CWI

Centrum voor Wiskunde en Informatica

ANNUAL REPORT

'91

Centrum voor Wiskunde en Informatica

ANNUAL REPORT

'91

Kruislaan 413, 1098 SJ Amsterdam, the Netherlands
P.O.Box 4079, 1009 AB Amsterdam, the Netherlands

CWI is the research institute of the Stichting Mathematisch Centrum (SMC), founded on February 11, 1946, as a non-profit institution aiming at the promotion of mathematics, computer science, and their applications. SMC is sponsored by the Dutch Government through the Netherlands Organization for Scientific Research (NWO).

ERCIM

CWI is founding member of ERCIM, the European Research Consortium for Informatics and Mathematics.

CWI
Centrum voor Wiskunde en Informatica
Centre for Mathematics and Computer Science

Kruislaan 413 1098 SJ Amsterdam The Netherlands	P.O. Box 4079 1009 AB Amsterdam The Netherlands
Telephone (from abroad)	020-592 9333 +31 20 592 9333
Telefax (from abroad)	020-592 4199 +31 20 592 4199

CONTENTS

This Annual Report is complementary to the Jaarverslag SMC (in Dutch), which concentrates on SMC's National Activities in Mathematics.

INTRODUCTION

Policy

CWI's long term research plans are set out at regular intervals, in the form of Policy Documents. Following on from the previous document covering the period 1988-1993, the Stichting Mathematisch Centrum (SMC) presented further details of the Plan for the period 1993-1997 to the Netherlands Organization for Scientific Research (NWO) in an Interim Policy Document published in November 1991. Key items in the section dealing with SMC's research institute CWI, were as follows:

- ongoing fundamental research, both theoretical and application-oriented;
- stronger promotion of synergetic effects between mathematics and computer science, with realization to include a number of multidisciplinary projects (one of which, Mathematics & the Environment, is described elsewhere in this Annual Report), and a generally greater stress on 'computational mathematics';
- greater attention to the acquisition of research contracts and participation in national and European programmes.

The memorandum also announced new research directions, parts of which were already embarked on in 1991. Included are wavelets, large-scale computation, multimedial systems and advanced information systems.

Computer science research at CWI had previously been evaluated by an international committee (September 1991). CWI has an established reputation as an institute performing high quality theoretical research. The committee recommended that future emphasis should be more on linkage with practice, with no loss of stringent quality standards. It was also suggested that fewer but larger research groups should be formed, and that these should cooperate with industry and universities in covering the entire gamut from theory to practice.

The Computer Algebra Netherlands (CAN) expertise centre was established in 1989 and housed at CWI. The 1991 evaluation by NWO, which provided grant finance for the centre for the first three years, produced a positive outcome. In 1992 the SMC will provide a grant for the expertise centre, whose activities match well with SMC's research interests.

In 1991 CWI felt the full force of the headwinds which had been blowing since 1990. For the first time in many years, the report period closed with a negative balance. Disappointing income contributed to this, alongside higher outgoings. CWI has responded by giving greater priority to acquisition of research commissions. This was evidenced by the appointment of Dr G. van Oortmerssen as Managing Director, in succession to Mr J. Nuis who took early retirement last year. Acquisition of research contracts will be an important task of the new Managing Director.

The report year was also marked by far reaching changes in the area of personnel. Most of the measures proposed the foregoing year to give CWI a healthy structure for the 1990s were implemented during 1991. This involved a painful process of slimming down. This was imperative due to urging from the side of NWO, CWI's main source of finance grants - and from the institute's own wish to streamline research (e.g. by fewer but larger research groups) and appropriate support. Following decisions to reduce the overall research programme back in 1990, outside consultants were called in to look at the support sections during 1991. The resulting reorganization proposal comprised a lighter structure and fewer personnel. The new organization (see page 11) was implemented effective 1st January 1992. It goes without saying that the entire operation made considerable demands on the staff's time and energy.

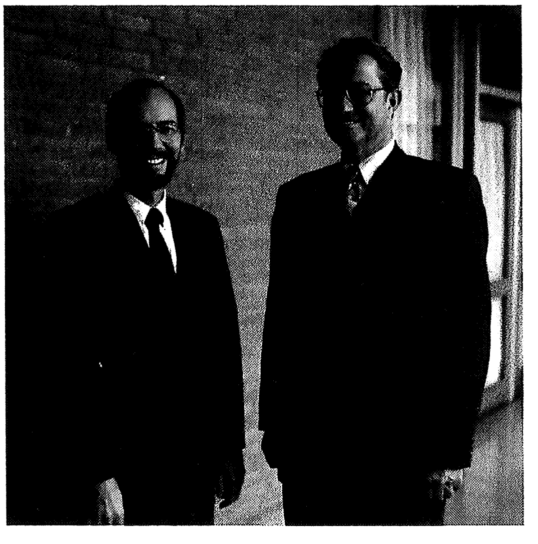
ERCIM

From the very start in 1988, when ERCIM (European Research Consortium for Informatics and Mathematics) was established at the initiative of GMD (Germany), INRIA (France) and CWI (Netherlands), an important aim has been to expand with new members from other European countries. Considerable effort has gone into realizing this during the past two years. SERC/RAL (UK) joined in 1990, followed in 1991 by INESC (Portugal) and CNR/IEI (Italy). The latter, NWO's Italian counterpart, is represented by a cluster of three computer science institutes in Pisa, one of which, IEI (Istituto di Elaborazione della Informazione) acts as correspondent. The report year also saw preparations made for the admission of Norway and Greece, and contacts were opened with Spain. An important criterion for admission is the presence of one or more institutes with a clear national role in computer science or applied mathematics research.

With an eye to formal status within the European Community, in 1991 ERCIM applied for registration as a European Economic Interest Group (EEIG). The ERCIM Bureau opened in April, for the first three years it will be based in Paris (INRIA Rocquencourt). Proof of ERCIM's European dimension was confirmed in June, in Paris, where the Bureau organized the *Research and Technology Transfer in Informatics for Europe* conference. It was attended by some 150 leading representatives of the European informatics research community. Aspects including coordination of ERCIM's fellowship programme and editing of the organization's newsletter were brought under the Bureau.

ERCIM's core activities also include the joint workshops held twice a year. The May workshop at RAL (UK) covered the subjects of *Visualization and Computer Graphics, Databases* and *Numerical Algorithms,* and the November event at INESC (Portugal) dealt with *Distributed Systems, User Interfaces and Multimedia,* and *Decision Support Systems.* The workshops are attracting growing numbers of participants, including some from non-ERCIM bodies. Proceedings of the workshops are being published, starting with the last event in Portugal.

ERCIM's postdoctoral fellowship programme is expanding steadily. Three fellowships were made available for 1990/91, and five for 1991/92. In the next round this will be increased to six. There is considerable interest with between 10 and 15 candidates per fellowship.



A change in management took place at CWI, when Managing Director J. Nuis (above) took early retirement in the fall of 1991. A few months earlier, G. van Oortmerssen (below left) was appointed as his successor. He and Scientific Director P.C. Baayen (below right) form CWI's present Board of Directors.

The ERCIM courses for advanced researchers started at end 1990 with *Large Scale Parallel Scientific Computing* as the first subject. All courses are held at several European locations. The *User Interfaces for Picture Systems* and *Studies in Computer Algebra for Industry* courses started up in 1991. All three of the courses mentioned above were directed by CWI staffers, H.J.J. te Riele, P.J.W. ten Hagen and A.M. Cohen respectively. In each case there was a grant from the European Community's COMETT II programme.

International and national programmes

CWI succeeded in maintaining the same level of involvement in international programmes (ESPRIT II, ESPRIT BRA, RACE, BRITE, SCIENCE, BCR). This was a considerable achievement given burgeoning competition and the increasing concrete application aspect of the programmes, making them less in line with CWI's research profile.

Alongside the ongoing ESPRIT projects, CWI participated in ESPRIT II's *COMPARE* project (Compiler Generation for Parallel Machines), other bodies including ERCIM partners GMD and INRIA, and ESPRIT's *COMPULOG* (Computational Logic) Network of Excellence.

As regards the European SCIENCE programme, it is remarkable that CWI coordinates no less than two of the four mathematics and informatics proposals selected for EC funding in 1991. The first of these is the *System Identification* programme, with as Dutch partner the Systems and Control Theory Network. Coordinator of the programme is J.H. van Schuppen, the director of the network and programme leader at CWI. (For administrative purposes the network comes under the University of Groningen.) The other programme in which CWI participates is *Mask* (Mathematical Structures in Semantics for Concurrency), coordinated by J.J.M.M. Rutten. CWI also participates in two ongoing SCIENCE projects: Evolutionary Systems and Combinatorial Optimization.

The initial phase of the BRITE project *Application of multigrid techniques to fluid dynamics problems* ended in 1991. If extended, CWI research will switch from two to three dimensional problems.

Another project which drew to an end was *RIPE* (RACE Integrity Primitives Evaluation), for which CWI is prime contractor. However, it was extended to at least mid-1992.

Participation in national programmes (SPIN, SION, NFI, STW, IOP) was actually expanded. The greater involvement of the Netherlands Computer Science Research Foundation (SION) in CWI research was manifest both at the policy level (appointment of three members of the Board of Trustees of SMC) and recommendations on the plans for CWI computer science research), and in actual research: four SION projects are presently underway at CWI.

A full list showing CWI involvement in national and international programmes is included in this Annual Report.

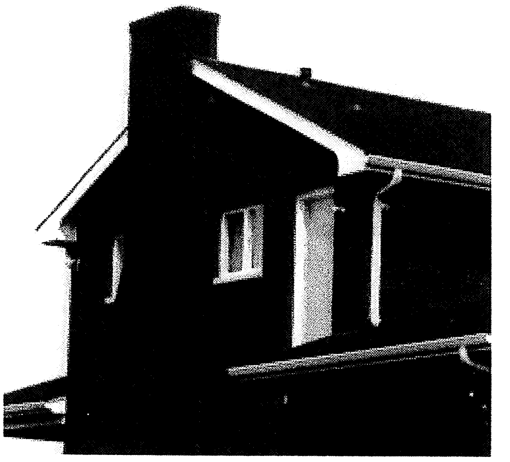
Research programmes

Re-thinking of the course to be taken by CWI in the 1990s had a number of consequences including a halt to a relatively small number of research projects in 1991; the actual total has now been reduced to around 25. A full list of research programmes is included in this Annual Report; more detailed information must necessarily be limited to selected aspects of ongoing research.

Following the 1990 decision to create multidisciplinary programmes cutting across departmental lines, the first of these, *Multimedia,* started in 1991. The departure in 1991 of the designated programme leader for *Mathematics & the Environment* meant that nothing could be realized beyond a definite plan. The programme got underway at the start of 1992. A plan was also made for the *Scientific Visualization* programme.

In *Image Analysis* research the previous years' upward line was ongoing in 1991. The research area already covered stochastic models, discretization, morphology, spatial statistics and support software, and was supplemented with the first results in the field of Markov models for object recognition, error metrics and iterative filters. Among newly started subjects are statistics for 3D images and granulometry. The work on *Reconstruction of NMR Images of the Human Heartbeat* was rounded off with M. Zwaan's Ph.D. thesis.

The ongoing consultation project *Basis Levels in Coastal Areas,* dating from 1984 (statistical research for the tidal waters section of the Public Works department), was virtually completed in 1991. Theoretical



work, results of which were used in the project, were reflected in A.L.M. Dekkers' Ph.D. thesis *On Extreme Value Estimation.*

CWI's leading position in computational number theory, with applications including *factorization of large numbers,* was confirmed by the 'crunching' of a special number with 101 digits on the new, national supercomputer - a Cray Y-MP 4/464 installed at SARA (Academic Computing Services Amsterdam). The factorization occurred almost sixty times faster than had been predicted just a few years ago.

Two research projects on numerical mathematics were rounded off with a Ph.D. thesis: *Numerical Methods for 3D Shallow Water Equations on Supercomputers* (E.D. de Goede, research commissioned by the Public Works department), and *Parallelism in the Numerical Integration of Initial Value Problems* (B.P. Sommeijer).

Intense scientific activity in the Software Technology Department was reflected in six Ph.D. theses in 1991. The subjects covered *Object Oriented Languages* (F.S. de Boer), *Logical Programming* (A. Eliëns, R.N. Bol), *Process Algebra* (J.F. Groote) and *Algebraic Specifications* (P.R.H. Hendriks, H.R. Walters).

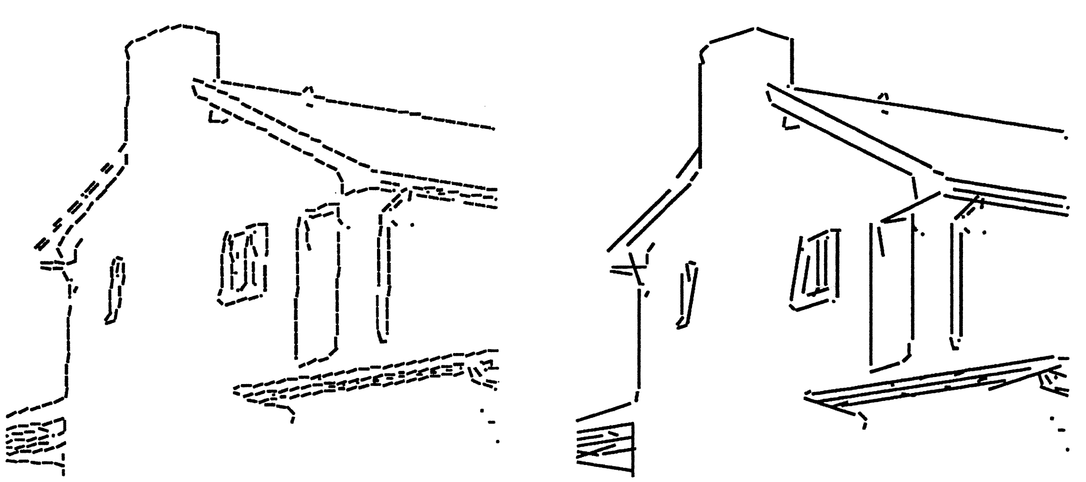
The design of an *interactive graphics workstation* based on an unconventional architecture resulted in a complete prototype. A special edition of the CWI Quarterly was devoted to this and other CWI research in the area of computer graphics.

The fundamental research into communication and interaction between processes, which are important in massive parallel and distributed systems, and in flexible UIMS (User Interface Management Systems), has led to development of the *Manifold* language which allows definition of the dynamical interaction between a set of processes. Unlike the many other multi-process languages Manifold is notable for its stress on the interaction between processes.

P.M.B. Vitányi and M. Li (University of Waterloo) put the final touches to their comprehensive textbook entitled *Introduction to Kolmogorov Complexity and its Applications,* which will be published in 1992.

Joint research on *Databases,* in cooperation with several Dutch Universities, concentrated on development of an integrated framework for the description of information systems (ISDF), and the design of the core for a new generation of database management systems tailored to graph-like objects (Goblin).

Examples of cooperation with bodies outside the academic world were *Performance Analysis of Computer and Communication Systems* (with PTT Research) and *Mathematics & the Environment* (with RIVM). As part of Shell fellowship activities, research was conducted into *Maintenance Optimization in Major Industrial Systems.* There was definite interest from industry (Philips Research) for the *Mathematical Methods for Semi-Conductor Simulation* project, conducted (and ended in 1991) under the national Innovative Research Programme into IC-Technology. CWI also works closely with many university research groups; a particular example is the cooperation in the area of *Computational Linguistics* with Utrecht University's Language and



In CWI's Image Analysis programme, a technique for grouping short line segments has been developed which is used for recognizing linear patterns in images.

Construction and installation of off-shore platforms is a complicated and costly business, and so is their maintenance. CWI research, in the form of a Shell fellowship, deals with the theoretical foundation of maintenance optimization by studying certain queueing models.
Photo: courtesy NAM, Assen

Speech Research Institute.

The NWO Priority Programme supports selected research fields for longer periods (8 years). In 1991 the *Non-Linear Systems* theme secured a grant under the programme. The coordinator is O. Diekmann who leads CWI's 'Mathematical modelling and analysis' programme.

Knowledge transfer, Centre role

Once again in 1991 there was an increase in the number of courses and conferences organized wholly or in part by CWI. In addition to the above-mentioned ERCIM courses for advanced researchers CWI was involved in a number of events.

In August CWI organized the *14th International Symposium on Mathematical Programming* in cooperation with the Free University of Amsterdam and the universities of Amsterdam, Eindhoven, Rotterdam and Tilburg. As well as drawing 800 participants, the event also attracted considerable press coverage. The *Logic in Computer Science* and *CONCUR '91* conferences also proved popular, with 230 and 100 participants respectively. As in 1990, CWI hosted an international *Lie Seminar.*

The *Wavelets* course, following on from the activities of CWI's eponymous working group, was particularly successful with around 100 participants. A course on *Bootstrap Methods* drew forty participants, a large number given the specialist nature of the subject. Such was the popularity of the

Portability with UNIX and C course that it had to be repeated. A total of 45 researchers participated in an international workshop organized as part of *REX* (Research and Education in Concurrent Systems). The annual vacation course for school teachers focused on *Geometric Structures* (160 participants).

Alongside the various publications in periodicals, congress reports and so on, several books by, or with input from, CWI researchers were published during the report year. Examples include:

- *History of Mathematical Programming: A Collection of Personal Reminiscences* (J.K. Lenstra, A.H.G. Rinnooy Kan, A. Schrijver, editors, CWI & North-Holland, Amsterdam);
- *IMACS Symposia on Parallel Scientific Computing, Amsterdam* (H.J.J. te Riele, T.J. Dekker, H.A. van der Vorst, editors, Applied Numerical Mathematics V.7 No.5, V.8 No.2);
- *Logic in AI* (J. van Eijck, editor, LNCS 478, Springer-Verlag);
- *Verification of Sequential and Concurrent Programs* (K.R. Apt, E.-R. Olderog, TMCS, Springer-Verlag);
- *Advances in Object-Oriented Graphics* (E.H. Blake, P. Wisskirchen, editors, Eurographic Seminars Series, Springer-Verlag).

In addition to publication of research results, a key form of knowledge transfer is the nurturing of a scientific cadre for the community at large. Among related achievements in the report year were eight Ph.D. theses, of which six for research at the Software Technology Department. CWI's dedication to knowledge transfer is also clear from the close links built up with the academic world. No less than 20 CWI staff presently hold part-time professorships at Dutch universities. In 1991, two members of staff were appointed to professorships: A.J. Baddeley (Applied Mathematics, Leyden University) and K.R. Apt (Foundations of Artificial Intelligence, Amsterdam University).

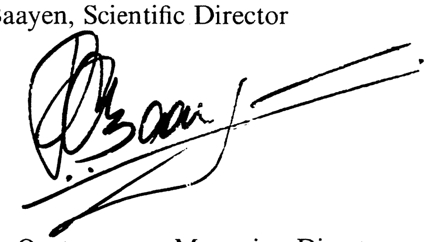
The activities related to operations research, stochastics and system & control theory are a very meaningful demonstration of CWI's central role. CWI coordinates many, regular seminars and national congresses. Scarcely a year goes by in which CWI does not wholly or partly coordinate a major congress. The institute also provides the secretariat of the National Stochastics and Operations Research & System Theory working parties, as well as publishing related newsletters and playing a central role in two graduate networks in the field of System & Control Theory and Operations Research.

Visitors to CWI

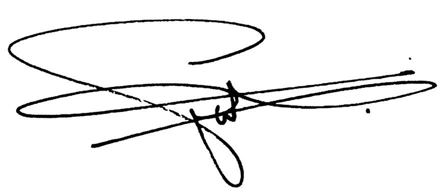
CWI welcomed many researchers for longer or shorter periods during 1991. Several scientific policy bodies also expressed interest in the institute and sent delegations during the report year. Among these were the Dutch parliament's permanent committees for Economic Affairs, Education, and Scientific Policy which made familiarization calls on all the institutes at the Amsterdam Science Centre. Representatives of NWO's Council for the Natural Sciences, the Advisory Board for Science and Technology, and the Director General of the Education and Science Ministry also visited CWI.

Reorienting CWI to the future, and in particular the definite steps taken in 1991, have kept us more than fully occupied. Health and beauty are often equated with a slim figure. The popular slogan in achieving this is 'no pain - no gain'. We have certainly experienced the pain during the report period, but it is too early to judge the results. However, it is our personal conviction that the sacrifices made will pay off in the near future. May we also take this opportunity to express great appreciation for the understanding and commitment devoted by all members of staff to the future prospects of the institute.

P.C. Baayen, Scientific Director



G. van Oortmerssen, Managing 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 falls under The Netherlands Organization for Scientific Research (NWO), the main source of funding.

In line with its statutory purpose 'to foster the systematic pursuit of pure and applied mathematics and computer science in The Netherlands', SMC immediately set up an institute for fundamental research, the Mathematical Centre. From the outset this institute played an important role in the development of computer science in The Netherlands. A change to the present name, CWI, in September 1983, reflected the major expansion of research in this field. On the national level this growth led to the setting-up in 1982 of the Netherlands Computer Science Research Foundation (SION), the independent NWO research organization for computer science. Its formal connection with SMC is twofold: SION nominates three members of SMC's Board of Trustees and advises SMC about CWI's research programme in computer science.

SMC also finances National Research Activities in Mathematics at Dutch Universities. This consists of some 55 research projects, 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.

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

In 1991, preparations were made for two additional types of activities: *Special Attention Areas* and *Special Years.* These will start in 1992 on the subjects 'Mathematical aspects of nonlinear dynamical systems' and 'Logic', respectively.

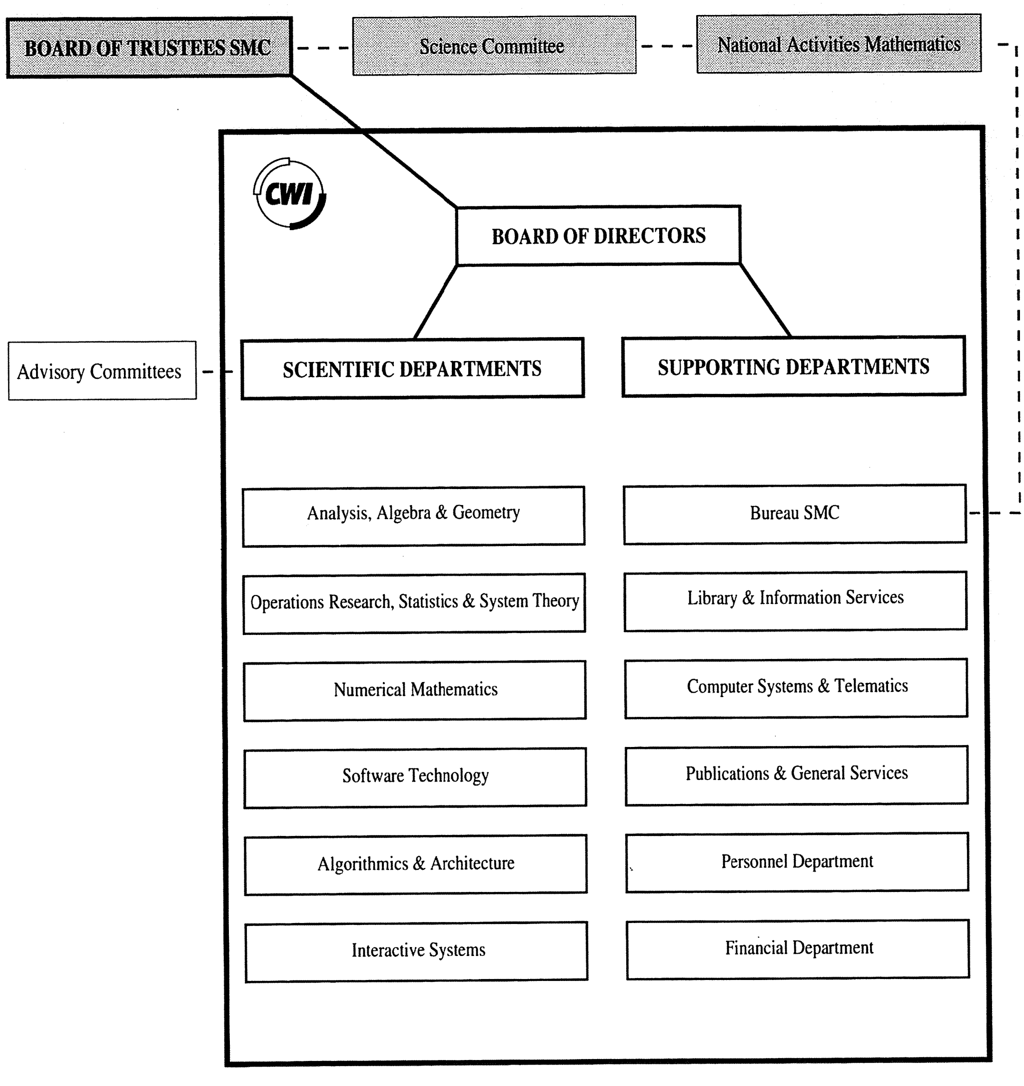
SMC is administered by a Board of Trustees. Actual administration is delegated to the Board of Directors of SMC, which is also responsible for CWI. A Science Committee advises the Board of Trustees on matters of research policy and organization involving both the National Working Parties and CWI. The Science Committee is made up of researchers from universities and CWI. A number of Advisory Committees make recommendations to CWI scientific departments on implementing research plans.

