V., Open Univ.
D.C.A. Bulterman

FERSA: Facial Expression Recognition as a driver for lip-Synchronous Animation
January 1992 - December 1993
Valkieser Groep
P.J.W. ten Hagen

Cray Research Grants

Cray Y-MP4 software for a three dimensional transport model for shallow seas
February 1993 - February 1994
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Numerical simulation of brine flow for predicting the potential transport of radioactive pollutants. The 3D case
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RESEARCH STAFF

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Operations Research, Statistics & System Theory

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Algorithmics & Architecture

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Interactive Systems

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Computer Systems & Telematics

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Analysis, Algebra and Geometry

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Numerical Mathematics

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Software Technology

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Algorithmics and Architecture

H. Brinksma	(UT)
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Interactive Systems

F.W. Jansen	(TUD)
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FOREIGN VISITORS

Analysis, Algebra and Geometry

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W. van Assche (Belgium)
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Software Technology

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Z. Suraj (Poland)
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Algorithmics and Architecture

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K. Clenaghan (UK)
C. Crépeau (France)
D. Dubhashi (Germany)
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C.A. Galindo-Legaria (Mexico)
F. Giannotti (Italy)
S. Katz (Israel)
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Z. Navarro-Villicaña (Mexico)
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M. Ruszinkó (Hungary)
P. Safonov (Russia)
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Ph. Tsigas (Greece)
V.A. Uspensky (Russia)
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Interactive Systems

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Computer Systems & Telematics

T. Dimitrova (Bulgaria)
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PUBLICATIONS

Department of Analysis, Algebra and Geometry

AM 1: **Algebra, discrete mathematics, and computer algebra**

Papers in Journals and Proceedings

A.E. BROUWER (1993). A new infinite series of regular uniformly geodetic code graphs. *Discr. Math., 120*, 241-247.

A.E. BROUWER, I.J. DEJTER, C. THOMASSEN (1993). Highly symmetric subgraphs of hypercubes. *J. Alg. Comb., 2*, 25-29.

A.E. BROUWER, W.H. HAEMERS (1993). The Gewirtz graph - an exercise in the theory of graph spectra. *Europ. J. Comb., 14*, 397-407.

A.E. BROUWER (1993). On complete regularity of extended codes. *Discrete Math., 117*, 271-273.

A.E. BROUWER (1993). The linear programming bound for binary linear codes. *IEEE Trans. Inform. Th., 39*, 677-680.

A.E. BROUWER, T. VERHOEFF (1993). An updated table of minimum-distance bounds for binary linear codes. *IEEE Trans. Inform. Th., 39*, 662-677.

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A.E. BROUWER (1993). The complement of a geometric hyperplane in a generalized polygon is usually connected. F. DE CLERCK ET AL. *Finite Geometry and Combinatorics* - Proc. Deinze 1992, London Math. Soc. Lect. Note Ser., 191, Cambridge University Press, 53-57.

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