Research at CWI is also evaluated by international visiting committees. The first evaluation, in 1987, covered statistics, stochastics and system theory. The next, in 1989, dealt with algebra, analysis, geometry, optimization and numerical mathematics. In 1991 CWI's computer science research was evaluated.

CWI's goal is fundamental and advanced research into mathematics and computer science, with special emphasis on areas to which the research may have relevant applications. Research is fundamental in that it mainly concerns those problems lacking standard methods of solution. It is advanced, in that CWI aims at a high level, both nationally and internationally. Preference is given to subjects with internationally relevant development potential.

The organization structure of SMC and CWI is shown on the opposite page. The structure of the scientific departments is less rigid than it appears, given considerable inter-departmental collaboration. This has led to the definition of Multidisciplinary Research cutting right across the departmental research groups - and staffed by members of these groups.

Compared to the previous year, the supporting staff has been thoroughly reorganized. The sectors Research Management & Presentation, Social-Economic Affairs and Technical Support were dissolved. The tasks



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

of these sectors were partly taken over by two newly created units: the *Bureau SMC* and *Publications & General Services* and partly by already existing units. Some tasks were discontinued.

The sectors Computer Systems & Telematics and Library & Information Services, remaining mainly unaffected in their tasks, provide CWI with state-of-the-art computer facilities and a well stocked library, respectively. Thus the institute is ideally equipped to handle the dynamic and interdisciplinary demands of present day research.

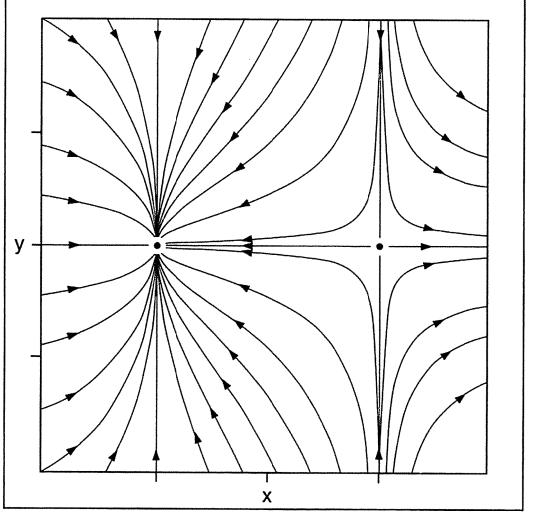
RESEARCH HIGHLIGHTS

Dynamical Systems

What is a dynamical system?

At the end of the 19th century it became clear that many (differential) equations describing classical mechanical systems could not be solved explicitly. And even if explicit solutions were known, the formulas were often so complicated that it was difficult to extract useful information from them. And so, in addition to the analytical methods used up to that time, geometrical methods were developed to obtain at least a qualitative insight in the global behaviour of such systems.

The idea is as follows. Consider a 'real life' system S (at the start of this century, S typically would be a mechanical system, but today one might also think of a chemical, biological, meteorological, ... system). Assume that S is stationary and deterministic, i.e., the laws governing the behaviour of S are time-independent (thus, there are e.g. no changing external influences) and the evolution of the system is completely determined by the initial state. For simplicity, assume that at any moment the state of S can be described by n real parameters; stated otherwise, every state



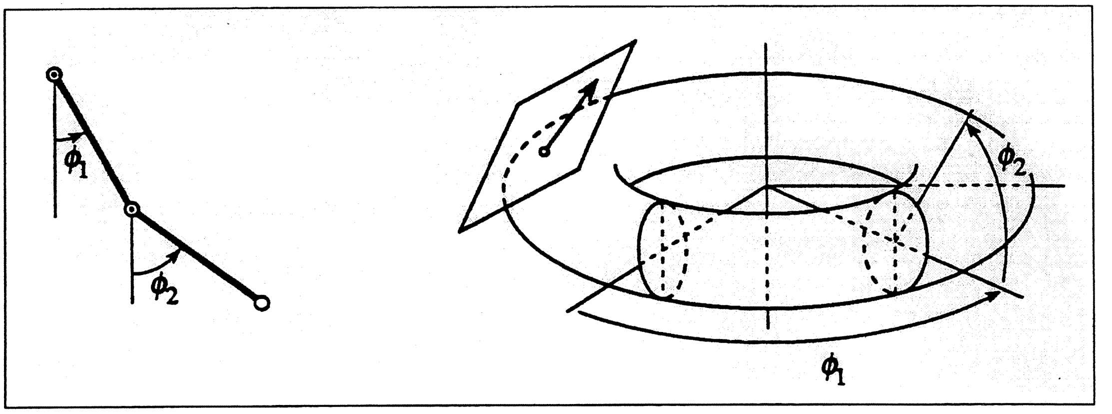
Phase portrait of the non-linear dynamical system $x' = -1+x^2$, $y' = -y$. Although explicitly solvable, the system's behaviour is much easier to read off from the phase portrait than from the formal solution.

of S is described by a point $x=(x_1, \ldots, x_n)\in\mathbb{R}^n$. The subset of $\mathbb{R}^n$, consisting of all points that can possibly describe a state of S, is called the *phase space* of S. (For example, a free moving particle has $\mathbb{R}^6$ for a phase space: its state is given by its position together with its velocity, each of which is described by three real numbers.) If S evolves in the course of time such that at time t it has state $x(t)$, then the point $x(t)$ describes a curve in the phase space: a *trajectory* (often also called *orbit*) of S. If one considers all possible trajectories of S through all possible initial states then one gets a 'picture' of the phase space as a union of (oriented) curves: the so-called *phase portrait.* But the picture one has to keep in mind is that of the points of the phase space moving (or flowing) along the trajectories when time increases; this is called a *dynamical system* (or *flow*). The description of the behaviour of S using such a dynamical system means a shift in attention from individual solutions of the equations governing S to the complete set of all possible trajectories. It is often easy to read off from a phase portrait what will be the qualitative behaviour of the system in the long run, which in turn depends on its initial position.

For this to be useful one needs a theory which, firstly, relates geometrical features of the phase portrait of S with significant physical features of S itself and, secondly, enables one to obtain a phase portrait for S without solving the equations describing S with all possible initial positions. Such a theory was, indeed, developed by Poincaré, Lyapunov, Markov, Birkhoff, and many others in the first half of the 20th century.

Three views of $\mathbb{R}^n$

Above we have assumed that the state of S could be described by points in $\mathbb{R}^n$. Often,



The phase space of a double pendulum is the tangent bundle of a torus.

however, more complicated spaces are needed, sometimes even infinite-dimensional ones; the fact that these more complicated spaces can occasionally be embedded in $\mathbb{R}^n$ for some large n is quite irrelevant. For example, the phase space of a double pendulum is the tangent bundle of a torus (roughly, the union of all tangent planes). As to the type of spaces needed one can make a rough tripartition. This can best be illustrated by again considering systems modeled in $\mathbb{R}^n$.

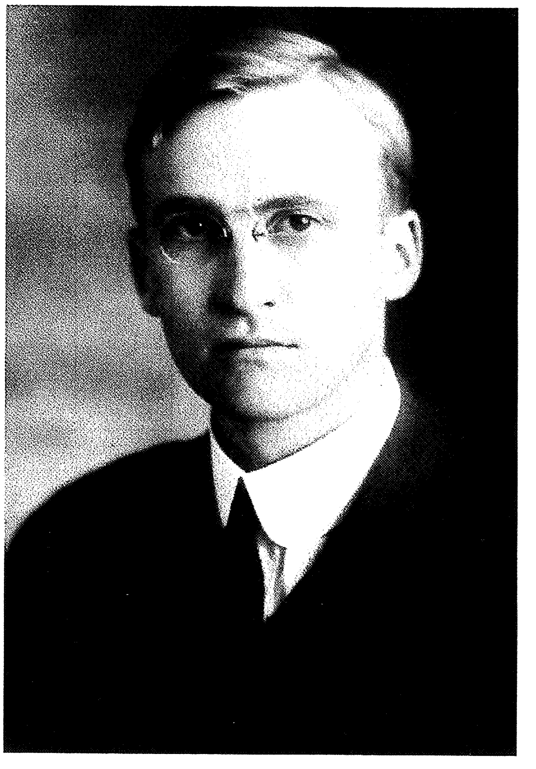
Firstly, one can see $\mathbb{R}^n$ as a *metric space* or, slightly more generally, as a topological space. In this structure one can ask questions like the following: is there an invariant set A in the phase space (invariant under time translation, e.g., an equilibrium state, or a periodic trajectory) such that, if the system's initial state $x(0)$ is close enough to A, its trajectory ultimately converges to A, i.e., $x(t) \to A$ for $t \to \infty$? (Such a set A may be called an 'attractor', though the precise, technical, definition of 'attractor' is more complicated.) A well-known example from electric circuit theory is the behaviour of a system with negative resistance, governed by the Van der Pol equation. A similarly interesting question of great practical importance is whether in a given system there is an initial state $x(0)$ such that $x(t)$ approaches $x(0)$ infinitely often and arbitrarily close without ever becoming equal to $x(0)$ (recurrent, nonperiodic behaviour; e.g. predicted by Poisson for the solar system; not possible in a 2-dimensional phase space). Or: what is the structure of sets of trajectories in the phase space with the property that every trajectory in that set is dense within it, i.e., can approach every point in that set? These are called *minimal sets*, because they have no proper closed invariant subsets. They may be considered as the 'irreducible' parts of a flow. Their frequent occurrence (many attractors are minimal) and complicated structure (a general classification is still lacking) make them interesting objects for further investigation.

Secondly, one can consider $\mathbb{R}^n$ as a *differentiable manifold*: in addition to the metric structure there is now the possibility to use notions like the direction of a trajectory in a point of the phase space, or the touching of certain invariant submanifolds of a flow in contrast to transversal intersection. Among the many possibilities that this richer structure offers we mention in particular the study of conditions under which significant features of a phase portrait do not (or, conversely, do) change after a small perturbation. This is a question of great theoretical and practical importance. Even the most sophisticated mathematical model only approximates reality. The sensitivity of such a model to small perturbations gives some insight into its value to represent essential features of reality.

Finally, one can view $\mathbb{R}^n$ as a *measure space*: for many systems it makes sense to define the notion of 'volume' of all subsets of a certain type in such a way that these sets keep the same volume as time proceeds. These systems (which are, in a sense, 'incompressible' or 'non-dissipative') enable more detailed treatment of many questions about the topological or differentiable structure of the flow (e.g., there will always be recurrent behaviour). Moreover, this structure is indispensible for the description of very large and complicated systems: it enables the study of averages of observable quantities of the system described by the flow.

The three fields of research in which one considers flows on topological spaces, differentiable manifolds and measure spaces

Two founding fathers of the theory of dynamical systems were (left) the Frenchman Henri Poincaré (1854-1912) and (right) the American of Dutch descent George David Birkhoff (1884-1944).



are called, respectively, topological dynamics, differentiable (also: smooth) dynamics, and ergodic theory. Because of the difference of structure of the underlying spaces these fields have completely different flavours, and widely divergent specializations are required (roughly: general topology, global analysis and differential geometry, and probability theory, respectively). Nevertheless, there is a growing interaction between these fields.

At present much research in dynamical systems theory is devoted to systems with 'strange attractors' exhibiting 'chaotic behaviour': deterministic systems which in the long run exhibit a stochastic behaviour. Such systems often have an attractor with a 'pathological' topological structure. In relation to the view on dynamical systems presented here it is important to note that such structures were known to topologists and studied as early as the 1920s (think of notions like the Cantor set, Menger curve, Sierpinski triangle and Hausdorff dimension). Many beautifully coloured computer generated pictures have been published of late. The study of such systems in general requires techniques from all three fields mentioned above.

Research at CWI

A number of past and present CWI projects relate to dynamical system theory. This comes as no surprise as it has more in common with a philosophy - a way of looking at systems - than with a precisely defined research area.

Past projects include Spectral Atmospheric Models, Stochastic Population Dynamics and Stochastic Processes; and ongoing research in Systems and Control and in Biomathematics also comprises elements of dynamical systems theory. However, from 1976 onwards one project has specifically studied dynamical systems - in particular topological dynamics - under various headings (Topological Transformation Groups, Topological Dynamics, Dynamical Systems).

Research in this project has been rather abstract. The flows are admitted to have a phase space of arbitrary topological structure. Also 'time' is not considered as a real parameter, but as a variable running through an arbitrary topological group (a simple, and frequently occurring example of such a broader notion of time is discrete time). In fact, one studies the 'behaviour' of points of a topological space under the action of a topological group, where the term 'behaviour' has to be understood in a sense meaningful for (or: which can be traced back, historically, to) the qualitative analysis of dynamical systems as explained above. This generalization does not make the considerations any more complicated, and has the advantage of giving better insight into the nature of dynamical systems. The research in the project has been concentrated on the study of compact minimal flows: flows on compact Hausdorff spaces where all trajectories are dense. One of the fundamental tools in this theory was created by R. Ellis in the 1960s: dynamical properties of compact minimal flows are expressed in terms of algebraic properties of certain semigroups related with these flows. Several important contributions to this theory were made at CWI in the period 1976-1984, most of these have been published in CWI Tract 22.

As yet this 'abstract' theory of dynamical systems has very few applications. A notable exception is the theory of non-autonomous differential equations, i.e. equations of the type $x'=f(x,t)$, where the time variable explicitly appears, thus invalidating certain nice group properties of the solutions (older work by G.R. Sell, more recent work by I.U. Bronshtein). Another exception is Ellis' recent proof of Moore's Ergodicity Theorem, which plays a fundamental role in Margulis' theory on lattices in connected (semi-) simple Lie groups. There is a strong belief that more applications are possible. For instance one might consider a geodetic flow on a surface of negative curvature. Much work still has to be done in this direction. A serious handicap is that most results of this 'abstract' theory are scattered over several mathematical journals, and not written in a style that invites non-specialists to consult them. Therefore, about 1983 the plan was conceived to write a book in which all material relevant for the 'abstract' theory of minimal flows is exhibited in a manner accessible to all (including non-experts). This book, 'Elements of Topological Dynamics' (ca. 700 pages), will appear in print late 1992 or early 1993.

After the closure of this project the expertise gained will be exploited in a completely different direction in the context of Biomathematics. Here the attention will be more on applications and, in particular, on chaotical systems; a combination with research in ergodic theory should prove fruitful.

Percolation and Critical Phenomena

Introduction

Percolation theory deals with the study of large-scale connections in random media. It was introduced in the late fifties by Broadbent and Hammersley to get a better understanding of transport phenomena in disordered media, like filtration of gas or fluid in porous stone, the spread of disease in an orchard, or rumours in human society. It soon became relevant in statistical physics as a model which has interesting critical behaviour, i.e. where the behaviour drastically changes when a parameter of the model exceeds a threshold value (e.g. the critical temperature marking the transition from a normal to a superconducting state of matter). Moreover, while very simple to define, it has the essential properties and difficulties of more realistic models. Not only is percolation itself an example of critical behaviour, it also plays an occasionally subtle role in other critical phenomena like spontaneous magnetization, polymerization and instability of certain large communication networks. Its wide importance is indicated by the title of an article by the (1991 Nobel prize winning) French physicist De Gennes: *'La percolation: un concept unificateur'.*

We will briefly discuss the basic percolation model, a time-dependent extension of this model, and one of the physical phenomena where percolation is relevant: spontaneous magnetization. Finally we briefly review CWI research in this field, which emphasizes mathematically rigorous results.

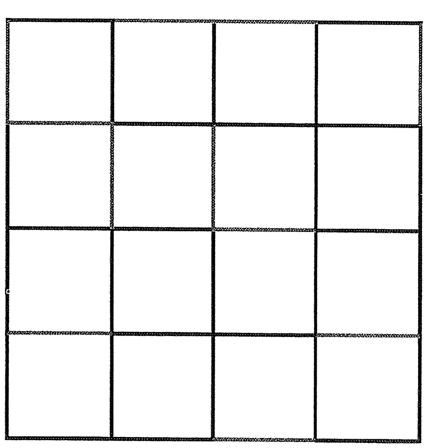


Figure 1
A 4x4 sponge with open (green) and closed (red) edges. The blue-coloured cells become wet if the sponge is surrounded by fluid.

Percolation

In Figure 1 we see a 2-dimensional 'sponge', consisting of square-shaped 'cells'. Each cell is separated from its neighbours by four edges. Suppose each edge, independent of the others, is with probability p *open* (permeable) for a certain fluid and with probability $1-p$ *closed.* If fluid surrounds the sponge, it will enter the sponge and spread wherever it can by using the open edges. A natural question is what will typically happen in a very large sponge. It turns out that there exists a critical probability P_c, such that, roughly speaking, for $p<P_c$ only the cells close to the surface get wet, while for $p>P_c$ the fluid really percolates (i.e. reaches a non-vanishing fraction of the cells as the size of the sponge tends to infinity).

Instead of studying large finite sponges we could study an infinite sponge which covers the entire plane. A natural question is then: suppose a single cell in this infinite sponge is a source of fluid which spreads wherever it can via the open edges; can the fluid reach an infinite number of cells? The answer is: if $p<P_c$ this does not happen (has probability 0), but if $p>P_c$ this event has a non-zero probability (the percolation probability) denoted by $\Theta(p)$.

Above, the sponge is represented by the square lattice. We could also take other lattices like the triangular lattice or the three-dimensional cubic lattice. For the square lattice P_c is exactly $1/2$ (this has a difficult proof), but for most lattices the exact value of P_c is not known. Much research is done to estimate P_c and to describe the behaviour of $\Theta(p)$ for p close to P_c (see Figure 2).

The model discussed here is called *independent bond percolation.* If the randomness involves the cells instead of their edges, we speak of *site percolation*; if the edges do not behave independently we speak of *dependent percolation.*

Instead of the filtration of fluid the process can also be interpreted as, e.g., a disease in a population (if $p > P_c$ a single infected individual can cause an epidemic).

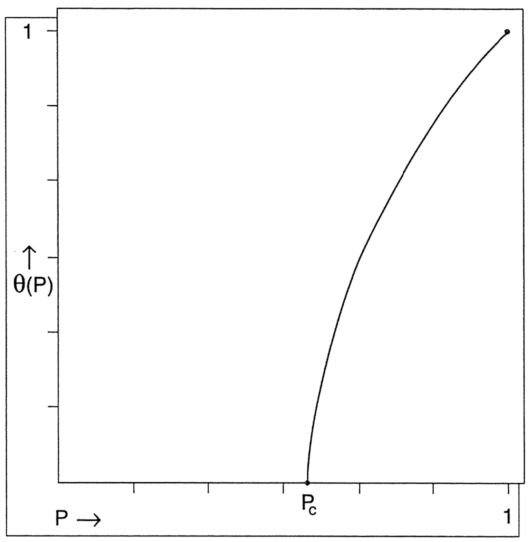


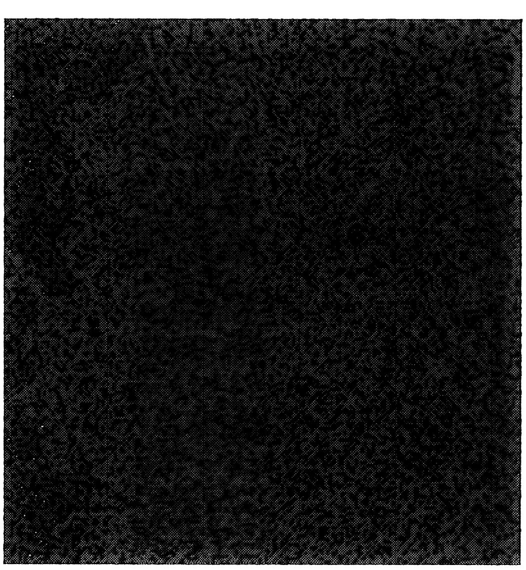
Figure 2
Typical shape of the graph of the percolation probability Θ (P). It is believed that Θ (P_C)=0, as suggested by the picture. This has been proved for two and for sufficiently high dimensions, but in general (e.g. for three dimensions) this is an open problem.

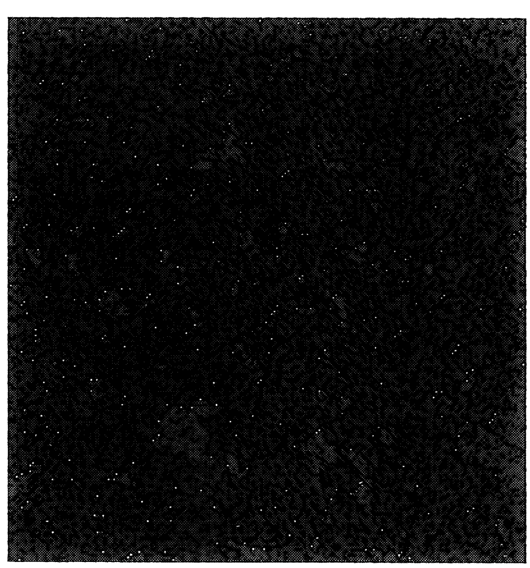
Time-dependent percolation

The percolation model discussed above is static: it describes *which* cells get wet but not *when.* An extension of the model which does involve time is *first-passage percolation.* First we choose a probability distribution P on the non-negative real numbers. Instead of the attribute 'open' or 'closed', each edge now receives, independent of the other edges, a random number (called its *time coordinate*), drawn according to the probability distribution P. The time coordinate of an edge represents the time it takes the fluid to pass that edge. This is illustrated in Figure 3. Instead of studying large finite sponges we turn to the infinite sponge. Let τ_n denote the time at which the cell located n steps to the right of the source is reached by the fluid. One of the first results in the theory is that (if P satisfies certain conditions) τ_n / n almost surely converges to a constant μ, called the time constant. In the one-dimensional case (i.e. if the sponge is an infinite one-dimensional string of cells) this is merely the strong law of large numbers and μ is the first moment of P. In two and higher dimensions μ is not exactly known (except for trivial choices of P) and much effort is put into making reasonable estimates. Other subjects of study are the speed of convergence of τ_n / n to μ, and the asymptotic ($t \to \infty$) shape of the set of cells which are wet at time t.

Spontaneous magnetization

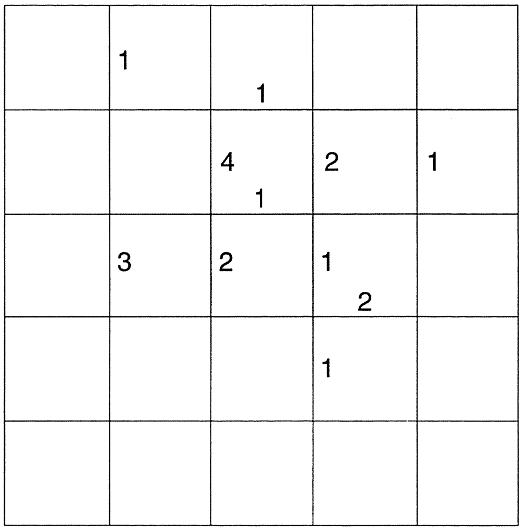
A famous mathematical model of magnetization is the Ising model. Here the physical medium is represented as a lattice, where each vertex has a spin equal to either $+1$ or -1 (see Figure 4, the two-dimensional case). Neighbour spins attract each other (i.e. have a tendency to be equal) but there is no direct interaction between spins which are not neighbours. More precisely, if all spins but one are known, then the conditional probabilities that this unknown spin has value $+1$ or -1 are $e^{\alpha s} / Z$ and $e^{-\alpha s} / Z$ respectively.



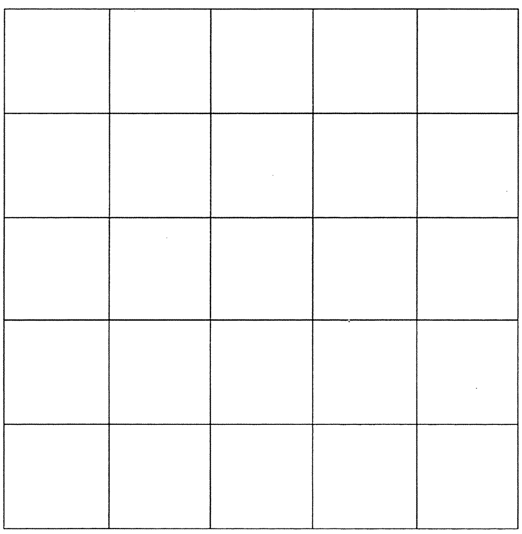


Site percolation on the square lattice: a large (200x200) sponge, whose cells are passable with probability p, has been 'invaded' by fluid (red) from the left. Left: a typical configuration for p = 0.57; right: the same for p = 0.62 . The critical value for this model is about 0.593 . This simulation was done with the program SitePerc in the package IpsMovie which complements the book 'Lecture Notes on Particle Systems and Percolation' by Richard Durrett (Wadsworth & Brooks/Cole, 1988).

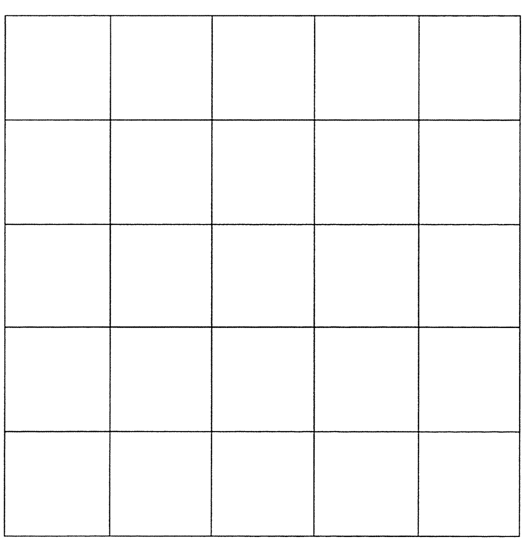
Figure 3:
(1) Example of a 5x5 sponge with time coordinates. Edges without a number are assumed to have time coordinates larger than 4. The blue cell is a source.



(2) The situation two time units after the source in Fig.3 starts to work.



(3) Situation at time 4.



Here s denotes the sum of the spins of its neighbours, α is a positive parameter determining the interaction strength, and Z is just the normalizing factor $e^{\alpha s} + e^{-\alpha s}$. The complete symmetry between $+$ and $-$ might suggest that in a large box the fraction of $+$ and $-$ spins is approximately $1/2$. This is indeed what happens if α is small: then the interaction is so weak that spins at large distances behave almost independently and (as in the case of complete independence) the fractions of both types of spins are approximately equal. However, if α is larger than some critical value, spins at arbitrarily large distances have a non-negligible influence on each other (not directly, but via their neighbours, the neighbours of their neighbours, etc.). As a result, with very large probability the fraction of either $+$ or $-$ spins is essentially larger than $1/2$, causing a non-zero overall magnetic field: this is spontaneous magnetization. This behaviour is even more manifest if we study the infinite system: the phenomenon can then be described in terms of (non)-uniqueness of so-called Gibbs measures.

All kinds of variations of the model exist: higher dimensions; long-range interaction; presence of an external field; repellent interaction, etc.

A nice and useful relation with percolation is given by the Fortuin-Kasteleyn representation in which spontaneous magnetization corresponds to certain (dependent) percolation.

Work at CWI

Above we have discussed critical behaviour of the 2-dimensional Ising model with nearest-neighbour interaction. The one-dimensional analogue can be described by the classical theory of aperiodic finite-state Markov chains. As such Markov chains have a unique equilibrium state, these 1-dimensional Ising models do not exhibit critical behaviour. However, certain 1-dimensional Ising models with *long-range* interaction do have critical behaviour. So-called $1/r^2$ models are particularly interesting. Some years ago an important conjecture for these models was proved independently and by different methods by American researchers and at CWI. This result is considered as a major contribution to the theory of Ising models.

More recently, in cooperation with Cornell University, first-passage percolation was studied. The investigation looked at whether the time constant strictly decreases under certain changes of the time coordinate distribution. This appeared to be closely connected with the following problem: consider all possible paths in the sponge from the source to the cell n steps to the right. Let Π_n be the path with the shortest travel time (i.e. for which the sum of the time coordinates of the edges is minimal). This path π_n has, by definition, a preference for edges with small time-coordinates. Is it possible that Π_n essentially avoids certain values of the time coordinates? More precisely, let $A \subset \mathbb{R}^+$ be such that $P(A)>0$. Is it possible that $1/n \times$ (the number of edges crossed by Π_n which have time coordinate in A) tends to 0 as n goes to infinity? We have proved among other things that, under certain mild conditions, the answer is negative. One of those conditions is that the probability that an edge has time coordinate 0 should not be larger than the critical probability for bond-percolation (otherwise there are infinitely long paths on which all edges have time coordinate 0, and the fluid will, roughly speaking, explode along these paths). The proof of the result uses block-rescaling techniques (large blocks of cells are considered as single cells in an auxiliary percolation model) to show that Π_n crosses many (of order n) blocks sharing the same, specially chosen property. Then a modification technique is used to show that Π_n also crosses many blocks with a modified property. This property is chosen in such a way that we can then conclude that Π_n has of the order n edges with time coordinate in A.

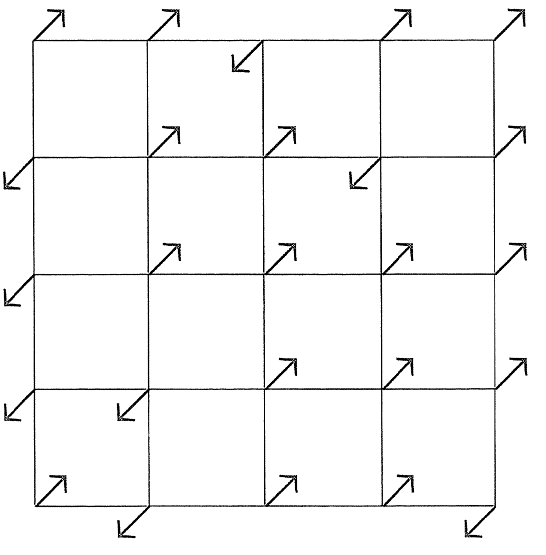


Figure 4:
One of the 2^{25} possible configurations of a 5x5 spin system.

↗ denotes +1
↙ denotes -1

Most recent work involves application of percolation theory to the 2-dimensional Ising antiferromagnet (where the interaction between neighbours is repellent instead of attractive), and to the hard-core lattice gas model (in cooperation with Chalmers University, Gothenburg). This last model is not only relevant in statistical physics, but also in operations research: it is the equilibrium state of a communication network where calls are generated for transmission at the nodes, but ignored (lost) if the node, or at least one of its neighbours, is busy. This again gives an example of critical behaviour: if the arrival rate is small, there is only short-range dependence, but if it is sufficiently large, a change at a given node can influence nodes at arbitrarily large distance.

Semi-conductor Device Simulation

Introduction

During the last three decades the development of semi-conductor devices has been explosive. Semi-conductor devices are components of electric circuits, varying from diodes and several transistor types to thyristors. In integrated circuits, or 'chips', many of such transistors are integrated on a single silicon crystal. The first integrated circuits, which became commercially available in the early 1960s, contained just a few devices. Today, however, it is possible to produce integrated circuits containing tens of millions of devices per single chip. This progress was made possible by reducing the dimensions of the individual devices. Naturally, it is important to test the chips before mass production, e.g. to establish the behaviour of the electric currents. However, because of the down-scaling, the devices became less accessible for direct measurements. Hence the increasing use of simulation in the development of new devices. Declining costs of computer resources (thanks to the above-mentioned miniaturization) now make these simulations much cheaper than experimental investigations. Moreover, simulations are more flexible, so their use may yield a better end product, because it is feasible to consider many more options.

The essential step in the production process of semi-conductor devices is the localized introduction of impurities or dopant atoms in the semi-conducting material. The presence of these dopant atoms greatly affects the electric properties of the semi-conductor. In a device simulation this electric behaviour is predicted given the distribution of the dopant concentrations (the doping profile) and the geometry of the device. In 1988 CWI started the IOP IC-Technology project 'Numerical Device Simulation'. This project investigates the development of efficient numerical algorithms for the device simulation.

Device simulation

Usually the electric behaviour of a device is described by the drift-diffusion model: the electrons move under the influence of the applied voltage, and electron diffusion is accounted for by making certain simplifying assumptions on their collective behaviour. Mathematically the model consists of a system of three non-linear partial differential equations, the semi-conductor equations. The model was first proposed by Van Roosbroeck in 1950.

Early device modeling was based on the division of the interior of the device into a few different regions, in which explicit analytic solutions are obtained by making some (very) restrictive assumptions. The solutions in the different regions are then matched at the boundaries to produce an overall solution. This classical approach gives some understanding of the operation of the device, but because of the restrictive assumptions it has limited applicability and is not particularly suited for engineering purposes.

In practical situations a more fruitful approach is to solve the semi-conductor equations by numerical means. The first step is then the discretization of the problem. Hence the device is covered by a computational grid. On this grid we define a set of simple basic functions, and we approximate the solution by a finite sum of those basic functions. In this way the original set of three partial differential equations is converted into a huge system of (10,000 or more) algebraic equations that can be solved on a computer. It is clear that accurate approximations require very fine grids. However, the finer the discretization grid used, the larger the system of equations that needs to be solved.

Multigrid

As the semi-conductor equations are non-linear they cannot be solved directly. The only feasible solution method is iteration. Relaxation methods are a special, simple form of iteration, well-suited for our purposes. The basic idea is to consider one point of the grid and solve the equations related to

Employee of an IC-plant watching a conveyor-belt with silicon slices. Each slice contains about 100 IC's (size ~1 cm^2). Each IC contains about one million devices (size ~ 5μm^2). CWI performed numerical computations on such individual devices, using a combination of multigrid and adaptive techniques. The work was part of the national IOP-programme on IC Technology.

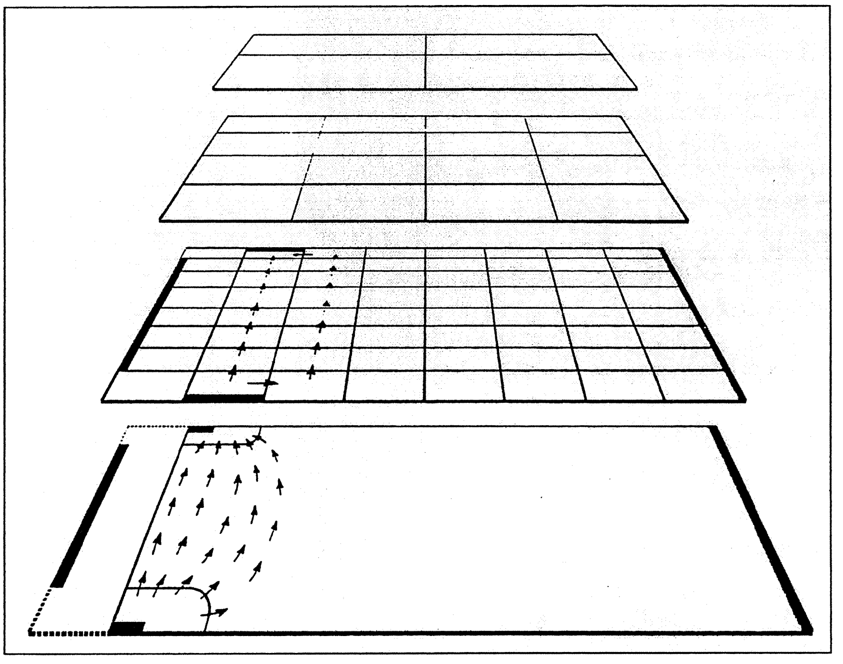
Photo: courtesy Philips Research.

that point for the variables associated with that point, whereas all other variables are kept fixed. This is done for all grid points (one 'sweep'). As a result the solution 'relaxes' to a new solution, after which the procedure is repeated. Examples of commonly used relaxation methods are Jacobi or Gauss-Seidel relaxation. In Gauss-Seidel relaxation the new values for the variables are substituted immediately, whereas in the Jacobi-relaxation the new values are applied only after all points of the grid have been visited. As an alternative to these point-relaxation methods it is also possible to relax whole lines of points; this is called a line-relaxation.

Such iterative techniques have the disadvantage of slowing down if the mesh gets finer, therefore multigrid acceleration techniques are considered. The major advantage of multigrid is that in a number of cases the amount of computational work needed to solve the discretized system of equations, can be shown to be proportional to the number of points in the discretization grid. In fact, in those cases the method is not only optimal with respect to the amount of work, but also with respect to the memory usage.

The basic idea of multigrid is to use a sequence of grids which contain an increasing number of grid points. The equations on the finest grid are then solved by a combination of relaxation sweeps on that finest grid, and corrections calculated on a coarser grid. This idea is used recursively: the equations on the coarser grids are again solved approximately by a multigrid method; the equations are only solved accurately on the coarsest grid. It is this recursion which yields the aforementioned optimality. We remark that the choice of a proper relaxation procedure is of prime importance for the efficiency of any multigrid method.

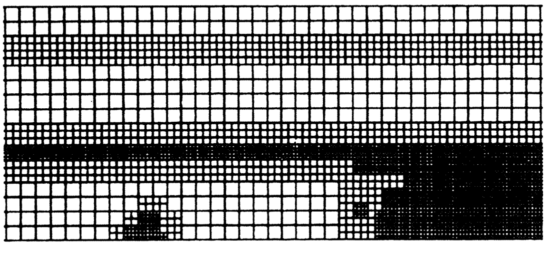
The multigrid principle was originally proposed in the 1960s by Fedorenko and Bakhvalov. During the late 1970s and in the 1980s the multigrid method gained broad acceptance, and is presently being used to solve problems in a wide class of application areas, including aerodynamics and petrol reservoir simulation.



Application of multigrid methods can substantially speed up the numerical solution of semiconductor equations. The semiconductor device (bottom, arrows indicate electric currents) is covered with a hierarchy of increasingly coarser grids (here drawn as separate levels on top of each other). During the iterative solution of the equations on the finest grid, it transpires that use of a coarser grid accelerates computation of the intermediate steps. The same procedure can be applied to the coarser grid, etc. Efficient communication between the levels is of course essential for the success of this method. CWI successfully combined multigrid techniques with adaptive methods (allowing for local grid refinements) to solve the semiconductor equations.

Multigrid for device simulation

In view of the success of the multigrid method for other application areas one is also tempted to try it for numerical device simulation. However, it is by no means straightforward to apply the multigrid technique here. The problem is strongly non-linear and the unknown variables (e.g. electron densities) vary enormously in magnitude throughout the device: in typical problems we observe a variation of more than 15 orders of magnitude.



Example of adaptive grid.

Earlier research at CWI had already shown that the multigrid method is well suited for one-dimensional device simulation. In the IOP IC-Technology project CWI researchers focused on its application to two-dimensional device simulation.

The first algorithms developed were based on a standard point Gauss-Seidel relaxation method. A good grid independent convergence behaviour was obtained for a bipolar transistor problem: the convergence rate of the algorithm does not deteriorate if the mesh-size gets smaller.

The concept of the use of increasingly finer grids offers another possibility for constructing efficient algorithms: instead of refining the mesh uniformly over the computational domain, we merely refine the mesh in those small regions where the solution changes rapidly. The coarse grids in the multigrid algorithm are then also used to decide where the mesh is to be refined. This combination of multigrid and adaptively constructed grids yields a highly efficient algorithm. We were able to carry out adaptive calculations, e.g. for the transistor problem.

In 1991 CWI research turned towards more difficult test problems, such as MOSFET-devices. It transpired that the point Gauss-Seidel relaxation was not effective enough for these problems. Hence, a more powerful relaxation method was invented, based on a combination of Jacobi- and so-called zebra-relaxation. The latter is a variant of line Gauss-Seidel relaxation. The lines are divided in two groups (white and black), which are relaxed consecutively. This combination turned out to be very effective, and good convergence rates were observed, also for the MOSFET-devices.

The main result of this research is that it clearly shows how multigrid can be used as an extremely efficient technique for the numerical solution of the discretized semiconductor equations, in particular where the system of non-linear equations becomes very large.

Term Rewriting Systems

Introduction

Many computations can be modeled as step-by-step transformations or rewriting of a string of symbols (words, expressions, terms), intended to reach some final result as an answer (a 'normal form'). Such a rewrite step, to be perceived as an atomic computation step, consists of replacing part of the expression by a simpler part, according to the rules of a 'term rewriting system'. Hence, for example in arithmetic:

$$(3+5)\cdot(1+2) \to 8\cdot(1+2) \to 8\cdot 3 \to 24.$$

Sometimes rewriting is also called 'reduction'. The rewriting process is non-deterministic: the answer 24 can be obtained by different rewriting sequences, e.g. also

$$(3+5)\cdot(1+2) \to (3+5)\cdot 3 \to 3\cdot 3+5\cdot 3 \to$$

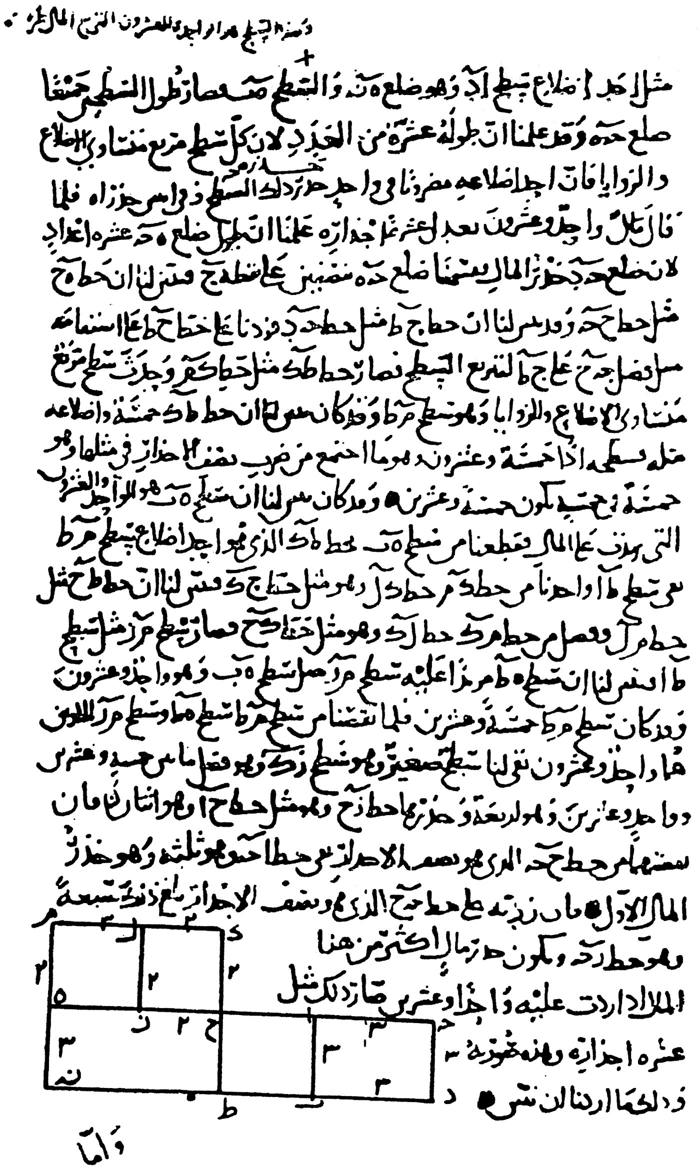
$$9+5\cdot 3 \to 9+15 \to 24.$$

The study of term rewriting systems belongs to the area of symbolic computation. The main applications of term rewriting are in the fields of abstract data types and algebraic specifications, automated theorem proving, functional programming and logic programming.

Development

The roots of term rewriting can be traced back to the ancient Greek and Arab world: e.g. the algorithm of Euclid computing the greatest common divisor of two natural numbers, and computation rules for arithmetic in Arabic scriptures giving rise to 'algebra'.

The first proper systematic development and study of term rewriting systems occurred in the 1930s with the invention of two prime examples of term rewriting systems called λ-calculus (λ for short) and Combinatory Logic (CL) by the pioneering logicians H.B. Curry, S.C. Kleene, A. Church and J.B. Rosser, who used these systems to formalize for the first time the notion of a computable number-theoretic function. (An example of such a function is squaring a number; in general,



Part of the 9th century Arabic work 'al-Jabr wa l-muqabala' by the great mathematician al-Khowarizmi (whose name also lives on in the term 'algorithm'), dealing with the solution of the quadratic equation $x^2+21=10x$. The term 'al-Jabr', literally meaning 'restoration', refers to the removal of negative terms by transfer to the other side of an equation, whereas 'l-muqabala' indicates the placing of terms next to each other for comparison. Modern term rewriting systems are still based on similar principles to those used almost a thousand years ago.

any operation on numbers that can be computed by an ideal computer such as the Turing machine, is a computable function.) Surprisingly, it turned out that λ and CL have the same computational power as Turing machines. Both systems are extremely simple to set up, but generate a large and rich theory. For example, Combinatory Logic consists of three rewrite rules:

$$(((S{\cdot}x){\cdot}y){\cdot}z) \rightarrow ((x{\cdot}z){\cdot}(y{\cdot}z))$$

$$((K{\cdot}x){\cdot}y) \rightarrow x$$

$$(I{\cdot}x) \rightarrow x$$

Here S, K, I are the basic constants and x, y, z are variables for terms. It is understood that a part of a term, built from S, K, I, and matching the left-hand side of one of these rules, may be replaced by the corresponding right-hand side. The binary operator '·' is called application; often its notation is suppressed. Thus we have e.g. the two step rewrite sequence

$$(((SK)I)I) \rightarrow ((KI)(KI)) \rightarrow I$$

which cannot be prolonged since the final term I is irreducible (a 'normal form'). Not all terms in CL can be rewritten to a normal form: for instance $((SI)I)((SI)I)$ cannot. This term admits a cyclic rewriting sequence, as in the display.

$$\underline{((SI)I)((SI)I)}$$
$$\downarrow$$
$$\uparrow \quad \underline{(I((SI)I))}(I((SI)I))$$
$$\downarrow$$
$$((SI)I)\underline{(I((SI)I))}$$

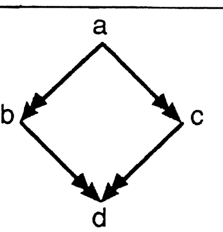
Cyclic rewriting sequence in Combinatory Logic. Underlining indicates the subterm being rewritten.

Since rewriting is a non-deterministic procedure (i.e. sometimes different parts of a term can be rewritten), rewriting sequences starting from the same term may lead to quite different terms. Fortunately, the famous Church-Rosser theorem for λ and CL states that any two 'diverging' rewritings of the same term can be continued to converge again. One of its consequences is the consistency of the systems λ, CL; another, that whenever a term can be rewritten to an answer (an irreducible term, mostly called 'normal form'), this answer is unique. A system satisfying the Church-Rosser theorem is also called 'confluent'.

A particular feature of the system is its 'type-freeness'. Usually, mathematical objects have types, distinguishing e.g. a function from its arguments; the function has a higher type than the arguments, thereby ruling out self-application, where a function is one of its own arguments. But in λ and CL self-application is allowed, as e.g. in the term $(I{\cdot}I)$. The systems λ and CL are quite strong: every computable function can be represented in them. Compared to the 'special purpose' term rewriting system in the display which only computes addition and multiplication on natural numbers, the systems λ and CL are 'general purpose' systems.

add(x, zero)	→	x
add(x, succ(y))	→	succ(add(x,y))
mult(x, zero)	→	zero
mult(x, succ(y))	→	add(x, mult(x,y))

Term rewriting system computing addition and multiplication of natural numbers, generated by zero *and* successor.



Confluence: for all reducts **b**, **c** *of* **a** *there exists a common reduct* **d**.

Originally arising from mathematical logic, λ and CL became firmly established in computer science in 1969, when D. Scott devised the first mathematical model for them which led to a breakthrough in the theory of 'denotational semantics' of programming languages. The endeavour of denotational semantics is to assign a proper mathematical meaning to programs; e.g. the function 'squaring a number' is the mathematical meaning of a computer program which outputs the square of a number. In the mathematical meaning one abstracts from the actual way that the program performs the squaring (the operational semantics). Apart from foundational relevance, λ and CL also turned out to possess practical relevance: for example, J. McCarthy (1962) derived his inspiration for the design of the programming language LISP from λ.

In parallel with the type-free versions of λ and CL, mathematical logic has studied typed versions of λ and CL, which adhere to the intuitive distinction between (the type of) a function and its argument, thus forbidding self-application. In striking contrast with type-free λ-calculus and CL, the typed versions generally obey the termination property: infinitely long rewriting sequences are non-existent.

Proving the termination property of typed λ-calculi often involves great sophistication. Today the area of typed λ-calculi and constructive type theory is the subject of vigorous investigation in theoretical computer science.

An altogether different branch in term rewriting started with a seminal paper by Knuth and Bendix, who introduced (1971) the method of 'critical pair completion' as a means to solve the word problem in equational theories describing algebraic structures such as groups, rings, etc. The word problem is the problem of deciding whether some equation in e.g. the language of groups, is true.

The method is nowadays applied for a variety of purposes, including automated theorem proving, computing with equations, 'inductionless induction' (or 'proof-by-consistency'), as well as applications in computer algebra (e.g. determination of Gröbner bases of ideals in polynomial rings).

In recent years attention has been given to a generalization of term rewriting called 'graph rewriting'. The main idea, arising from the need for efficient implementation of term rewriting, is not to duplicate subterms when rewriting, but to share subterms by using pointers to just one copy. Cyclic graphs are also allowed.

Nationally, one of the main enterprises contributing to the development of theory and applications of term rewriting systems was the Automath project, initiated by N.G. de Bruijn (1970) and presently recognized world-wide as a pioneering project laying the foundation for constructive type theory and automatic proof verification. Another main enterprise was the introduction by H.P. Barendregt of the state-in-the-art in pure (i.e. untyped) λ-calculus into the national scene (leading in 1981 to an authorative monograph which has become a standard reference), as well as its further development by him and co-workers, presently being continued in a major project concerned with typed λ-calculi.

Contributions by CWI

Particularly during the last decade, CWI has made several contributions to theory and applications of term rewriting. In our study of denotational semantics, there has been an occasional employment and study of extensions of λ, serving to extend an imperative programming language with function procedures. Term rewriting techniques were employed and improved in order to prove consistency of axiom systems for concurrent, communicating processes (Process Algebra). Term rewriting techniques are often incorporated and extended in the design of algebraic specification formalisms. More than a decade ago, CWI contributed to the work of J.A. Bergstra and J.V. Tucker by developing a substantial part of the computational theory of abstract data types, thereby indicating scope and limitations of term rewriting, and thus establishing a solid theoretical foundation for such algebraic specifications. Moreover, CWI research in logic programming profits from several connections with term rewriting, especially via the techniques of conditional rewriting and narrowing. For an example of a conditional term rewriting system see the display, where '$\twoheadrightarrow$' stands for an arbitrary long rewrite sequence. Narrowing is a powerful rewrite technique for solving equations (between first-order terms containing variables) in the presence of an equational theory given by a 'well-behaved' (i.e. confluent and terminating) rewrite system.

$$
\begin{array}{lcl}
0<0 & \to & \text{false} \\
0<S(x) & \to & \text{true} \\
S(x)<0 & \to & \text{false} \\
S(x)<S(y) & \to & x<y \\
S(x)-S(y) & \to & x-y \\
0-x & \to & 0 \\
x-0 & \to & x \\
gcd(x,y) & \to & gcd(x-y,y) \Leftarrow y<x \twoheadrightarrow \text{true} \\
gcd(x,y) & \to & gcd(x,y-x) \Leftarrow x<y \twoheadrightarrow \text{true} \\
gcd(x,x) & \to & x
\end{array}
$$

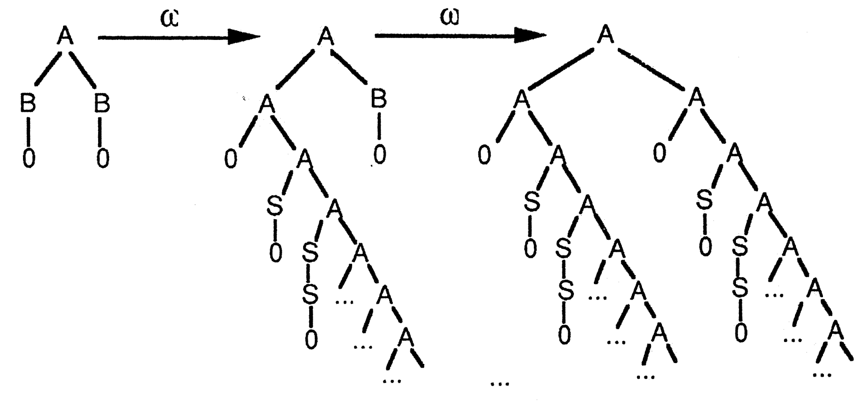
Conditional term rewriting system computing the gcd of natural numbers (generated by 0 and successor S) using two conditional rewriting rules.

Finally, the research group studying algebraic and syntactic methods explicitly focuses on term rewriting systems. This group has operated mainly in the framework of two ESPRIT Basic Research Actions: Integration and Semagraph. The first programme aimed at the integration of the paradigms of logic programming, functional programming and object-oriented programming. CWI contributed by developing a theory of modularity for conditional rewriting. Here it is investigated to what extent properties of (conditional) rewriting such as confluence and termination are 'modular', that is, preserved when combining several rewriting systems into a large one.

In Semagraph, which concerns semantics and pragmatics of graph rewriting, CWI has contributed by developing, jointly with the University of East-Anglia, a theory of infinitary term rewriting. The idea here is that in functional programming one is often dissatisfied with computing normal forms which by definition are finite objects, and so instead one aims to compute infinite objects such as the sequence of prime numbers. Infinitary rewriting deals with such infinite 'terms', and with rewrite sequences of infinite length, in fact a length which is measured by some transfinite ordinal number.

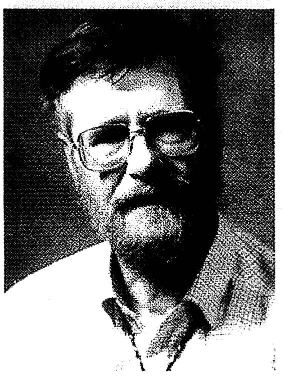
Infinitary term rewriting provides a foundation for graph rewriting; the connection is readily seen by noting that a cyclic graph gives rise by 'unwinding' to an infinite tree (an infinite term).

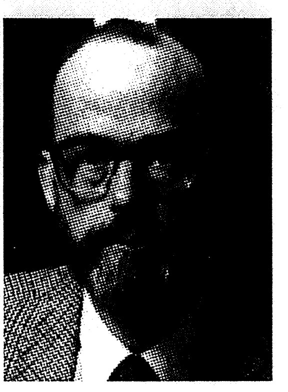
Recent research is concerned with extensions of the usual rewrite format, other than those mentioned before (conditional, infinitary, graph rewriting). A specific subject of interest is a general framework for term rewriting with bound variables (Combinatory Reduction Systems) arising by adding the main feature of λ (bound variables) to ordinary term rewriting systems. These CRSs have a wide scope, and also encompass typed λ-calculi, and some rewriting mechanisms recently found in process algebra relating to 'mobile processes' (processes with a dynamic network of connections) and real-time versions of process algebra.



Transfinite rewrite sequence of length $\omega + \omega$, using rewrite rule $B(x) \to A(x,B(S(x)))$.

Constructive Algorithmics





In the 1960s C.A.R. Hoare (right) and E.W. Dijkstra (left) pioneered the use of formal methods in program construction.

Introduction

Two prominent concerns in program design and implementation are correctness and efficiency. Given the formal specification of a programming problem, it is required to construct an efficient program satisfying the requirements listed in the specification. Efficient programs are usually complex, containing many important details, and therefore hard to get correct. Evidently correct programs, on the other hand, are often not of an acceptable efficiency. Ever since the 'software crisis' was recognized, already in the sixties, the necessity of using formal methods in program construction has been widely acknowledged. Hoare and Dijkstra have done much pioneering work in this area, in particular on the formal derivation of imperative programs.

A specific approach to the construction of correct and efficient programs is Transformational Programming. A specification, described in some formal language, is considered to be an evidently correct but likely very inefficient program. By means of a series of meaning-preserving transformation steps, the specification is transformed into a correct and efficient program. At CWI a specific Transformational Programming theory, called Constructive Algorithmics, has been under investigation since 1978.

Constructive algorithmics

Our research aims at increasing and extending the applicability of the transformational approach. It is concerned with the development of various concepts, notations, formalisms and methods on a high level of abstraction, for deriving programs from a specification. The issues investigated include the unification of specification formalisms and formalisms for denoting programs into formalisms which are amenable to calculation, and the development of specialized theories for certain data types or classes of problems.

Specifically, we investigate the method developed by Bird [1][2], and Meertens [3], known as 'Constructive Algorithmics' or 'Bird-Meertens Calculus'. In this calculus one derives a program from its specification by means of algebraic manipulation. Ideally, we start off with a specification, and using equational reasoning, replacing equals for equals, we arrive at an efficient program by means of a straight-line calculation. Replacing equals for equals is done on the basis of laws. The only intellectual activity required is the selection of the law to be used when several are applicable. The following example shows a calculation of a well-known equality in arithmetic.

$$(x-a)(x+a)$$
$$=$$
$$x(x+a)-a(x+a)$$
$$=$$
$$x^2+xa-ax-a^2$$
$$=$$
$$x^2-a^2.$$

This is the ideal situation indeed; sometimes more is needed than pattern matching and replacing equals for equals.

Language and laws

Derivations in Bird-Meertens calculus are conducted in a formal language. This language is suitable for calculation: the elements in it satisfy many useful laws, and this is evidenced by the many calculations of algorithms which have been constructed over the last decade. Furthermore, the elements in the language can be easily implemented in or translated into existing computer languages. This justifies the terminology 'calculating with programs' for deriving programs in this calculus.

The formal language in which calculations are conducted is based on a specific theory of data types. A data type such as *list, tree, array,* etc. is defined as an initial object in a category of functor-algebras. Consider the function which sums a list of natural numbers. This recursive function is a so-called 'catamorphism' on the data type *list* of natural numbers. Catamorphisms are defined as follows. By definition of initial objects and algebras, there exists a unique homomorphism from an initial algebra to all algebras in the category. These unique functions are called catamorphisms. The uniqueness can be equationally characterized, which makes this approach ideal for the kind of calculation aimed at. The Fusion Theorem, which gives the condition that has to be satisfied in order to 'fuse' the composition of a function with a catamorphism into another catamorphism, is one of the very useful consequences of the uniqueness of catamorphisms. The Fusion Theorem is the main means of deriving programs. There are classes of special catamorphisms (functional forms) which satisfy extra laws. An example of such a class is that of structure-preserving map operators. On the data type *list*, the map operator takes a function and a list and applies the function to each element in the list. As an example, it satisfies the map-distributivity law: the composition of two maps is a map again.

A theory of lists

One of the first issues in constructive algorithmics was the development of a theory of lists. The data type *list*, denoted by $(A\star, +\!\!+, \square, \tau)$, is an initial element in the category of monoids enriched with an operation with type A. $A\star$ is the set of lists, $+\!\!+ : A\star \times A\star \rightarrow A\star$ is the associative operator that concatenates two lists, with as identity element the empty list $\square$, and τ: $A \rightarrow A\star$ constructs a singleton list (a list with one element). A catamorphism defined on the data type *list* is the composition of a reduction $\oplus/$ and a map $f\star$. $\star$ is a postfix operator that is defined on types as well as functions. Given a function f, $f\star$ satisfies

$$f\star[a,b,c] = [fa,fb,fc].$$

Given an associative operator $\oplus$, the reduce $\oplus/$ satisfies

$$\oplus/[a,b,c] = a \oplus b \oplus c.$$

Below we give a typical example of a calculation within the calculus. This calculation pertains to the following problem: let a list of lists of, say, natural numbers be given; a 'selection' from this list is formed by picking exactly one element of each list in this list of lists. The value of a selection is the product of its elements; what is the highest value of all possible selections?

The cross-product $X_{+\!\!+}/\cdot\tau\star\star$ returns all selections, the reduction $\times/$ returns the value of a selection, and the reduction $\uparrow/$ returns the highest value, so the problem at hand can be formally specified by

$$\uparrow/\cdot\times/\star\cdot X_{+\!\!+}/\cdot\tau\star\star.$$

Intuition tells us that an efficient way to determine the highest value of any selection is to determine the value of the selection obtained by picking the maximum element of each list in the list of lists, so

$$\uparrow/\cdot\times/\star\cdot X_{+\!\!+}/\cdot\tau\star\star.$$
$$= \quad \text{claim}$$
$$\times/\cdot\uparrow/\star.$$

Here is the formal derivation of this equality.

$$\uparrow/\cdot\times/\star\cdot X_{+\!\!+}/\cdot\tau\star\star$$
$$= \quad \text{Fusion, } \times/\star \text{ is } (X_{+\!\!+}, X_{\times})\text{-fusable}$$
$$\uparrow/\cdot X_{\times}/\cdot\times/\star\star\cdot\tau\star\star$$
$$= \quad \text{map-distributivity (twice)}$$
$$\uparrow/\cdot X_{\times}/\cdot(\times/\cdot\tau)\star\star$$
$$= \quad \oplus/\cdot\tau = id \text{ for all operators } \oplus$$
$$\uparrow/\cdot X_{\times}/\cdot id\star\star$$
$$= \quad id\star = id \text{ (twice)}$$
$$\uparrow/\cdot X_{\times}/$$
$$= \quad \text{Cross-law, } (\uparrow, \times) \text{ is a dioid}$$
$$\times/\cdot\uparrow/\star.$$

Research at CWI

The group's research has focused on three main themes in constructive algorithmics.

An important recent result was the discovery by M.M. Fokkinga of a very elegant category-theoretical formulation of the notion of 'law' imposed on a data type, which abstracts from the algebraic signature by using instead its encapsulation as an endofunctor, see Fokkinga's Ph.D. thesis 'Law and Order in Algorithmics', Twente University, to appear in 1992.

Theory similar to the theory of catamorphisms can be developed for classes of functions which satisfy specific recursive equations (not necessarily those of catamorphisms). Paramorphisms, see Meertens [4], are an example of such a class of functions. Other examples can be found in Fokkinga's thesis.

The research approach emphasizes example-driven theory development, which focuses on a specific problem or a class of problems (and methods). Examples of theories developed by J.T. Jeuring in his Ph.D. thesis 'Theories for Algorithm Calculation', Utrecht University, to appear in 1992, are a theory of combinatorial algorithms on words or segment problems, a theory of incremental algorithms, and a theory for the derivation of algorithms on multidimensional arrays.

References

1. R.S. Bird (1987). An introduction to the theory of lists. M. Broy (ed.). *Logic of Programming and Calculi of Discrete Design,* Vol. F36, NATO ASI Series, Springer-Verlag, 5-42.
2. R.S. Bird (1989). Lectures on constructive functional programming. M. Broy (ed.). *Constructive Methods in Computing Science,* Vol. F55, NATO ASI Series, Springer-Verlag, 151-216.
3. L. Meertens (1986). Algorithmics—towards programming as a mathematical activity. J.W. de Bakker, M. Hazewinkel, J.K. Lenstra (eds.). *Proceedings of the CWI Symposium on Mathematics and Computer Science,* Vol. 1, CWI Monographs, North-Holland, 289-334.
4. L. Meertens (1990). *Paramorphisms.* CWI report CS-R9005, to appear in Formal Aspects of Computing.

MANIFOLD

Introduction

Parallel computing penetrates an ever increasing part of Information Technology. Examples are scientific visualization, sophisticated user interface design, complex multidisciplinary systems such as intelligent CAD/CAM systems for concurrent engineering, and distributed open systems required for factory automation. Here, parallelism is not only used to achieve realistic performance, but even more as a conceptual tool to tackle complexity. An important problem is how to organize the communication among a set of autonomous processes in a complex system. A possible solution is provided by MANIFOLD, a model for parallel systems under development at CWI. Its basic feature is the separation of functionality and communication.

Why MANIFOLD?

Although the hardware technology of parallel computers has already passed its infancy, major advances in this field are still necessary to meet the challenges of new application areas such as mentioned above. Apart from this, the potential of the existing parallel hardware technology is still drastically under-utilized in today's applications. One of the deeper impediments to full use of this potential lies in the field of parallel programming. A fundamental problem is the coordination and control of the communications among the sequential fragments that comprise a parallel program. A major obstacle is the lack of a coherent model of how parallel systems should be organized and programmed. An additional problem is that many user communities are unwilling and/or cannot afford to ignore their previous investment in existing algorithms and 'off-the-shelf' software and migrate to a new and bare environment. This implies that a suitable model for parallel systems must be *open* in the sense that it can accommodate components that have been developed with little or no regard for their inclusion in an environment where they must interact and cooperate with other modules.

Separating the communication issues from the functionality of the component modules in a parallel system makes them more independent of their context, and thus more reusable. It also makes it possible to delay decisions about the interconnection patterns of these modules. This is particularly important in distributed computing, where application modules are distributed over loosely coupled processors, perhaps running under quite different environments in geographically different locations. The implied communications delays and heterogeneity of the computational environment encompassing an application, become more significant concerns than in other types of parallel programming. This mandates, among other things, more flexibility, reusability, and robustness of modules with fewer hard-wired assumptions about their environment.

The goal of the MANIFOLD project is to develop a system for managing complex interconnections among independent, concurrent processes. MANIFOLD is based on separation of functionality and communication and is quite suitable for massive parallelism. The primary concern in the MANIFOLD language is not *what* functionality the individual processes in a parallel system provide, but *how* these processes are interconnected and how their interaction patterns change during the execution life of the system.

What is it like?

In order to inspire an intuitive feeling for what MANIFOLD is, we mention some similarities and differences with other models and systems, such as shell scripts, event-driven programming and dataflow programming [1].

First of all, MANIFOLD can be viewed as a *conductor* orchestrating the interactions among a set of cooperating concurrent processes, without interfering with their internal operations. As such, MANIFOLD programming is vaguely reminiscent of writing shell scripts in a system like UNIX™. As with a shell script, the concurrency and interconnection issues are completely outside of the processes. However, the possibilities for defining and dynamically changing the interconnections among processes in MANIFOLD go much beyond what is offered in such simple shell scripts.

Interactions among processes in MANIFOLD are handled by an entity with multiple inlets and outlets, called a *manifold*, which has a finite number of *states*. Each state defines a specific connection pattern. Connection patterns define links between the input and output ports of various processes, called *streams.*

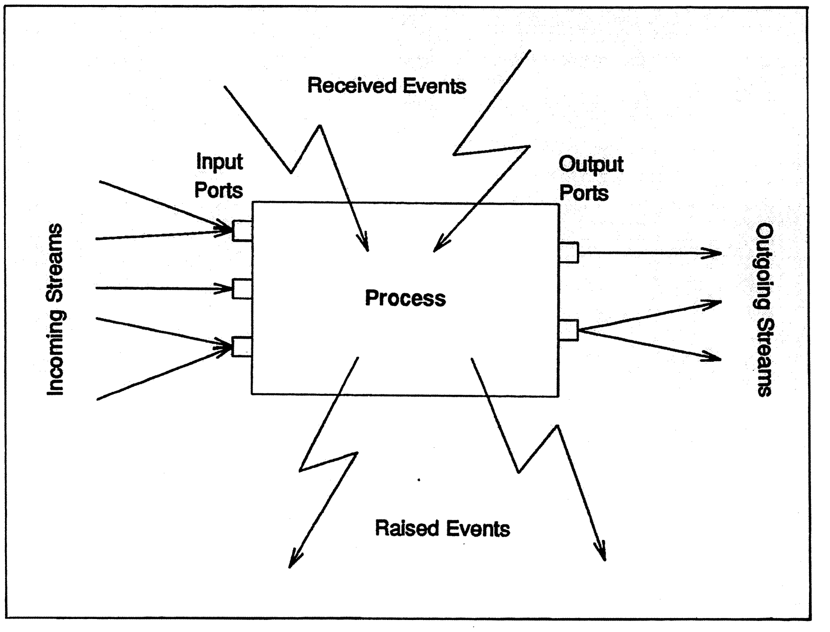
A manifold changes its connection pattern as a result of observing in its environment *events* in which it is interested. As such, events are the principal control mechanism in MANIFOLD, which makes it an event-driven programming system.

Although the streams among processes in MANIFOLD are reminiscent of dataflow networks, there are several major differences. In MANIFOLD the connection patterns among processes change dynamically, in addition processes are created and deleted dynamically. Furthermore, since manifolds are also processes, the combined graph of a MANIFOLD program is indeed not a simple graph, but a complex, dynamically changing graph of connections among processes.

Although conceptually the dominant control mechanism in MANIFOLD is event-driven, the dataflow type, data-driven style of control through streams is at least as important. A manifold can internally raise an event for itself, causing a state transition. This may, for instance, be due to the arrival of a unit of information, and may also depend on the contents of this information. Thus, there is a smooth transition between the two control mechanisms in MANIFOLD. The coexistence of event-driven and data-driven control gives MANIFOLD a unique flavor.

The MANIFOLD model

The basic components in the MANIFOLD model are processes, events, ports, and streams. The internal operation of some of these processes is written in the MANIFOLD language, thus enabling a description of their internal behaviour using the MANIFOLD model. These are the processes which we have denoted as manifolds above. In general, a process in MANIFOLD neither knows nor needs to know the identity of the processes with which it exchanges information.



The model of a process in MANIFOLD.

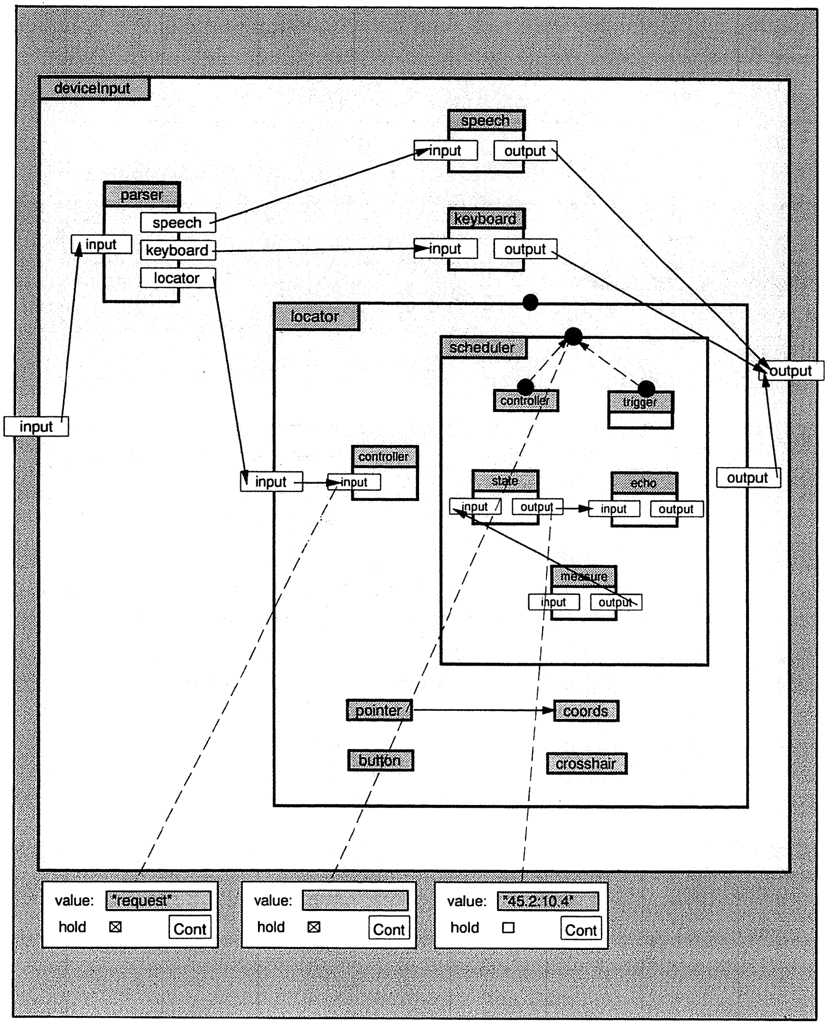
The interconnections between the ports of processes are made with streams of information units between two ports. Streams are constructed and removed dynamically. The units of information exchanged through ports and streams, are *passive* pieces of information which are produced and consumed at the two ends of a stream in a manner analogous to conventional I/O operations, with their relative order preserved.

Another mechanism is information exchange through events: *active* pieces of information, raised by their sources and dissipated through the environment. Events are observed asynchronously and once picked up, they preemptively cause a change of state in the observer. Events are the primary control mechanism in MANIFOLD.

Applications

The MANIFOLD programming language is well suited for describing complex and dynamic interaction patterns that are prevalent in user interface software. The concept of agents (intelligent autonomous entities), which is sometimes seen as the next major step in user interface development, accords nicely with the MANIFOLD language.

On the other hand MANIFOLD is also capable of expressing the lower levels and hardware related aspects of user interfaces, as



A visual programming interface for MANIFOLD.

we have shown in our MANIFOLD implementation of the GKS input model [2]. In multimedia systems, special purpose hardware will continue to be of great importance for proper replay of documents.

The MANIFOLD programmer must deal simultaneously with a number of independently executing processes. A visual interface, containing among other things facilities for debugging the intricate interactions between the individual processes, will give him the indispensable overview of an executing parallel program. In addition we will investigate to what extent visual interaction techniques can be applied to MANIFOLD programming itself.

Current status

We are presently completing our first implementation of the MANIFOLD system [3]. The MANIFOLD compiler translates MANIFOLD source programs through an intermediate language into Concurrent C^{++} source code. The resulting program is then handed over to the Concurrent C^{++} compiler, the result of which is linked with the run-time MANIFOLD library routines. The final executable code can run on a network of Sun SparcStations, or (potentially) on a network of Silicon Graphics workstations.

MANIFOLD combines event-driven programming and dataflow-type communication networks. We are also working on the formal semantics of MANIFOLD to study some of its interesting properties. We have defined an operational semantics for the core of the MANIFOLD, and are presently extending it to cover all of its features.

References

1. F. ARBAB, I. HERMAN (1991). MANIFOlD: A language for specification of inter-process communication. *Proceedings of EurOpen Autumn Conference,* Budapest (September 16-20, 1991).
2. D. SOEDE, F. ARBAB, I. HERMAN, P.J.W. TEN HAGEN (1991). The GKS input model in MANIFOLD. *Computer Graphics Forum* **10** (3) (September 1991).
3. F. ARBAB, I. HERMAN, P. SPILLING (1991). *An Overview of MANIFOLD and its Implementation.* Technical Report CS-R9142, Centre for Mathematics and Computer Science (CWI), Amsterdam.

CMIF: the CWI Multimedia Interchange Format

Introduction

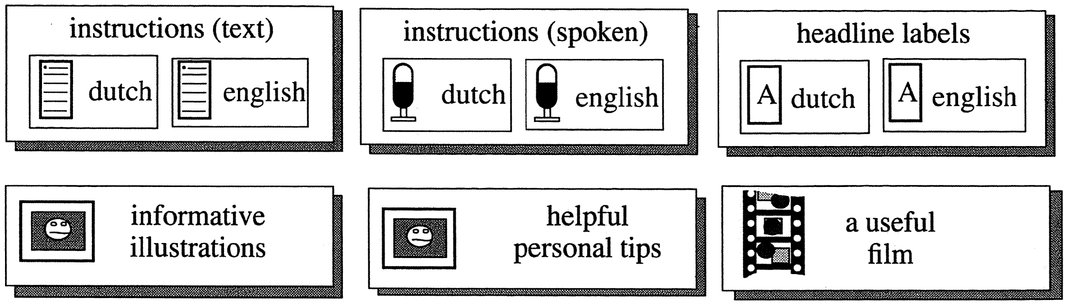
One of the goals of CWI's multimedia research is to study methods for supporting *transportable* and *dynamic* multimedia documents. Transportable documents are collections of multimedia information that can be presented on a wide range of dissimilar computing environments. Dynamic documents are those in which the contents of each presentation can be determined at run-time as well as when the document is authored. In order to support transportable and dynamic documents, the CWI Multimedia Interchange Format (CMIF) has been defined to encode the architecture-independent semantic and syntactic name of multimedia presentations.

To put CMIF in perspective, consider the current state of multimedia computing. According to the sales and marketing literature produced by most computer vendors, multimedia computing is a solution in search of user-generated problems. Facilities currently exist that allow even modest personal computers to simultaneously manipulate a variety of (chiefly output) media in a way that provides a dazzling display of technological cleverness and audio/video wizardry. Birds flying across medium-resolution colour screens can be frozen in mid-air, then cut out of their environment and pasted on top of a composite background, all with remarkable ease; images can be video mixed, then translated, rotated and scaled at a speed that once was impossible with even the highest-performing (and highest costing!) workstations. Novice users can manipulate information from CD-ROMs that contain data of several media, giving promise of better teaching tools for children or clearer maintenance and repair guides for automobile mechanics.

At first glance, current generation multimedia systems can do nearly everything that a user could hope for, with the implied promise that even not-yet hoped for things are just around the technological corner. In reality, however, there are several major problems that confront the user of multimedia systems. One problem is that the data elements being manipulated often consist of raw data rather than structured information; the bird flying in the example above usually is little more than a sequenced video FAX consisting of a representation without any inherent meaning. This can limit the amount of processing that can ultimately take place by application programs or support hardware. A second problem is that the representation and manipulation of data is highly machine and/or device dependent. This means that information cannot easily be shared among different types of systems or devices. A third problem is that the synchronization present within multimedia applications is often implicitly encoded as a function of the speed of a particular system and interface, limiting the ways that interaction among elements can be expressed and (ultimately) implemented.

CMIF addresses these problems by decoupling the specification of data representation from the specification of data interaction within multimedia documents. We do this by imposing structure rules for partitioning the components of a document and by providing a set of higher-level synchronization primitives that can be used to describe the semantic interaction among the individual structure elements. This decoupling is essential if multimedia support is to be provided in a heterogeneous environment. In such environments, we cannot assume that all workstations will provide the same degree of processing power and I/O capacity or that they provide a similar level of support for any particular type of multimedia data. (For example, the screen sizes may vary, the number of colours available on a graphics display may be different, the audio processors (if present!) may be dissimilar, etc.) As a result, if documents need to be transported across multiple system types, information on the nature of document data and data interaction must be explicitly provided in a manner that will allow the document to be 'compiled' for use on a specific system. At a more abstract level,

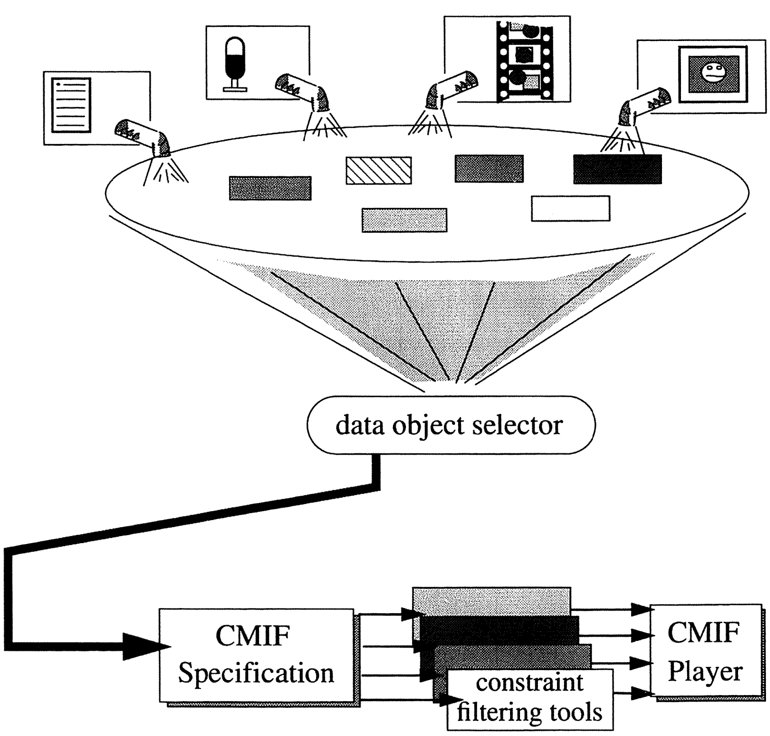
Figure 1
The components of a multimedia presentation.



decoupling of representation and interaction can also provide a means for adding semantic information to the data representation that can be used to more dynamically navigate through a presentation.

CMIF provides decoupled document support via a set of structure primitives that can be used to describe data objects, a set of synchronization primitives that can be used to describe the desired synchronization among the data objects, and a CMIF player that is used to 'play' multimedia presentations based on CMIF documents. (Note that the player is not, strictly speaking, a component of CMIF but simply an application that interprets CMIF documents). In the following sections, we will give a brief description of the components of CMIF. The accompanying box gives an overview of how CMIF is used to define a particular application.

Figure 2
Making a CMIF multimedia document.



Defining and manipulating CMIF documents

The first step in creating a CMIF document is to define and gather the collection of data objects that will be used in a presentation. Figure 1 shows those objects that are used in the example in the accompanying box. Each of these components will be built using specific tools that are tailored to a particular media type. (Objects can be either data files or programs that generate data interactively.) CMIF does not dictate a particular underlying data representation model. Instead, it allows the characteristics of the underlying data be defined in a series of 'style sheets' that can be used by the CMIF player to determine how a general type of multimedia data should be handled on a particular target system. By combining the style information of each data type with the synchronization information present in the CMIF specification, the player has the potential to adapt a given document to a particular execution environment.

Data events

Once the data has been created, a presentation can be constructed as shown in Figure 2. Here, a selection is made from the set of available data objects (or data object generators). Since each selected data object may appear one or more times in a document, a mechanism is required to differentiate a particular instance of an object from the basic definition of the object itself. CMIF makes this differentiation in terms of a document *event descriptor.* In general, event descriptors contain the location of the data object and access information that can be used to abstract the document processing from document data. The event descriptor is used for a variety of purposes. First, it provides a shorthand description of the contents of a particular object, meaning that the charac-

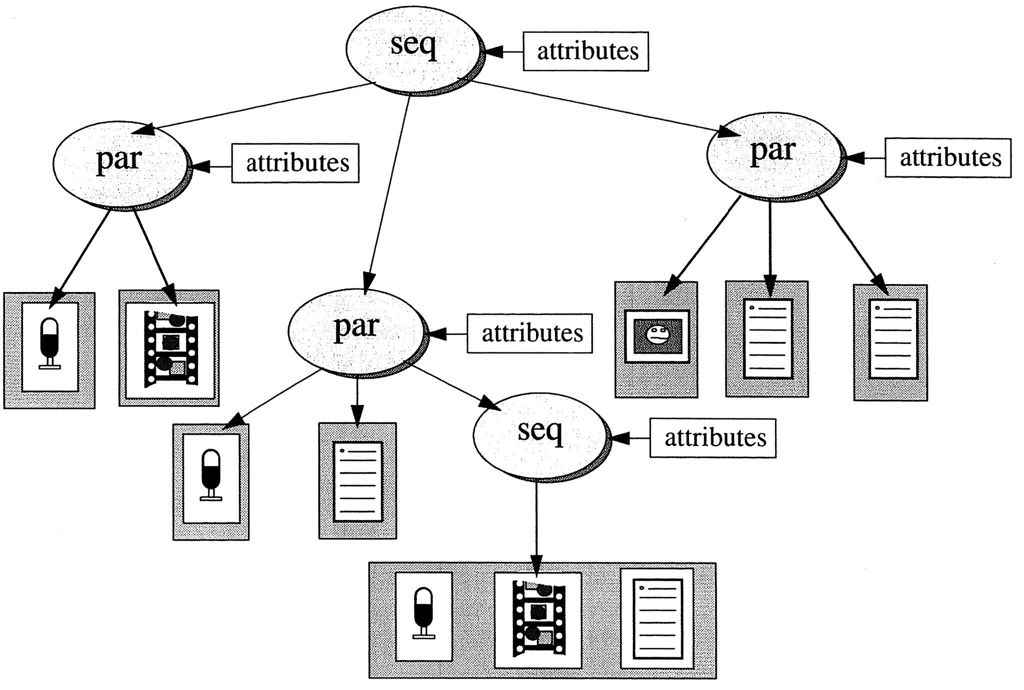


Figure 3
The CMIF hierarchy specification.

teristics of a (potentially large) data set can be manipulated in an efficient manner. Second, it contains an encoding of the run-time properties of each object, for use by the CMIF player to (pre-)allocate resources on a local workstation. Third, it contains information that can be used to synchronize the presentation of objects. Fourth, it can contain information that is used to navigate through documents in a content-based manner.

Document structure components

The relationships among the event descriptors selected for a document are described in terms of an *event hierarchy specification* and a *logical channel allocation specification.* The hierarchy specification describes the content-based relationships of events as a collection of parallel and sequential nodes of a document tree. (See Figure 3.) The channel specification describes the media-based relationships in a document by defining logical groups of data that need to be handled in some common way. (See Figure 4.)

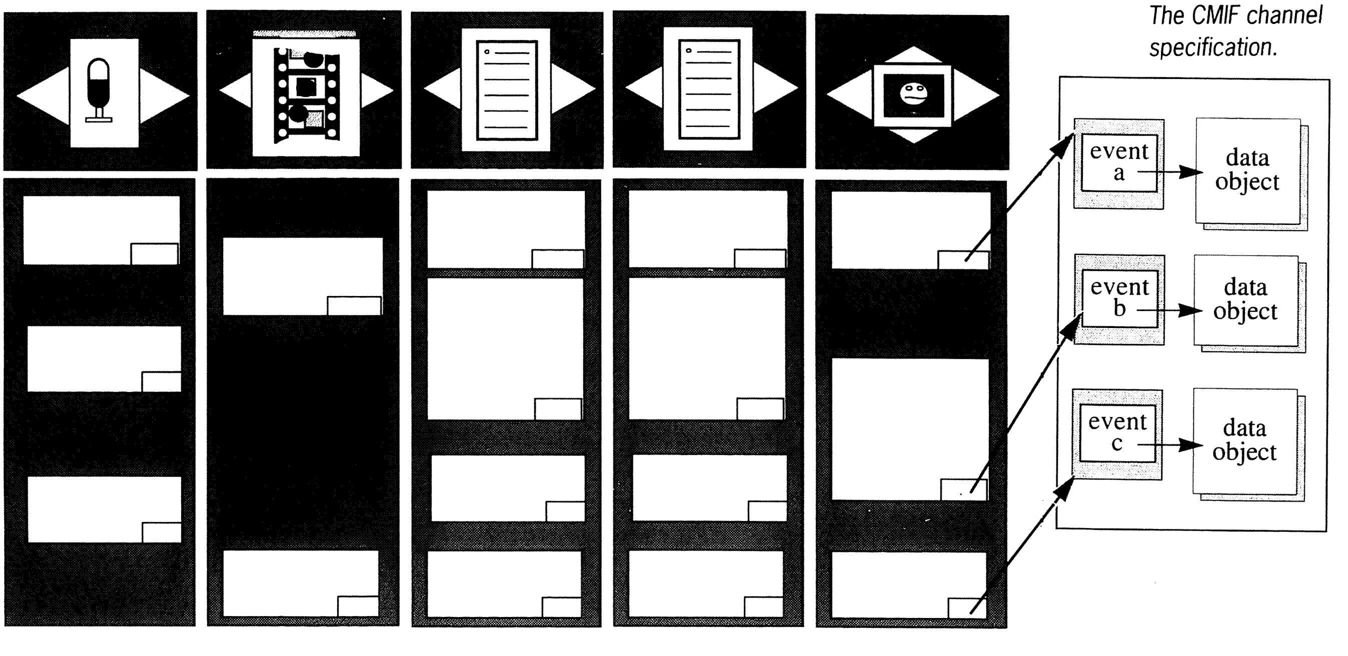


Figure 4
The CMIF channel specification.

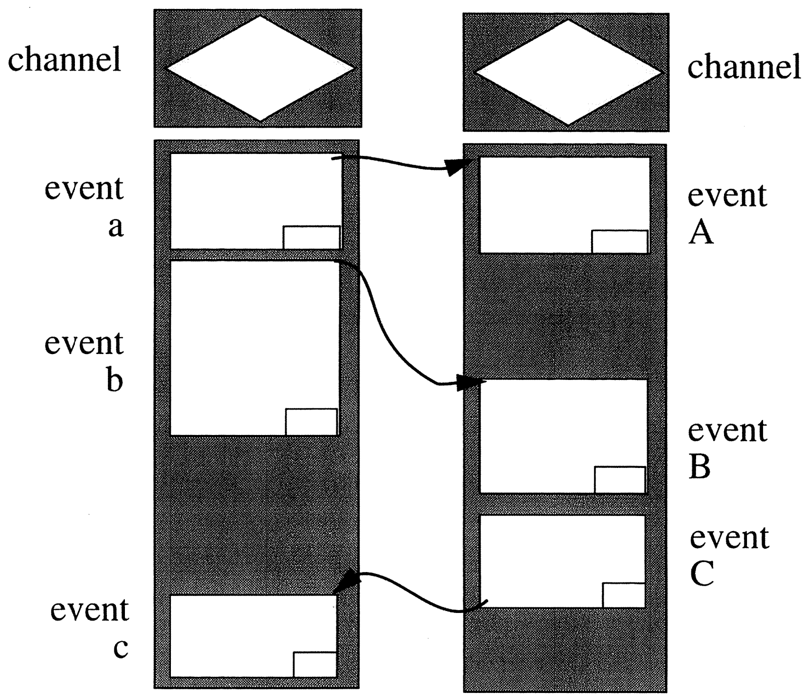
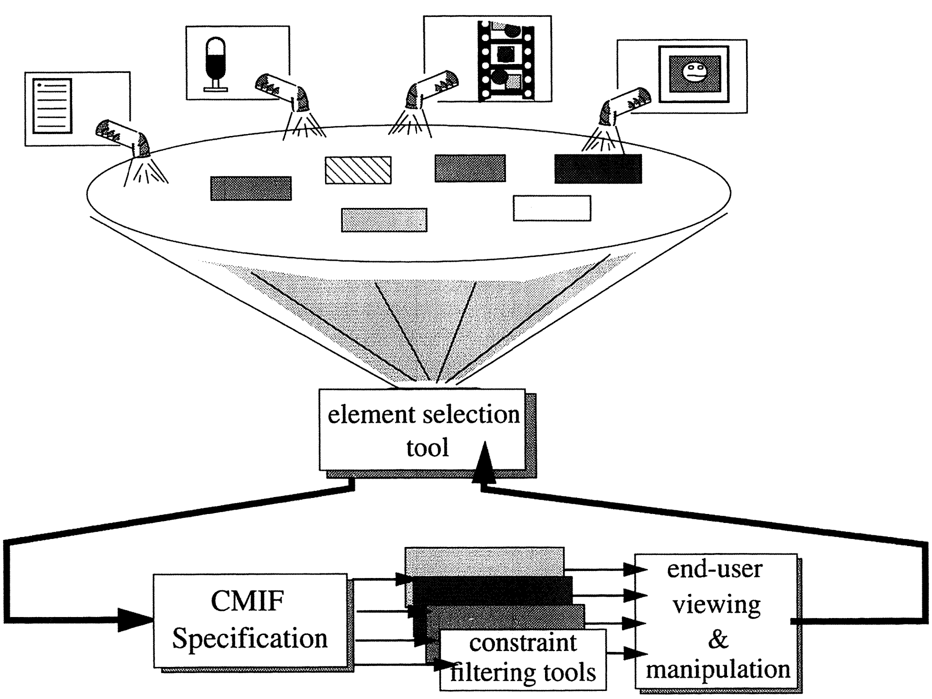


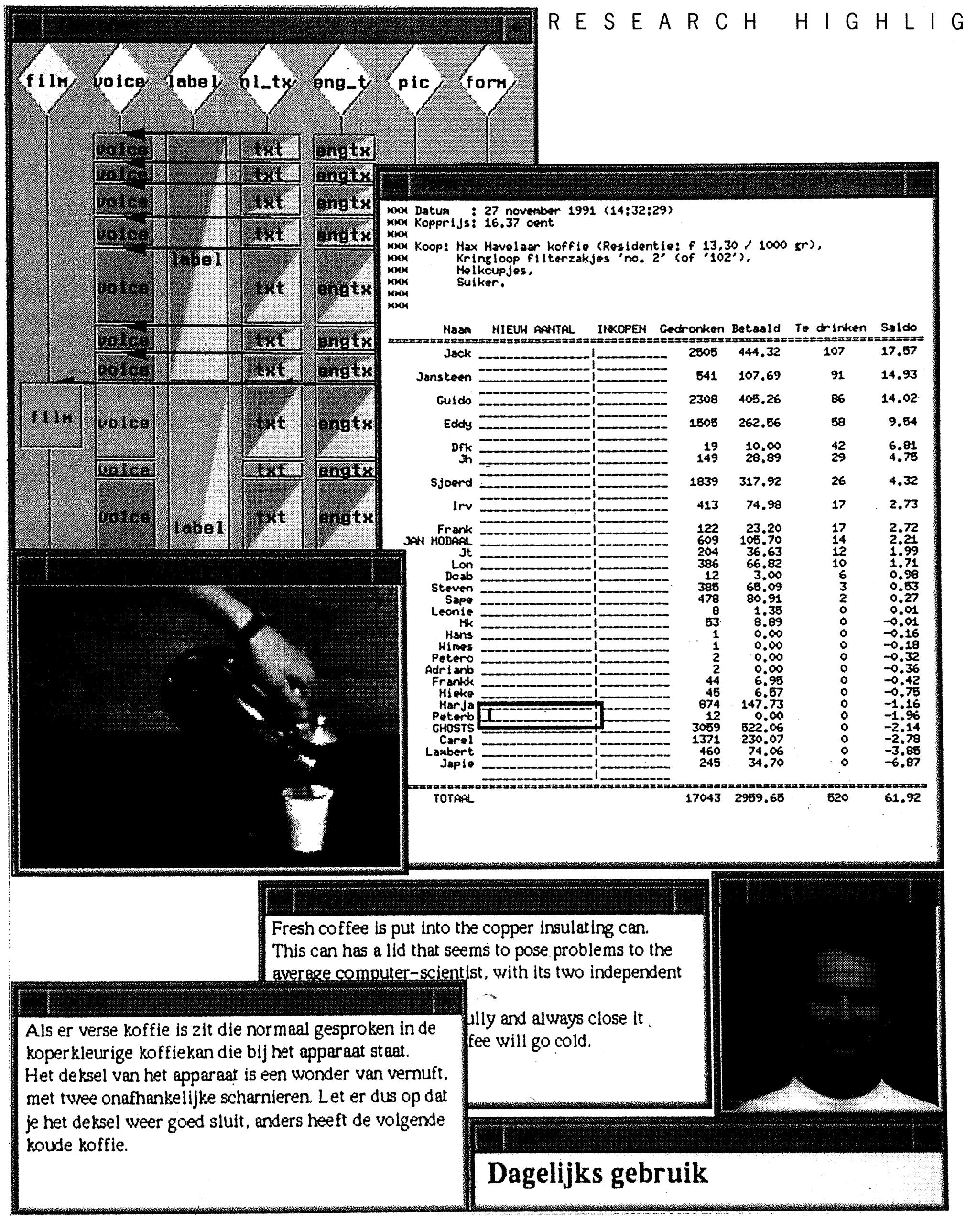
Figure 5
Explicit inter-channel synchronization.

Together, these specifications describe the scheduling and synchronization dependencies that need to be resolved on a local system when the document is presented.

CMIF synchronization descriptors
Both the hierarchy and channel specifications are also used for describing the semantic relationship among events in a document. The document tree is traversed in a sequential, depth-first manner; parallel relationships among nodes are defined by sequencing tags provided with each node. The hierarchy can be compiled into a *block specification* that defines a general partitioning of structural elements of a document, much in the way that a table-of-contents specification of a conventional document can be used to define the overall structure of a book. (An important difference between multimedia documents and books is that structural elements in a book typically do not contain parallel blocks.) The channel specification provides two means of defining synchronization: first, each event on a single channel is scheduled sequentially, under the implicit control of the scheduling order derived from the hierarchy specification. Second, a user can define explicit synchronization relationships among events on other channels. (See Figure 5.) The synchronization can be specified in a

Figure 6
Dynamic document support.





A typical multimedia example: making coffee

Multimedia documents produced using CMIF can take many forms. In this illustration, we show a document that explains how a departmental coffee facility is managed. All of the windows that are displayed are generated by the CMIF player. A user has a CMIF control panel (not shown) allowing a presentation to start/stop/pause/reset, much in the same way that a cassette player has a user control panel.

In this presentation, we see a *channel specification* for the document (labelled 'Time chart') indicating that the presentation consists of one film channel, one voice channel, one label channel, two text channels (one for Dutch text and one for English text), and two static picture channels: one for a 'real' picture and the other for an illustration of various types of coffee order and consumption forms.

The shading on the channel specification is used to show the current status of the document. The player will scan the document and prefetch components that it knows it will need (based on the synchronization relationships in the document structure). In the illustration, we see that the film is currently active, as are the two text, two image and one label channels. (The audio portion is also active.)

CMIF documents are constructed using a structure editor. A user can define a number of channels of various types, manipulate global attributes of these channels (such as sampling rates, picture formats, etc.) and then map out the contents of a document by specifying the required timing relationships among the event blocks. In the simple timing relationship shown, all of the Dutch text blocks are keyed to the explicit start of the (Dutch-language) voice events. All of the other blocks are self-timed, using the implicit hierarchy of the document.

number of ways: relative to the beginning of an event, relative to a particular frame or sample of data or relative to the end of an event. In all cases, a synchronization interval can be specified that can be used by the player to control a document under a range of local constraints.

For simple documents, or for documents that will only be played on a single architecture, implicit synchronization appears to be sufficient to describe the relationships among data events. For more complex documents, however, each synchronization relationship can be used to define the bounds of an adaptive document scheduler.

Research directions

The current CMIF structure provides a framework for the description of statically defined documents. While the current synchronization constructs appear to provide a useful mechanism for supporting transportable documents, only minimal support is available for dynamic documents. As is shown in Figure 6, dynamic support can consist of transforming the static selection and composition model of Figure 2 into one where the selection of successor nodes is done interactively via a selection mechanism in a document player. By combining 'instant' data object creation tools, the CMIF structure can be used to support interactive documents (such as electronic conferences or interactively annotated presentations). One drawback to this approach is that it requires an extensive method for querying a potentially large and physically distributed object database. Another problem is that the efficiency of the presentation of a multimedia document relies heavily on resource allocation algorithms that make use of prior knowledge of the content, structure and synchronization characteristics of a document. A more basic problem, however, is that selection of data objects in a document should be guided by a statically or dynamically defined hyperstructure that describes associations among the information represented by the data objects. We are currently studying methods for integrating hyperdata structure support into the object definition models and to better understand the relationship of presentation synchronization to information synchronization in multimedia documents.

Mathematics & the Environment

Why?
Environmental research needs further stimulation in order to advance Man's understanding of the working of the environment and all aspects of its pollution. This research is multidisciplinary and involves the interfacing of sciences including meteorology, oceanography, hydrology, geology, biology, physics, chemistry and mathematics. Mathematics is vital as an essential resource for setting up theories and models for a wide diversity of problems. These can only be investigated via simulation models heavily leaning upon techniques from the mathematical and computational sciences. CWI has a broad expertise in these fields. The report year saw the preparation of a multidisciplinary programme, Mathematics & the Environment, combining all CWI research projects with applications to the environmental sciences. Its main aims are:
- to develop advanced mathematical methods;
- to contribute to strategic and applied multidisciplinary research;
- to transfer knowledge by training young researchers.

The programme starts early in 1992. Here we map out the field and CWI's research plan for the near future.

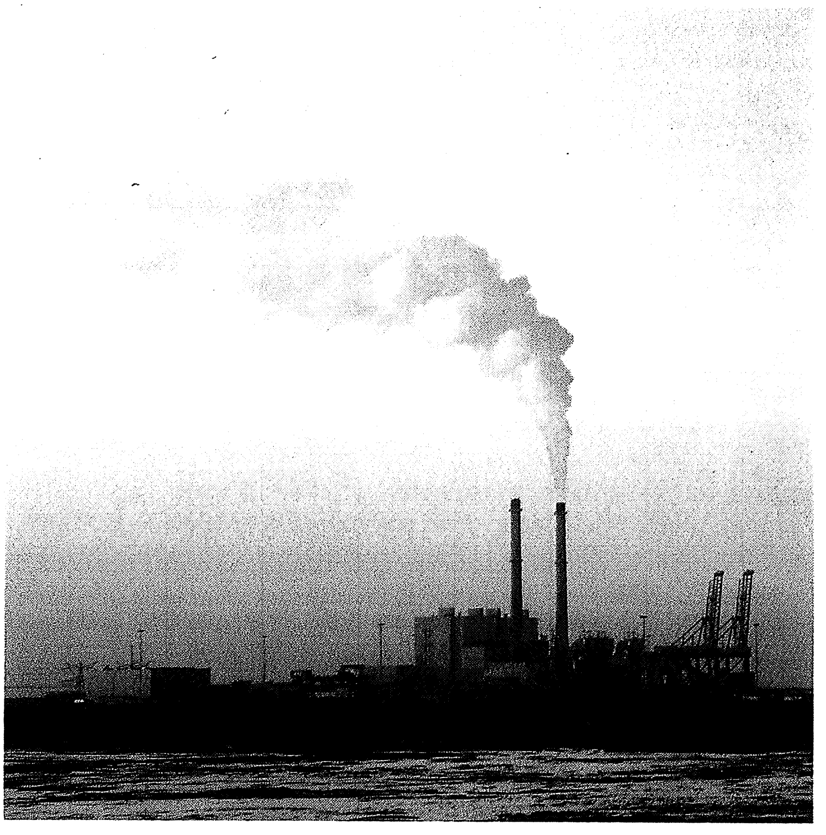
Background
Research activities may concern theory, algorithms, computer implementation, and may interface with virtually any mathematical and computational discipline. There is a widespread need for realistic models to simulate natural systems. Such models occur in biosphere dynamics, population dynamics, hydrology, regional air pollution, global energy and climatic change, and the diffusion of toxic chemical compounds. The relevant disciplines include numerical mathematics (e.g. computational fluid dynamics), large-scale computation on super- and parallel computers together with visualization and massive data handling, image reconstruction, inverse methods and parameter estimation, dynamical system theory and chaos, statistics, operations research, optimization and optimal control, and biomathematics.

The value of mathematical modeling has been long acknowledged. Indeed, since 1945 it has increasingly and systematically replaced much experimentation in design and problem solving, because it is cheaper, faster and more flexible. This ongoing process has been accelerated by the advent of very fast super- and parallel computers with large memories. Hence, modern aircraft are invariably the product of computer aided design which in turn leans to a significant extent on mathematical achievements. Mathematical modeling is also crucial in space technology, including space shuttle design.

The environment is presently under threat from pollution. Water, air and the soil - the three basics - are all equally at risk, globally and locally. And while climatic change is a major issue, economic and social factors make it unsafe to ignore more localized, regional problems; examples here are pollution of air, drinking water, food production, fisheries and forests. Massive research investment in technology and space exploration makes little sense if our own environment is allowed to deteriorate.

Fortunately, recent years have brought growing recognition that resources for environmental research must be increased significantly. The Dutch government has also allocated funds for a variety of activities in the environmental sector, in particular related to both long-term strategic and applied research. The mathematical and computational sciences are basic to the study of environmental issues, since the majority of pollution problems can only be investigated with the use of simulation models heavily leaning upon mathematical and computational techniques.

There are more reasons why a simulation model can be more attractive to use than real-scale models or laboratory experiments.



Coal-fired power station (Maas delta near Rotterdam).
Photo: Joop van Reeken studio/J. van Reeken.

In fact, it is indispensable where the environmental problem under study cannot be experimented with in reality. Studies on the behaviour and fate of highly toxic, chemical compounds in the environment also necessitate an extensive use of simulation models. There is increasing interest in the development of so-called integrated models which meld a diversity of simulation models from different applications in one supermodel. One of the main ideas behind this development is to provide decision support for policy makers.

Projects at CWI

Below we summarize various projects envisaged in the CWI programme on Mathematics & the Environment. A complete account of the programme is given in a special report available at CWI.

Numerical simulation of brine flow

Realistic mathematical modeling of environmental problems usually leads to a complex system of differential equations. Their solution often requires advanced numerical techniques. CWI has been commissioned by the Dutch National Institute of Public Health and Environmental Protection (RIVM) to investigate the numerical modeling of brine transport near and away from underground salt formations. The aim is to predict the transport of radio-active pollutants. The resulting systems of evolutionary partial differential equations are severely nonlinear and must be solved implicitly over long time intervals in high precision. Numerical solution of the 1D-problem is well feasible on workstations like SUNs and SGIs or mini-computers like the Alliant. In order to handle this problem in more than one space dimension, we apply an adaptive-grid method developed at CWI and based on the notion of local uniform grid refinement. As the anticipated runtime and memory use may become so large that access to supercomputers becomes vital, even when grid adaptivity is employed, a CRAY Y-MP implementation of this regridding method is envisaged for 1992. The adaptive-grid method under consideration can be more generally applied to time-dependent problems having solutions with steep local solution transitions, like steep travelling fronts.

Mathematical techniques for the study of the population biology of infections

Veterinary epidemiology is the study of the spread, in space and time, of diseases in animal populations, with the object of tracing factors which are responsible for, or contribute to, the occurrence of a disease. Mathematical models can enhance our understanding of the causal relationship between phenonema at the population level and mechanisms which act in and between individuals. Moreover, they are helpful in evaluating the possible effect of control measures. In cooperation with the Central Veterinary Institute (CDI) in Lelystad, CWI aims at the operationalization of recent abstract mathematical results concerning the basic reproduction ratio R_0 in the context of specific animal diseases, in particular Aujeszky's disease. The effectiveness of control strategies for the elimination of infectious disease agents from (networks of) animal farms will be evaluated on the basis of structured population models. In the near future CWI will - in cooperation with CDI, RIVM and Leyden University - take up research of interest to epidemic models for seal populations in the Dutch Wadden Shallows.

Algorithms for mathematical air pollution models

At present air pollution modeling focuses on so-called LRTAP models (Long-Range Transport of Air Pollution). An LRTAP model is composed of advection-diffusion-reaction differential equations, one for each chemical species involved. For application in practice, LRTAP models belong to the computationally most expensive models. For example, a model recently proposed by the Danish Environmental Research Institute accommodates 35 different chemical species with 70 chemical reactions. If spatially discretized on a 2D 100x100 grid (still coarse on the European scale), its solution requires the numerical integration of at least 350.000 non-linear ordinary differential equations, to be carried out over long time intervals.

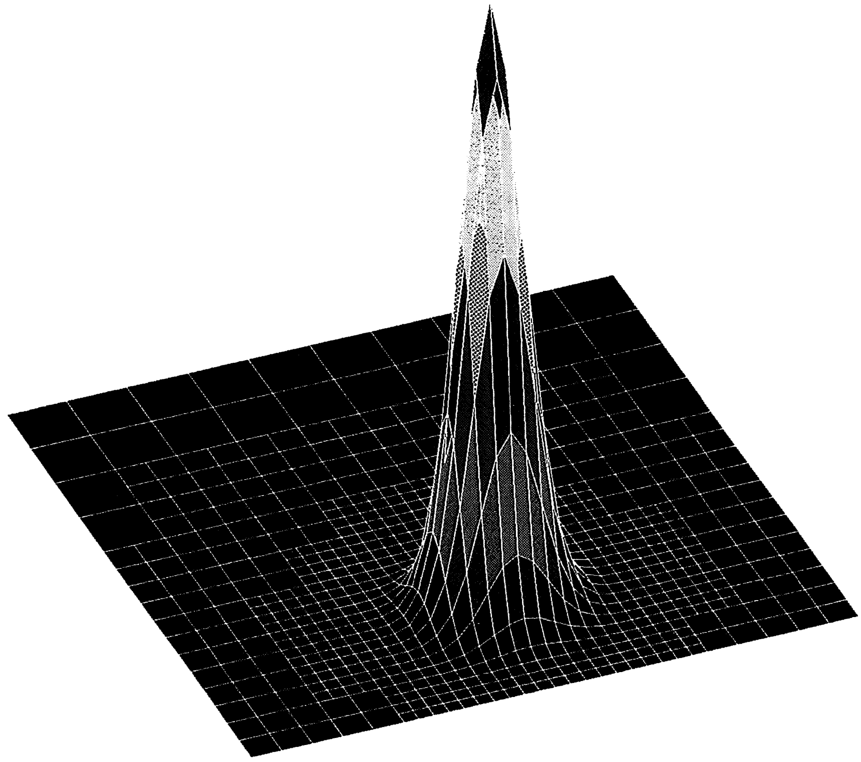
CWI will contribute to the development of advanced numerical algorithms for LRTAP modeling. Numerical schemes for advection-dominated phenomena are hampered by the phenomenon of numerical dispersion, which can ruin the computation, especially in long-time simulations. Here multi-dimensional upwind schemes, successfully applied in computational fluid dynamics, may offer an improvement. In hazardous air-pollution large differences in concentrations occur. Adaptive-grid methods are very well applicable to such cases. The technique of local uniform grid refinement is particularly suitable. Large, complex models are, for computational reasons, often split up into simpler parts. This splitting can introduce quite large errors and interfere with the dynamics originating from the coupling of the physical phenomena involved. By using fast iterative equation solvers, like multigrid and preconditioned techniques, it may be possible to avoid splitting altogether.

System identification of compartmental systems - a mathematical tool in public health and environmental protection

The theory of 'compartmental systems' - a particular class of dynamic systems frequently used in biology and mathematics - can be usefully applied in controlling the storage of nuclear waste, SO_2-emissions, or toxic substances in food and industrial products. Using concepts of system & control theory, CWI will develop algorithms and theory for compartmental systems, focusing on system identification. Questions posed by public health and environmental protection may be translated into the language of compartmental systems, e.g., how to obtain a realistic and not too complex system for prediction and control, from possibly scarce data. Research issues involve realization, parameter estimation, possibly order estimation and complexity, and validation. Both linear and nonlinear deterministic and stochastic compartmental systems will be studied. In close cooperation with RIVM, the results of the research will be made applicable for improving decision making in public health and environmental protection.

Parallel solution techniques for a 3D coupled shallow-water/transport model

The study of pollution by sediment transport in shallow seas requires a 3D dynamical simulation of the hydrodynamics and the sediment/pollutant transport. This type of combined simulation is among the objectives of the EEC programme NOWESP (NOrth West European Shelf Program). NOWESP concentrates on the Continental Shelf and studies (i) the effects of the dispersal of Rhine water and other major West European rivers in the North Sea, (ii) quantification of biogeochemical fluxes, and (iii) the behaviour of the shelf as interaction between land and the ocean. Long-term effects turn the simulations into a tremendous computational task



The reliability of a numerical model should be tested before practical use. The Molenkamp test is well known in the field of air pollution. This test amounts to solving a hyperbolic partial differential equation, whose solution represents a model plume of air rotating in the plane. The aim of the test is to minimize changes in the plume's shape by optimizing the numerical method.

which can only be accomplished by using advanced mathematical models on the fastest supercomputers. CWI's efforts in this field will comprise: (i) newly designed 3D parallel vectorized flux models, including advanced parallel linear algebra techniques, (ii) adaptive-grid techniques to accurately resolve local regions of high spatial activity, and (iii) estimation of numerical discretization errors to assess the quality of the computed solution. In The Netherlands, CWI will cooperate with the Tidal Water Division of the Dutch Water Control and Public Works Department, and with Delft University of Technology.

Fractal dynamics
Many important physical phenomena, such as fully developed turbulence, exhibit fractal and multi-scale self-similar behaviour. However, it has so far proved extremely difficult to show that the underlying equations do indeed give rise to such behaviour. Developing realistic mathematical models requires full understanding of this behaviour. To this end, CWI aims to study models with built-in multi-scale self-similar structures: (i) a tree type model, (ii) a fractal measure model, and (iii) a scaling length power series model. The objective is to explore numerically by simulation and analytically the power of these models, to find their inter-relations, and to examine whether the model output can satisfy some of the well-known 'chaos' dynamical equations and the equations modeling (e.g.) atmospheric phenomena. It is planned to carry out the project within the framework of the NWO priority programme 'Nonlinear Systems'.

A multigrid-based vortex method for the simulation of wind turbine flows
From the environmental point of view, wind energy is attractive as it does not pollute. Wind turbine aerodynamics is an important research area. CWI will study the numerical modeling of wind turbine flows, with a focus on vortex methods, i.e. considering only those regions in which vorticity occurs. The applicability and efficiency of advanced numerical methods, such as multigrid and grid-adaptation techniques, will be investigated. Such methods have proven to be important numerical modeling tools for a variety of applications in fluid dynamics. Attention will also be devoted to the steering of flow computations by interactive visualization. The project aims at developing user-oriented software for wind turbine areodynamicists.

Research Workstations:

- SGI 4D35G
(14 @ 35 MIPS)
60K 3-D vec/sec
- SGI 4DRPC Indigo
(35 @ 33 MIPS)
55K 3-D vec/sec
- SGI 4D310 VGX
(1 @ 33 MIPS)
1.1M 3-D vec/sec
- SUN SLC
(20 @ 12,5 MIPS)
- SUN ELC
(13 @ 18 MIPS)
- DEC DECstation 3100
(2 @12,5 MIPS)
- SUN Sparcstation 1
(40 @ 12,5 MIPS)
- SUN Sparcstation 1+
(22 @ 15 MIPS)
- DEC VS-2000
(10 @ 2 MIPS)
- Switch-386c
(6 @ 20 MIPS)
- NCD X-Windows
(20 @ 0 MIPS)
- DEC VS-3500
(2 x 2 @ 3,5 MIPS)

Compute Server:

- Floating Point Systems/Cray S510A
*(1 @72 MIPS SPARC CPU w/
4 x 7 @ 40 MIPS i860 MPC)*

File Servers:

- SGI 4D420
(1 x 2 @40 MIPS)
4,5 GB disk space
- SGI 4D260
(1 x 6 @25 MIPS)
2 GB disk space
- SUN 4/490
(1 x 1 @ 25 MIPS)
2,5 GB disk space
- SUN 4/280
(4 x 1 @ 10 MIPS)
20 GB disk space

Network Services:

- Local Ethernets
(3 x 10Mb/sec per office)
- SURFnet-2
(Dutch National Research Network)
- NLnet & EurOpen
(Dutch & European UNIX Network)
- RIPE
(European IP Research Network)
- Modem Pool
(20 x 9600bps Trailblazer modems)

Print Server:

- DEC VAX-11/750
(1 Agfa 9800PS Phototypesetter)
(14 Laserprinters)

Administrative/Home Support:

- 100 x Apple Macintosh-Plus
3 x SGI Indigo
60 x 9600bps Trailblaser modems

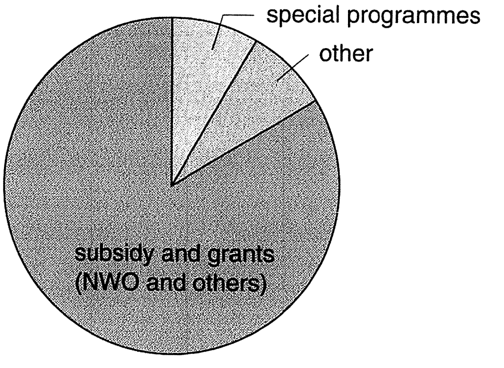
CWI Computing Equipment Resources (as of December 31, 1991)

FINANCIAL AND OTHER DATA

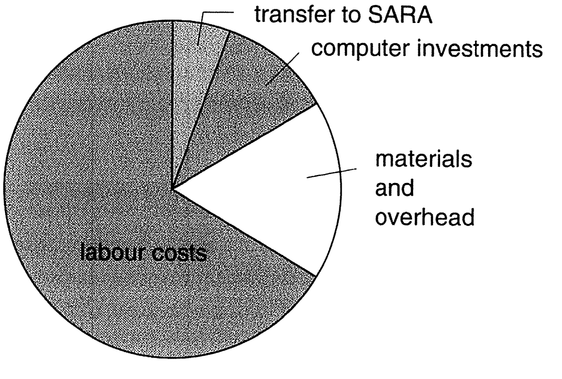
FINANCES 1991

In 1991, SMC spent Dfl. 24.91 million, of which about Dfl. 2.05 million was allocated to research by the national working parties and Dfl. 22.86 million to CWI.
The expenses were covered by a subsidy from NWO (Dfl. 19.64 million), other subsidies and grants (Dfl. 1.02 million), from the international programmes (mainly EC programmes, e.g. ESPRIT and RACE) (Dfl. 1.69 million), and from national programmes (Dfl. 0.07 million).
Finally, an amount of about Dfl. 1.99 million was obtained as revenues out of third-party-services, sponsorships and other sources.
During 1991 CWI also employed over twenty researchers in externally financed positions, for example by STW and industry. These are not included in the adjacent financial summary.

income CWI



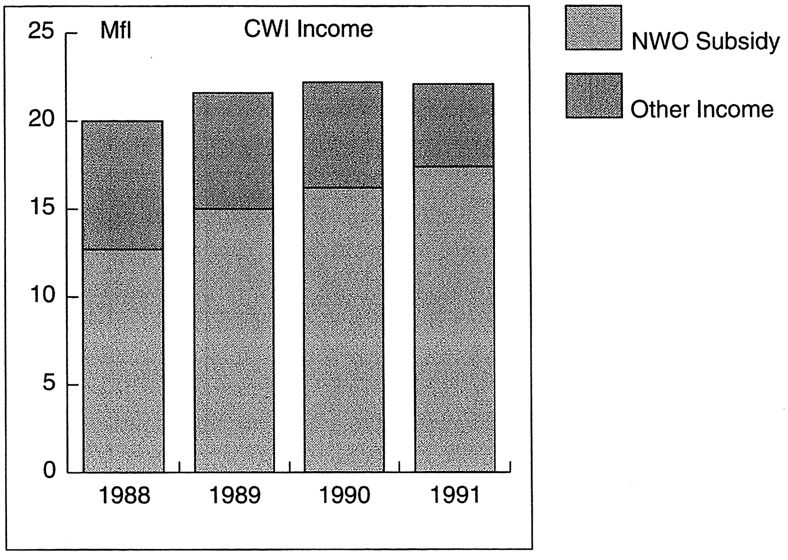
expenses CWI



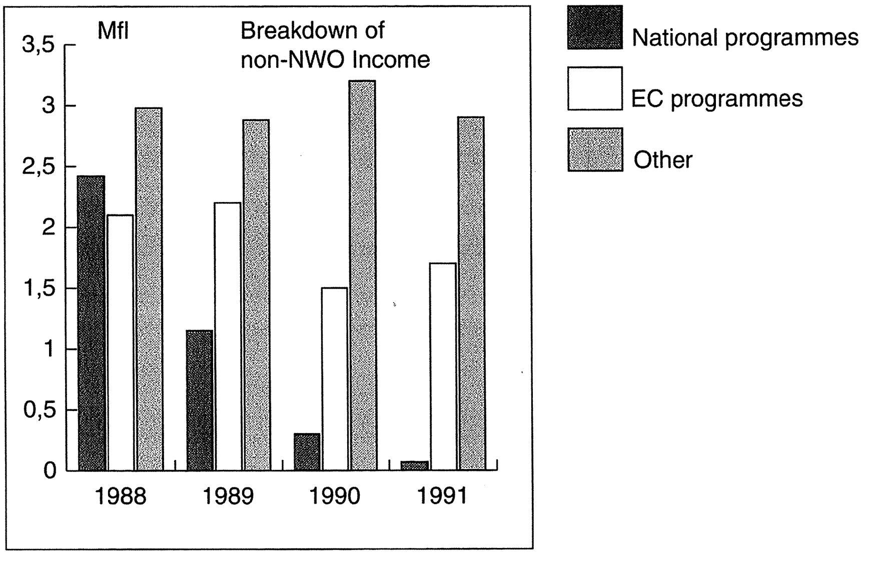
	national working parties	*CWI*	*SMC*
	* Dfl. 1000		
INCOME			
subsidy and grants			
- NWO	2203	17438	19641
- other	-	1023	1023
national programmes	-	66	66
international programmes	-	1687	1687
sponsorships	-	110	110
other revenues	124	1759	1883
total income	2327	22083	24410
EXPENSES			
labour costs	2031	15154	17185
materials and overhead	25	3912	3937
computer investments	-	2522	2522
transfer to SARA	-	1270	1270
total expenses	2056	22858	24914

FINANCES 1988 - 1991

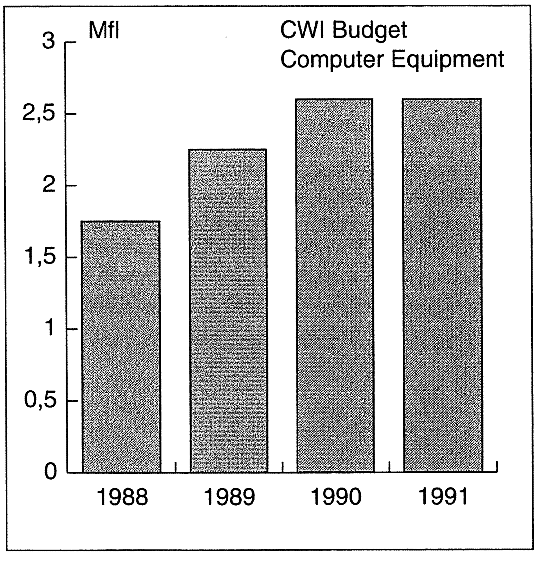
A

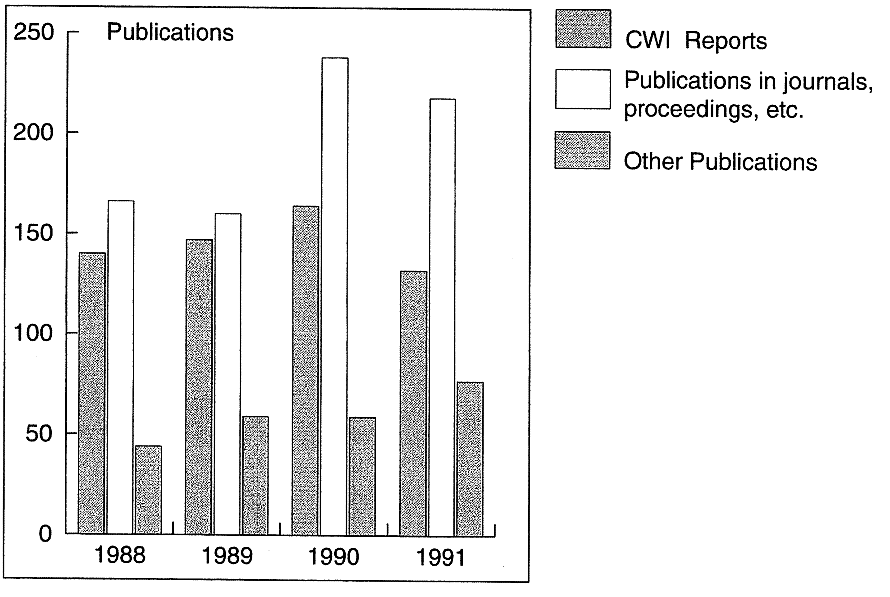


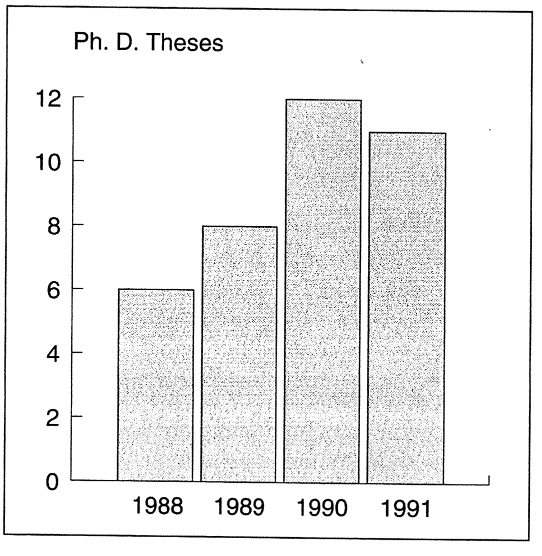
B



C







Library (ultimo 1991)	
39 000	books
1 500	subscriptions on journals
93 000	reports

CWI RESEARCH PROGRAMMES

Analysis, Algebra & Geometry

Algebra, discrete mathematical structures and computer algebra
Study of graphs/geometries/group theory and computer algebra. The main interest lies in graphs and groups of Lie type. This has led to the development of algorithms implemented in the software package Lie.
Subjects:
- Subgroups of Lie groups
- Geometrics and groups
- Graphs and groups
- Software development
- Computer algebra

Programme leader: A.M. Cohen

Analysis
Special functions, asymptotic expansions, Lie groups, quantum groups and integrable dynamical systems and some of the manifold interrelations between these topics.
Programme leader: T.H. Koornwinder
This group has been discontinued per January 1, 1992. Some subprojects find a continuation in other groups.

Modelling and analysis
Analysis of ordinary, partial and functional differential equations and integral equations corresponding to mathematical descriptions of biological processes.
Subjects:
- Infectious diseases
- General functional analytic theory for structured population models
- Banach space structure theory and semigroup operators
- Functional differential equations
- Prey-predator patch problems
- Evolutionary genetics
- Dynamic cardiac magnetic resonance imaging
- Three-dimensional reconstruction by confocal scanning laser microscopy
- Ocean acoustic tomography

Programme leader: O. Diekmann

Operations Research, Statistics & System Theory

Combinatorial optimization and algorithmics
Mathematical investigation of problems and algorithms involving the arrangement, grouping, ordering and selection of discrete objects.
Subjects:
- Design and analysis of algorithms
- Polyhedral methods and polynomial-time algorithms
- Multicommodity flows and VLSI-layout
- Computational geometry
- Parallel computations
- Multi-criteria machine scheduling problems
- Interactive planning methods

Programme leader: A. Schrijver

Analysis and control of information flows in networks
Mathematical modelling, analysis and control of information flows in computer systems and telecommunication networks.
Subjects:
- Analysis of mathematical queueing models
- Performance analysis of communication systems
- Performance analysis of computer systems
- Reliability and availability of networks

Programme leader: O.J. Boxma

System and control theory
Formulation and analysis of dynamical systems as models for dynamic phenomena, and the solution of control and prediction problems.
Subjects:
- Deterministic system theory
- Stochastic system theory
- Systems with a generalized state space
- Control of discrete-event systems
- Control-theoretic computations for element models

Programme leader: J.H. van Schuppen

Image analysis
Mathematical and statistical aspects of the

analysis of digital and related spatial data. The aims are to apply probabilistic models and statistical techniques to obtain new algorithms and assess the performance of existing ones. New developments include glance functions, granulometries and discrete scaling.
Programme leader: A.J. Baddeley

Statistics and probability theory
Fundamental research in probability and statistics, with special emphasis on stochastic processes, semiparametric statistical inference, and resampling techniques, e.g. bootstrapping. Fundamental research as well as applications are considered, especially in consultation, cooperative projects and STW projects.
Subjects:
- Stochastic processes
- Semiparametric inference for filtered experiments
- Asymptotic methods and resampling techniques
- Applied statistics and consultation

Programme leader: R. Helmers

Numerical Mathematics

Discretization of evolution problems
Analysis, development and documentation of algorithms for the numerical solution of evolution problems for differential equations and their application to industrial problems.
Subjects:
- Stability and convergence
- Method of Lines book
- Adaptive grid methods (STW)
- Static-regridding methods (RIVM)
- 3D Shallow-water equations
- Boussinesq model (Delft Hydraulics)
- Parallel initial-value-problem solvers for mechanical problems (UvA-Hanoi)
- Parallel initial-value-problem solvers for circuit analysis (submitted to STW)
- Parallel initial-value-problem solvers for partial differential equations

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

Steady boundary-value problems
Development and analysis of modern techniques for the efficient numerical solution of boundary value problems, in particular the study of multigrid and related methods and their application to industrial problems.
Subjects:
- The analysis of defect correction and adaptive techniques
- Application of multigrid techniques to fluid dynamics problems
- Reliable and efficient methods for the semiconductor device simulation equations (IOP)
- Parameter identification in ordinary differential equations (AKZO)

Programme leader: P.W. Hemker

Numerical software
Standardization of numerical software in Ada, development of efficient and portable numerical software for vector and parallel computers, and development of fast programs for solving classical problems from number theory. In a fourth (contract research) project, algorithms and high-level language implementations are being developed for the assessment of geometric forms from coordinate data.
Subjects:
- Development of numerical software in the programming language Ada
- Parallel numerical algorithms
- Computational number theory
- Chebyshev reference software
- Consultation and supporting projects

Programme leader: H.J.J. te Riele

Software Technology

Semantics
Research into semantic aspects of parallel computation according to various programming styles (imperative, applicative, logic, object-oriented); also foundational topics related to semantic modelling.
Programme leader: J.W. de Bakker

Concurrency and real-time systems
Research concerning process algebra, including real-time and probabilistic extensions. Specifications languages, system development methodology.
Programme leader: F.W. Vaandrager

Extensible programming environments
Algebraic specification of programming environments, incremental development of language definitions, implementation of algebraic specifications.
Programme leader: P. Klint

Algebraic and syntactic methods
Foundational research centering around term rewriting systems, with an emphasis on algebraic and syntactic methods; foundational research in process algebra.
Programme leader: J.W. Klop

Logic and language
Research concerning logic programming, deductive and knowledge-based database systems, non-monotonic reasoning and natural language processing.
Programme leader: K.R. Apt

Algorithmics & Architecture

Algorithms and complexity
Design and analysis of algorithms in distributed computing and VLSI. Fundamental studies and research in complexity theory.
Programme leader: P.M.B. Vitányi

Cryptology
The research concerns all aspects of cryptology related to information security. There is special emphasis on the protection of privacy of individuals in protocols for the transmission of messages, payment systems, and the treatment of personal data by various organizations.
Programme leader: D. Chaum

Computer Systems and Ergonomics
The methodology of integration of functions and applications in computer systems in order to provide end-users with easily manageable tools. (This project has been terminated during 1991).
Programme leader: S. Pemberton

Databases
Research on data models for databases and their associated software architectures.The research will be further focussed on the object-oriented approach, such as the formalization of an object-oriented database model, the development and the evaluation of efficient algorithms for object-oriented databases, and the storage management of replicated objects in a distributed system.
Programme leader: M.L. Kersten

Constructive algorithmics
Development of concepts, notations, formalisms and methods, on a high level of abstraction, 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 certain data types or classes of problems.
Programme leader: L.G.L.T. Meertens

Interactive Systems

Computer Graphics
The design of functionally complete basic graphics systems, with special support for interactive use. Results to be made available, on the one hand as (contribution to) international standards, on the other hand as implementations, again with special attention to efficiency required for high quality interaction.
Programme leader: A.A.M. Kuijk

Interaction
Interaction among computer processes and between humans and computers can be fundamentally approached from many viewpoints. In this research several coherent and yet independent viewpoints are taken to study a variety of problems. The coherence allows the researchers to share the experimental environments and/or to make the results available in the same context.
Programme leader: I. Herman

Intelligent CAD systems
The programme will, through the use of AI based methods and techniques, attempt to produce CAD systems which will be more complete, integrated, and have a high quality user interface. To implement such a system a language is being developed based on the object-oriented and logic programming paradigm. This language ADDL (Artifact and Design Description Language) has special dedicated features to encode existing and newly acquired knowledge about the design object, about the design process and about their relations. The encoding and treatment of design knowledge is studied in the context of geometric modelling, object-oriented databases, user interfaces and geometric reasoning.
Programme leader: F. Arbab

Computer Systems & Telematics

Multimedia kernel systems
Research on support systems for multimedia applications at the operating systems level. Areas of interest include the development of robust multimedia systems that offer acceptable levels of performance and fault tolerance as well as data and location transparency for higher-level interfaces. Research themes include basic support for the definition and access of multiple streams of component information (such as sound data, picture data and text data), development of interface structures to provide low-level assistance in manipulation and synchronization of data, and the development of replicated information manipulation services for both data storage and data processing.
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:
- Numerical simulation of brine flow
- Mathematical techniques for the study of the population biology of infections
- Algorithms for mathematical air pollution models
- System identification of compartmental systems - a mathematical tool in public health and environmental protection
- Parallel solution techniques for a 3D coupled shallow-water/transport model
- Fractal dynamics
- A multigrid-based vortex method for the simulation of wind turbine flows

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 various large-scale projects in which CWI participates. Whilst there is nothing new about cross-border contacts among scientists, recent years have seen a boom in national and international cooperation. The list of such programmes involving CWI grows apace, year after year.

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 II

GIPE II (2177): Generation of Interactive Programming Environments II
January 1989 - January 1992
Sema Metra (coordinator), INRIA, The Netherlands PTT, Planet, GIPSI, Bull
P. Klint

COMPARE (5399): Compiler Generation for Parallel Machines
January 1, 1991 - January 1, 1994
Ace BV, Steria, GMD, INRIA, Harlequin Ltd, Universität des Saarlandes
P. Klint

ATMOSPHERE (2565): Advanced Systems Engineering Environments
March 1989 - March 1991
Siemens, Bull, Société Française de Génie Logiciel, ESF Association, GEC-Marconi, Nixdorf, Philips
Associated contractor of Philips
J.C.M. Baeten

ESPRIT Basic Research Action (BRA)

CONCUR (3006): Theory of Concurrency: Unification and Extension
September 1989 - March 1, 1992
Univ. Amsterdam, Univ. Edinburgh, Univ. Sussex, Univ. Oxford, Swedish Institute of Computer Science, INRIA
Coordinator
J.C.M. Baeten

INTEGRATION (3020): Integrating the Foundations of Functional, Logic and Object-oriented Programming
July 1989 - April 1, 1992
CAIMENS, Philips, Università di Pisa, Centro de Inteligencia Artificial, Imperial College
Coordinator
J.W. de Bakker

SEMAGRAPH (3074): Semantics and Pragmatics of Generalized Graph Rewriting
July 1989 - March 1, 1992
Univ. East Anglia (coordinator), CNRS, Imperial College, Univ. Nijmegen, ICL
J.W. Klop

RACE

RIPE (1040): RACE Integrity Primitives Evaluation
November 1988 - July 1992
Other consortium members: Siemens AG, Philips Usfa BV, The Netherlands PTT Research, Universities of Louvain and Aarhus
Prime contractor
D. Chaum

SPECS (1046): Specification and Programming Environment for Communication Software
January 1988 - January 1993
Subcontractor of The Netherlands PTT Research
J.C.M. Baeten

SCIENCE

Evolutionary Systems: deterministic and stochastic evolution equations, control theory and mathematical biology

March 1990 - March 1993
Universities of Tübingen, Besançon, Graz, Mons and Zürich, Scuola Normale Superiore Pisa, Techn. Univ. Delft
O. Diekmann

Combinatorial Optimization: algorithmic approaches to large and complex combinatorial optimization problems
October 1990 - October 1993
Universities of Louvain, Augsburg, Grenoble (Université Joseph Fourier) and Valencia, CNR Rome
A. Schrijver

Other programmes

BRITE EURAM project AERO 1094: Solution adaptive Navier-Stokes solvers with grid-decoupled upwind schemes and multigrid acceleration
January 1990 - January 1992
Von Kármán Institute Brussels (main contractor), Free Univ. Brussels, Univ. Bari
P.W. Hemker

BCR- project: Chebyshev Reference Software
January 1990 - January 1993
NPL Teddington, Physikelisch-Technische Bundesanstalt
J. Kok

National Programmes

SPIN (Stimulation Project Team Computer Science)

PARTOOL: A parallel processing development environment
January 1989 - January 1993
TNO (coordinator), Philips, Techn. Univ. Delft, Univ. Utrecht
J.K. Lenstra

SION (Netherlands Foundation for Computer Science)

Mathematical morphology in hierarchical graph representations of images
TNO, Univ. Amsterdam
H.J.A.M. Heijmans

Nonwellfounded sets and semantics of programming languages
May 1, 1991 - May 1, 1995
J.J.M.M. Rutten

Typed lambda calculi
June 1, 1990 - June 1, 1994
Univ. Utrecht
M. Bezem

ECOS- Extensible Complex Object Server
May 1, 1990 - May 1, 1995
Free Univ. Amsterdam, Univ. Amsterdam
M.L. Kersten

NFI (National Facility Computer Science)

Design of decision support systems
January 1, 1991 - July 31, 1991
Techn. Univ. Eindhoyen
J.K. Lenstra

Systematic design of user interfaces
January 1, 1991 - December 31, 1991
Free Univ. Amsterdam
S. Pemberton

Beehive project
January 1, 1991 - May 15, 1991
S.J. Mullender

Performance analysis and control of distributed computer systems
October 1, 1990 - January 1, 1995
O.J. Boxma/J.H. van Schuppen

Structural and semantic parallels in natural languages and programming languages
January 1, 1991 - January 1, 1995
Univ. Amsterdam, OTS, Univ. Utrecht
D.J.N. van Eijck

Research and Education in Concurrent Systems (REX)
January 1988 - January 1993
Technical Univ. Eindhoven, Univ. Leiden
J.W. de Bakker

Transformational programming
January 1988 - January 1993
Univ. Nijmegen, Univ. Utrecht
L.G.L.T. Meertens

Intelligent CAD systems
October 1986 - January 1993
TNO/IBBC, Univ. Amsterdam
P.J.W. ten Hagen

Formal methods for the description of information systems and their analysis
September 1989 - September 1993
Universities of Eindhoven, Leiden, Limburg and Twente
M.L. Kersten

STW (Foundation for the Technical Sciences)

Two-dimensional time-dependent Boussinesq model
August 1988 - February 1991
P.J. van der Houwen

Statistical analysis of debugging and error counting models in software reliability
March 1989 - March 1992
Univ. Utrecht
K.O. Dzhaparidze

Adaptive grid techniques for evolutionary partial differential equations
September 1987 - September 1992
Shell
J.G. Verwer

New architecture for interactive raster graphics on the basis of VLSI
April 1987 - April 1992
Univ. Twente
P.J.W. ten Hagen

IOP (Innovative Research Programmes)

IC-Technology: numerical methods for semiconductor device modelling
October 1987 - February 1992
FOM, Technical Univ. Delft, Philips CAD-Centre Eindhoven
P.W. Hemker

SPI (Special Programme Computer Science)

Incremental program generators
March 1, 1990 - August 1, 1994
P. Klint

RESEARCH STAFF

Analysis, Algebra & Geometry

M. Hazewinkel (head of department)

A.E. Brouwer
A.M. Cohen
O. Diekmann
B. Dijkuis
M.S. Dijkhuizen
F.C.A. Groen (advisor)
J.A.P. Heesterbeek
T.H. Koornwinder
M.A.A. van Leeuwen
J. van de Lune
J.A.J. Metz (advisor)
J.M.A.M. van Neerven
A.B. Olde Daalhuis
J.B.T.M. Roerdink
S.N.M. Ruijsenaars
N.M. Temme
J. de Vries

Operations Research, Statistics & System Theory

O.J. Boxma (head of department)

A.J. Baddeley
H.C.P. Berbee
J. van den Berg
S.C. Borst
A.J. Cabo
J. Coelho de Pina
J.W. Cohen (advisor)
M.B. Combé
A.L.M. Dekkers
J. de Does
F.A. van der Duyn Schouten
K.O. Dzhaparidze
A.M.H. Gerards
R.D. Gill (advisor)
A. Gombani
W.P. Groenendijk
L.F.M. de Haan (advisor)
H.J.A.M. Heijmans
R. Helmers
J.A. Hoogeveen
M. Kuijper
B.J.B.M. Lageweg
J.K. Lenstra (advisor)
M.N.M. van Lieshout
P. Nacken
M.C.J. van Pul
J.A.C. Resing
A. Schrijver
J.M. Schumacher
J.H. van Schuppen
F.B. Shepherd
S.L. van de Velde
B. Veltman
P.R. de Waal
P. Wartenhorst
J.W. van der Woude

Numerical Mathematics

P.J. van der Houwen (head of department)

E.D. de Goede
P.W. Hemker
W.H. Hundsdorfer
J. Kok
B. Koren
H.T.M. van der Maarel
A.N. Malyshev
J. Molenaar
J. Mooiman
R.R.P. van Nooyen
H.J.J. te Riele
B.P. Sommeijer
R.A. Trompert
J.G. Verwer
H.A. van der Vorst (advisor)
P. Wesseling (advisor)
P.A. Zegeling

programmers:
J.G. Blom
W.M. Lioen
M. Louter-Nool
D.T. Winter
P.M. de Zeeuw

Software Technology

J.W. de Bakker (head of department)
K.R. Apt
J.C.M. Baeten
J.A. Bergstra (advisor)
R.N. Bol
A. van Deursen
D.J.N. van Eijck
W.J. Fokkink
J.F. Groote
J. Heering
J.M. Jacquet
J.F.T. Kamperman
P. Klint
J.W. Klop
A.S. Klusener
J.N. Kok
H.P. Korver
E.A. van der Meulen
A. Middeldorp
M. Moortgat
G. Morrill
C. Palamidessi
A. Ponse
J. Rekers
J.J.M.M. Rutten
F. Tip
Y. Toyama
F.-J. de Vries
H.R. Walters
J.H.A. Warmerdam

trainee:
C. Pieramico

Algorithmics & Architecture

L.G.L.T. Meertens (head of department)
L.G. Barfield
C.A. van den Berg
E.D.G. Boeve
J.N.E. Bos
D. Chaum
P. Clote
M.J. Coster
I.J.P. Elshoff
M.M. Fokkinga
M.W. van der Ham
E.J.L.J. van Heyst
R. Hirschfeld
J.T. Jeuring
M.L. Kersten
E. Kranakis
S.J. Mullender (advisor)
T.P. Pedersen
S. Pemberton
A. Plomp
G. van Rossum
H. Shin
A.P.J.M. Siebes
C.J.E. Thieme
J.T. Tromp
N.Th. Verbrugge
P.M.B. Vitányi
M.H. van der Voort
J.C.S.P. van der Woude

programmers:
F. van Dijk
A.J. Jansen
T.J.G. Krijnen

trainees:
G. Brands
P.J.M. Veugen

Interactive Systems

P.J.W. ten Hagen (head of department)
F. Arbab
E.H. Blake
C.L. Blom
V.C.J. Disselkoen
W. Eshuis
M. Haindl
I. Herman
H.E. Klarenbosch
A.A.M. Kuijk
D.B.M. Otten
J.L.H. Rogier
M.M. de Ruiter
E.P.B.M. Rutten
D. Soede
P. Spilling
P.J. Veerkamp
J. van der Vegt
R.C. Veltkamp

programmers:
M.A. Guravage
R. van Liere

trainee:
I.Chr. Maurice

Computer Systems & Telematics

D.C.A. Bulterman (head of department)
L. Hardman
G. van Rossum

programmers:
J.A. Janssen
K.S. Mullender

FOREIGN VISITORS

Analysis, Algebra and Geometry

J.-P. Aubin (France)
M.V. Berry (UK)
Ph. Blanchard (Germany)
G. Bolz (Germany)
A. Fitouhi (Tunisia)
H. Frankowska (France)
J. Geronimo (USA)
E.G. Kalnins (New Zealand)
A. Klimyk (USSR)
T. Krüger (Germany)
S. Oharu (Japan)
A. Pressley (UK)
S.S. Sazhin (UK)
S. Shpectorov (USSR)
L. Soicher (UK)
V.V. Statulevicius (USSR)
F.H. Szafraniec (Poland)
Ph. Tchamitchian (France)
J. Tits (France)
A. Yuzina (USSR)

Operations Research, Statistics, and System Theory

D. Alpay (Israel)
J.D. Aplevich (Canada)
J.-P. Aubin (France)
A. Banaszuk (USA)
L. Baratchart (France)
M. Berman (Australia)
C. Bezuidenhout (USA)
A. Björner (Sweden)
A.B. Bondi (USA)
T.C. Brown (Australia)
R.M. Burton (USA)
Chun Wa Ko (USA)
M. Deistler (Austria)
N.I. Fisher (Australia)
S.G. Foss (USSR)
H. Frankowska (France)
G. Glüsing-Luërssen (Germany)
A. Gombani (Italy)
H.J.G. Gundersen (Denmark)
H. Gzyl (Venezuela)
J. Haralambides (USA)
D. Hershkowitz (Israel)
R. Hummel (USA/France)
M. Ikeda (Japan)
E.A. Jonckheere (USA)
M. Kelbert (USSR)
K.K. Kilakos (Canada)
V.S. Korolyuk (USSR)
M. Laurent (France/Germany)
H. Levy (Israel)
L. Lovász (Hungary)
E. Mammen (Germany)
Ph. Nain (France)
B. Reed (Germany)
R.L. Sandland (Australia)
V. Schmidt (Germany)
D. Schulman (Denmark)
P.J. Schweitzer (USA)
F.B. Shepherd (Canada)
R. Sibson (UK)
J. Steif (Denmark)
P.G. Taylor (Australia)
S. Tragoudas (USA)
B. Wahlberg (Sweden)
U. Yechiali (Israel)

Numerical Mathematics

B.R. Bairi (India)
C. Blömer (Germany)
A. Bunse-Gerstner (Germany)
A.T. Chronopoulos (USA)
L.M. Degtyarev (USSR)
P. van Dooren (Belgium)
Fan Ki Ahn (Vietnam)
E. Gallopoulos (USA)
K. Gärtner (Germany)
Ch. König (Germany)
N.I. Koslov (USSR)
Y. Kuznetsov (USSR)
J. Linden (Germany)
G. Lonsdale (Germany)
M. do Ceu Lopes (Portugal)
A.N. Malyshev (USSR)
A.M. Odlyzko (USA)
H. Ritzdorf (Germany)
K. Stüben (Germany)
A.S. Vasudeva Murthy (India)
D. Vucinic (Belgium)
A.Y. Zacharov (USSR)

Software Technology

G. Agha (USA)
I. Attali (France)
R. Back (Finland)
E. Best (Germany)
A. Bossi (Italy)
G. Cepparello (Italy)
Th. Despeyroux (France)
T.B. Dinesh (USA)
M. van Emden (Canada)
J. Etchemendy (USA)
L. Ferrari (Italy)
K. Futatsugi (Japan)
D. Gabbay (UK)
P. Gaerdenfors (Sweden)
R.J. van Glabbeek (USA)
A. Gouda (USA)
N. Haines (UK)
J. Herber (Sweden)
A. Jeffrey (Germany)
M.I. Kanovic (USSR)
J.K. Kennaway (UK)
A. Knobel (UK/Japan)
B. Kowalski (UK)
D. Kozen (Denmark)
M.R.K. Krishna Rao (India)
K.G. Larsen (Denmark)
A. Mateescu (Rumania)
Y. Moscowitz (Israel)
L. Moss (USA)
Th. Muller (Germany)
F. Oles (USA)
P. Pananagaden (USA)
J. Parrow (Germany)
F. Pereira (USA)
D. Plump (Germany)
J. Power (UK)
V. Pratt (USA)
A. Rabinovich (USA)
J.-C. Raoult (France)
L. Rideau (France)
N. Roques (France)
G. Sacks (USA)
D. Scott (USA)
S. Smolka (USA)
J. Shepherdson (UK)
B. Thomsen (Germany)
F.W. Vaandrager (USA)
L. Viklund (Sweden)
W. Zadrozny (USA)
J.I. Zucker (Canada)

Algorithmics and Architecture

J. Alemany (USA)
V.L. Arlazarov (USSR)
A.D. Astakhov (USSR)
R.S. Bird (UK)
P. Clote (USA)
C. Crèpeau (France)
R. Hirschfeld (USA)
E. Dahlhaus (Germany)
J. Gibbons (UK)
J. Grudin (USA)
J. Haralambides (USA)
Ph. G. Kolaitis (USA)
L. Lamport (USA)
P.E. Mounier-Kuhn (France)
J. Oommen (Canada)
T. Pederson (Denmark)
M. Picchiola (France)
G. Sacks (USA)
M. Santha (France)
H. Shin (Korea)
R. Solomonoff (Germany)
R.M. Stallman (USA)
S. Tragoudas (USA)

Interactive Systems

M. Haindl (Czechoslovakia)
B. Khoshnevis (USA)
P.J. Willis (UK)

PUBLICATIONS

Department of Analysis, Algebra and Geometry

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

Papers in Journals and Proceedings

A.M. COHEN, G.C.M. RUITENBURG (1991). Generating functions and Lie groups. A.M. COHEN (ed.). *Computational Aspects of Lie Group Representations and Related Topics; Proceedings of the 1990 Computational Algebra Seminar at CWI, Amsterdam*, CWI Tract 84, CWI, 19-28.

A.M. COHEN (1991). Presentations for certain finite quaternionic reflection groups. J.W.P. HIRSCHFELD, D.R. HUGHES, J.A. THAS (eds.). *Advances in Finite Geometries and Designs*, Proceedings of the Third Isle of Thorns Conference 1990, 69-79.

M.A.A. VAN LEEUWEN (1991). The Robinson-Schensted and Schützenberger algorithms and interpretations. A.M. COHEN (ed.). *Computational Aspects of Lie Group Representations and Related Topics; Proceedings of the 1990 Computational Algebra Seminar at CWI, Amsterdam*, CWI Tract 84, CWI, 65-88.

M.A.A. VAN LEEUWEN (1991). An application of Hopf algebra techniques to representation of finite classical groups. *Journal of Algebra 140*, 210-246.

M.A.A. VAN LEEUWEN (1990). An even more symmetric form of Zelevinsky's pictures. *Proceedings of 10. Kolloquium über Kombinatorik*, Bielefeld.

Other publications

A.M. COHEN (ed.) (1991). *Computational Aspects of Lie Group Representations and Related Topics; Proceedings of the 1990 Computational Algebra Seminar at CWI, Amsterdam*, CWI.

AM 2: **Analysis**

Papers in Journals and Proceedings

W. VAN ASSCHE, T.H. KOORNWINDER (1991). Asymptotic behaviour for Wall polynomials and the addition formula for little q-Legendre polynomials. *SIAM J. Math. Anal. 22*, 302-311.

M. HAZEWINKEL (1991). Introductory recommendations for the study of Hopf algebras in mathematics and physics. *CWI Quarterly Vol. 4, No. 1*, 3-26.

T.H. KOORNWINDER (1991). Handling hypergeometric series in Maple. C. BREZINSKI, L. GORI, A. RONVEAUX (eds.). *Orthogonal Polynomials and their Applications*, IMACS Annals on Computing and Applied Mathematics 9, Baltzer, 73-80.

T.H. KOORWINDER (1991). The addition formula for little q-Legendre polynomials and the $SU(2)$ quantum group. *SIAM J. Math. Anal. 22*, 295-301.

Reports

AM-R9103 M. HAZEWINKEL. Soliton and Riccati equations, to appear in *Proc. Conf. on Gaussian Random Fields*, T. HIDA (ed.), World Scientific.

AM-R9105 T.H. KOORNWINDER. *Positive convolution structures associated with quantum groups*, to appear in Probability Measures on Groups X, H. HEYER (ed.), Plenum, 1992, pp. 249-268.

AM-R9111 R.G.M. BRUMMELHUIS. *Gårding inequalities for systems of pseudo-differential operators.*

AM-R9112 T.H. KOORNWINDER. *Askey-Wilson polynomials for root systems of type BC.*

AM 3: **Modelling and analysis**

Papers in Journals and Proceedings

O. DIEKMANN (1991). Modelling infectious diseases in structured populations. B.D. SLEEMAN, R.J. JARVIS (eds.). *Ordinary and Partial Differential Equations, Vol. III*, Pitman RNiMS 254, 67-79 (Longman).

O. DIEKMANN, J.A.J. METZ (1991). Exact finite dimensional representations of models for physiologically structured populations. I. The abstract foundations of linear chain trickery. J.A. GOLDSTEIN, F. KAPPEL, W. SCHAPPACHER (eds.). *Differential Equations with Applications in Biology, Physics and Engineering*, Lecture Notes in Pure and Applied Mathematics 133, Marcel Dekker, 269-289.

O. DIEKMANN, M. KRETZSCHMAR (1991). Patterns in the effects of infectious diseases on population growth. *J. Math. Biol. 29*, 539-570.

O. DIEKMANN, M. GYLLENBERG, H.R. THIEME (1991). Perturbation theory for dual semigroups. V. Variation-of-constants formulas. PH. CLÉMENT, E. MITIDIERI, B. DE PAGTER (eds.). *Semigroup Theory and Evolution Equations*, Lecture Notes in Pure and Applied Mathematics 135, Marcel Dekker, 107-123.

O. DIEKMANN, S.A. VAN GILS (1991). The center manifold for delay equations in the light of suns and stars. M. ROBERTS, I.N. STEWART (eds.). *Singularity Theory and Its Applications*, Warwick, 1989, Part II (Springer LNiM) 1463, 122-141.

O. DIEKMANN, S.M. VERDUYN LUNEL (1991). A new short proof of an old folk theorem in functional differential equations. PH. CLÉMENT, E. MITIDIERI, B. DE PAGTER (eds.). *Semigroup Theory and Evolution Equations*, Lecture Notes in Pure and Applied Mathematics 135, Marcel Dekker, 101-106.

O. DIEKMANN, M.W. SABELIS, V.A.A. JANSEN (1991). Metapopulation persistence despite local extinction: predator-prey patch models of the Lotka-Volterra type. *Biol. J. Linnean Soc. 42*, 267-283.

O. DIEKMANN, K. DIETZ, J.A.P. HEESTERBEEK (1991). The basic reproduction ratio for sexually transmitted diseases, part I: Theoretical considerations. *Math. Biosc. 107*, 325-339.

O. DIEKMANN, A.M. DE ROOS, J.A.J. METZ (1991). Studying the dynamics of structured population models: a versatile technique and its application to Daphnia, preprint, to appear in *Amer. Nat.*

O. DIEKMANN, M. GYLLENBERG, H.R. THIEME (1991). Semigroups and renewal equations on dual Banach spaces with applications to population dynamics. S. BUSENBERG, M. MARTELLI (eds.). *Delay Differential Equations and Dynamical Systems*, Springer LNiM 1475, 116-129.

H. INABA (1990). Threshold and stability for an age-structured epidemic model. *J. Math. Biol. 28*, 411-434.

M.C.M. DE JONG, O. DIEKMANN (1991). A method to calculate - for computer-simulated infections - the threshold value, R_0, that predicts whether or not the infection will spread, preprint, to appear in *Prev. Vet. Med.*

J.M.A.M VAN NEERVEN (1991). Reflexivity, the dual Radon-Nikodym property, and continuity of adjoint semigroups II. *Indag. Math. N.S. 2*, 243-250.

J.M.A.M. VAN NEERVEN (1991). On the topology induced by the adjoint of semigroup of operators. *Semigroup Forum 43*, 378-394.

J.M.A.M. VAN NEERVEN, B. DE PAGTER (1991). Certain semigroups on Banach function spaces and their adjoints. PH. CLÉMENT, E. MITIDIERI, B. DE PAGTER (eds.). *Semigroup Theory and Evolution Equations*, Lecture Notes in Pure and Applied Mathematics 135, Marcel Dekker.

J.M.A.M. VAN NEERVEN (1990). Reflexivity, the dual Radon-Nikodym property, and continuity of adjoint semigroups. *Indag. Math. N.S. 1*, 365-379.

J.M.A.M. VAN NEERVEN, J.P.M. PIJN, A. NOEST, F.H. LOPES DA SILVA (1991). Chaos or noise in EEG signals: dependence on state and brain site. *Electroencephalography and Clinical Neurophysiology 79*, 371-381.

J.B.T.M. ROERDINK, H.J.A.M. HEIJMANS (1991). Mathematical morphology for structures without translation symmetry. *Second Quinquennial Review 1986-1991*, Dutch Society for Pattern Recognition & Image Processing, reprinted from Sign. Proc. 15:271-277 (1988).

S.S. SAZHIN, N.M. TEMME (1991). The threshold of parallel whistler-mode instability. *Annales Geophysicae 9*, 30-31.

S.S. SAZHIN, N.M. TEMME (1991). Marginal stability of parallel whistler-mode waves (asymptotic analysis). *Annales Geophysicae 9*, 304-308.

J. DE VRIES (1991). The Furstenberg structure theorem in topological dynamics. *CWI Quarterly, Vol. 4, No. 1*, 27-44.

Reports

AM-R9101 C.P. SCHUT. *Idempotents.*

AM-R9102 N.M. TEMME. *Asymptotic inversion of incomplete gamma functions*, to appear in Math. Computation.

AM-R9106 N.M. TEMME. *Asymptotic inversion of the incomplete beta function*, to appear in JCAM.

AM-R9107 A.B. OLDE DAALHUIS. *Hyperasymptotic expansions of confluent hypergeometric functions.*

AM-R9109 F. BRAUER. *Infectious disease models with variable infectivity.*

AM-R9113 O. DIEKMANN. *An invitation to structured (meta)population models.*

AM-R9114 J.B.T.M. ROERDINK, M. BAKKER. *An FFT-based method for attenuation correction in fluorescence confocal microscopy.*

Other publications

M. ZWAAN (1991). *Moment Problems in Hilbert Space with Applications to Magnetic Resonance Imaging.* Ph.D. thesis, Free University Amsterdam.

Other publications from AM

M. HAZEWINKEL (1991). *Encyclopaedia of Mathematics Vol. 7*, Orb-Ray, KAP.

M. HAZEWINKEL (1991). *Applied algebra*, preprint, CWI.

M. HAZEWINKEL (1991). Symmetrie problemen. A.W. GROOTENDORST (ed.). *Meetkundige Structuren*, CWI Syllabus 28, CWI, 91-104.

M. HAZEWINKEL (1991). Wavelets understand fractals. *Wavelet course*, CWI, November 1991.

AM-R9104 V.V. KOROLYUK. *Random additive functionals with rapid Markov switchings.*

AM-R9108 V.V. KOROLYUK. *Diffusion approximation of stochastic integral functionals of jump Markov processes.*

AM-R9110 V.V. KOROLYUK. *Diffusion approximation of stochastic additive functionals of jump Markov processes.*

Department of Operations Research, Statistics, and System Theory

BS 1: Combinatorial optimization and algorithmics

Papers in Journals and Proceedings

A.M.H. GERARDS (1991). Compact systems for T-join and perfect matching polyhedra of graphs with bounded genus. *Operations Research Letters 10*, 377-382.

J.A. HOOGEVEEN (1991). Analysis of Christofides' heuristic: some paths are more difficult than cycles. *Operations Research Letters 10*, 291-295.

J.A. HOOGEVEEN, G. SIERKSMA (1991). Seven criteria for integer sequences being graphic. *Journal of Graph Theory 15*, 223-231.

J.H.M. KORST, E.H.L. AARTS, J.K. LENSTRA, J. WESSELS (1991). Periodic multiprocessor scheduling. E.H.L. AARTS, J. VAN LEEUWEN, M. REM (eds.). *PARLE '91: Parallel Architectures and Languages Europe; Volume I: Parallel Architectures and Algorithms*, LNCS 505, Springer-Verlag, 166-178.

L. LOVÁSZ, A. SCHRIJVER (1991). Cones of matrices and set-functions, and 0-1 optimization. *SIAM Journal on Optimization 1*, 166-190.

A. SCHRIJVER (1991). Disjoint circuits of prescribed homotopies in a graph on a compact surface. *Journal of Combinatorial Theory (B) 51*, 127-159.

A. SCHRIJVER (1991). Edge-disjoint homotopic paths in straight-line planar graphs. *SIAM Journal on Discrete Mathematics 4*, 130-138.

A. SCHRIJVER (1991). Decomposition of graphs on surfaces and a homotopic circulation theorem. *Journal of Combinatorial Theory (B) 51*, 161-210.

A. SCHRIJVER (1991). Short proofs on multicommodity flows and cuts. *Journal of Combinatorial Theory (B) 53*, 32-39.

A. SCHRIJVER (1991). Disjoint homotopic paths and trees in a planar graph. *Discrete and Computational Geometry 6*, 527-574.

A. SCHRIJVER, P.D. SEYMOUR (1991). A simpler proof and a generalization of the zero-trees theorem. *Journal of Combinatorial Theory (A) 58*, 301-305.

Reports

BS-R9106 C.J.H. MCDIARMID, B.A. REED, A. SCHRIJVER, F.B. SHEPHERD. *Induced circuits in planar graphs.*

BS-R9110 B. GAMBLE, W. PULLEYBLANK, B.A. REED, F.B. SHEPHERD. *Right angle free subsets in the plane.*

BS-R9113 J.A. HOOGEVEEN. *Single-machine scheduling to minimize a function of K maximum cost criteria.*

BS-R9121 C.J.H. MCDIARMID, B.A. REED, A. SCHRIJVER, F.B. SHEPHERD. *Non-interfering dipaths in planar digraphs.*

Other publications

J.K. LENSTRA, A.H.G. RINNOOY KAN, A. SCHRIJVER (eds.) (1991). *History of Mathematical Programming: A Collection of Personal Reminiscences*, CWI & North-Holland, Amsterdam.

BS 2: **Analysis and control of information flows in networks**

Papers in Journals and Proceedings

J. VAN DEN BERG, R.W.J. MEESTER (1991). Stability properties of a flow process in graphs. *Random Structures and Algorithms 2*, 335-341.

J.L. VAN DEN BERG, O.J. BOXMA (1991). The M/G/1 queue with processor sharing and its relation to a feedback queue (invited paper). *Queueing Systems 9*, 365-401.

O.J. BOXMA (1991). Analysis and optimization of polling systems. J.W. COHEN, C.D. PACK (eds.). *Queueing, Performance and Control in ATM*, Proc. ITC-13 workshop, North-Holland Publ. Cy., Amsterdam, 173-183.

O.J. BOXMA, J.W. COHEN (1991). The M/G/1 queue with permanent customers. *IEEE J. Sel. Areas. Commun. 9*, 179-184.

O.J. BOXMA, G.A.P. KINDERVATER (1991). A queueing network model for analyzing a class of branch-and-bound algorithms on a master-slave architecture. *Oper. Res. 39*, 1005-1017.

O.J. BOXMA, H. LEVY, J.A. WESTSTRATE (1991). Efficient visit frequencies for polling tables: minimization of waiting cost (invited paper). *Queueing Systems 9*, 133-162.

J.W. COHEN (1991). On the attained waiting time. *Adv. Appl. Probab. 23*, 660-661.

J.W. COHEN (1991). On two teletraffic congress programs: Roots and scope. A. JENSEN, V.B. IVERSEN (eds.). *Teletraffic and Datatraffic in a Period of Change*, Proc. ITC 13, North-Holland Publ. Cy., Amsterdam, 1059-1065.

P.R. DE WAAL, N.M. VAN DIJK (1991). Monotonicity of performance measures in a processor sharing queue. *Performance Evaluation 12*, 5-16.

P. WARTENHORST, F.A. VAN DER DUYN SCHOUTEN (1991). Availability analysis of a two-unit standby system with preemptive repair. B.R. HAVERKORT, I.G. NIEMEGEERS, N.M. VAN DIJK (eds.). *Proceedings of the First International Workshop on Performability Modelling of Computer and Communication Systems.*

Reports

BS-R9101 J.P.C. BLANC, P.R. DE WAAL, P. NAIN, D. TOWSLEY. *A new device for the synthesis problem of optimal control of admission to an M/M/c queue.*

BS-R9102 O.J. BOXMA. *Analysis and optimization of polling systems.*

BS-R9111 O.J. BOXMA, H. LEVY, J.A. WESTSTRATE. *Efficient visit frequencies for polling tables: minimization of waiting cost.*

BS-R9114 J.W. COHEN. *Zero drift random walk on NxN with reflection, ergodicity conditions.*

BS-R9125 S.C. BORST, O.J. BOXMA, M.B. COMBÉ. *An M/G/1 queue with dependence between interarrival and service times.*

BS-R9128 J.A.C. RESING. *Polling systems and multitype branching processes.*

Other publications

J. VAN DEN BERG (1991). *On the Number of Non-dominated Paths.* Preprint, December 1991.

J. VAN DEN BERG, H. KESTEN (1991). *Inequalities for the Time Constant in First-passage Percolation.* Preprint

Cornell University, August 1991.

J. VAN DEN BERG, J. STEIF (1991). *A Uniqueness Condition for Gibbs Measures, with Applications to the 2-dimensional Ising Anti-ferromagnet and Hard-core Gas Model.* Preprint, December 1991.

S.C. BORST, O.J. BOXMA, M.B. COMBÉ (1991). *Collection of Customers - A Correlated M/G/1 Queue.* Accepted for publication in the proceedings of ACM Sigmetrics/Performance '92.

J.W. COHEN (1991). *Analysis of Random Walks,* IOS Press, Amsterdam.

J.W. COHEN, C.D. PACK (eds.) (1991). *Queueing, Performance and Control in ATM.* Proc. ITC-13 workshop, North-Holland Publ. Cy., Amsterdam.

J.A.C. RESING (1991). *Cell Level Performance Analysis of ATM Multi-service Networks 1: Introduction.* Report PTT Research, March 1991.

J.A.C. RESING (1991). *Cell Level Performance Analysis of ATM Multi-service Networks 2: Tandem Queues with Deterministic Service Times.* Report PTT Research, June 1991.

H. TAKAGI, T. TAKINE, O.J. BOXMA (1991). *Distribution of the Workload in Multiclass Queueing Systems with Server Vacations.* Report IBM Research, Tokyo Research Laboratory.

P. WARTENHORST, W.P. GROENENDIJK (1991). *Transient Failure Behaviour of Repairable Systems.* Tech. Report AMER.91.018 Koninklijke/Shell-Laboratorium, Amsterdam.

BS 3: **System and control theory**

Papers in Journals and Proceedings

M. KUIJPER, J.M. SCHUMACHER (1991). Minimality of descriptor representations under external equivalence. *Automatica J. - IFAC 27*, 985-995.

M. KUIJPER, J.M. SCHUMACHER (1991). Realization of finite and infinite modes. *Proceedings ISIRS Conference*, Warsaw, Poland, July 1991.

J.M. SCHUMACHER (1991). System-theoretic trends in econometrics. A.C. ANTOULAS (ed.). *Mathematical System Theory: The Influence of R.E. Kalman*, Springer-Verlag, 559-577.

J.M. SCHUMACHER (1991). Equivalence of representations for a class of nonstationary processes. *Proceedings CDC*, Brighton, England, December 1991, 3-8.

J.H. VAN SCHUPPEN (1991). For which control objectives does tuning hold? G.B. DI MASI, A. GOMBANI, A.B. KURZHANSKY (eds.). *Modeling, Estimation and Control of Systems with Uncertainty*, (Proceedings IIASA Workshop), Progress in Systems and Control Theory, Volume 10, Birkhäuser Boston Inc., Boston, 445-448.

J.H. VAN SCHUPPEN (1991). Asymptotic selftuning for Gaussian stochastic control systems. C. COMMAULT et al. (eds.). *Proceedings of the First European Control Conference*, Grenoble, France, 1991, Hermès, Paris, 258-263.

J.H. VAN SCHUPPEN (1991). Routing of freeway traffic - A state space model and routing problems. *Proceedings of the 30th Conference on Decision and Control,* IEEE Press, New York, 2194-2195.

Reports

BS-R9103 M. KUIJPER. *Descriptor representations without direct feedthrough term.*

BS-R9108 M. KUIJPER, J.M. SCHUMACHER. *State space formulas for transfer poles at infinity.*

BS-R9112 J.M. SCHUMACHER. *A pointwise criterion for controller robustness.*

Other publications

M. KUIJPER, J.M. SCHUMACHER (1991). *State Space Formulas for Transfer Poles at Infinity.* Preprint, June, submitted for publication in the Proceedings of the International Symposium MTNS-91, Kobe, Japan.

J.H. VAN SCHUPPEN (1991). *Tuning of Gaussian Stochastic Control Systems.* Preprint, submitted for publication.

J.H. VAN SCHUPPEN (1991). *Stochastic Realization of Finite-Valued Processes and Primes in the Positive Matrices.* Preprint, June, submitted for publication in the Proceedings of the International Symposium MTNS-91, Kobe, Japan.

J.H. VAN SCHUPPEN (1991). *Routing of Freeway Traffic - A State Space Model and Routing Problems.* Preprint, March.

BS 4: **Image analysis**

Papers in Journals and Proceedings

H.J.A.M. HEIJMANS (1991). Theoretical aspects of grey-level morphology. *IEEE Trans. PAMI 13*, 568-582.

H.J.A.M. HEIJMANS (1991). Morphological discretization. U. ECKHARDT, A. HUBLER, W. NAGEL, G. WERNER (eds). *Proceedings of the 5th Workshop on Geometrical Problems of Image Processing*, Georgenthal, Berlin, Akademie Verlag, 99-106.

M.N.M. VAN LIESHOUT (1991). A Bayesian approach to object recognition. U. ECKHARDT, A. HUBLER, W. NAGEL, G. WERNER (eds). *Proceedings of the 5th Workshop on Geometrical Problems of Image Processing*, Georgenthal, Berlin, Akademie Verlag, 185-190.

R.A. MOYEED, A.J. BADDELEY (1991). Stochastic approximation of the MLE for a spatial point pattern. *Scandinavian Journal of Statistics 18*, 39-50.

P. NACKEN (1991). Hierarchical graph representation of image structure based on intensity extrema. U. ECKHARDT, A. HUBLER, W. NAGEL, G. WERNER (eds). *Proceedings of the 5th Workshop on Geometrical Problems of Image Processing*, Georgenthal, Berlin, Akademie Verlag, 191-198.

R.P.C. RODGERS, A.J. BADDELEY (1991). Monte Carlo study of random packing on the surface of a sphere. *Journal of Applied Probability 28*, 539-552.

C. RONSE, H.J.A.M. HEIJMANS (1991). The algebraic basis of mathematical morphology. Part II: Openings and closings. *Comp. Vision, Graphics and Image Proc: Image Understanding 54*, 74-97.

Reports

BS-R9104 H.J.A.M. HEIJMANS, J. SERRA. *Convergence, continuity and iteration in mathematical morphology.*

BS-R9105 H.J.A.M. HEIJMANS. *Morphological discretization.*

BS-R9109 A.J. BADDELEY, M.N.M. VAN LIESHOUT. *Recognition of overlapping objects using Markov spatial processes.*

BS-R9115 A.J. CABO, P. GROENEBOOM. *Limit theorems for functionals of convex hulls.*

BS-R9118 H.J.A.M. HEIJMANS. *Discretization of morphological operators.*

BS-R9124 A.J. BADDELEY, R.A. MOYEED, C.V. HOWARD, A. BOYDE. *Analysis of a three-dimensional point pattern with replication.*

BS-R9126 P.F.M. NACKEN. *A metric for line segments.*

BS-R9127 A.J. BADDELEY. *Hausdorff metric for capacities.*

Other publications

A.J. BADDELEY (1991). Stereology. Chapter 10 of *Spatial Statistics and Digital Image Analysis*: a cross-disciplinary report, National Research Council USA (Washington: National Academy of Science Press, 1991).

H.J.A.M. HEIJMANS, L. VINCENT (1991). *Graph Morphology in Image Analysis.* Harvard Robotics Laboratory Technical Report 91-11.

BS *: **Statistics and probability theory**

Papers in Journals and Proceedings

J. VAN DEN BERG, R.W.J. MEESTER (1991). Stability properties of a flow process in graphs. *Random Structures and Algorithms 2*, 335-341.

R. HELMERS (1991). On the Edgeworth expansion and the bootstrap approximation for a studentized *U*-statistic. *Annals of Statistics 19*, 470-484.

M.C.J. VAN PUL (1991). Statistical models in software reliability. *Proceedings Interface '91*, Seattle, April 22.

Reports

BS-R9107 A.L.M. DEKKERS, L. DE HAAN. *Optimal choice of sample fraction in extreme-value estimation.*

BS-R9116 D.M. CHIBISOV. *Asymptotic optimality of the chi-square test with large number of degrees of freedom within the class of symmetric tests.*

BS-R9117 J. LESLIE, C. VAN EEDEN. *On a characterization of the exponential distribution on a type 2 right censored sample.*

BS-R9119 K.O. DZHAPARIDZE. *On constructing kernel polynomials of a spectral function: application to ARMA models.*

BS-R9120 V.S. KOROLYUK, YU.V. BOROVSKIKH. *U-statistics of increasing degrees with asymptotically Poisson distributions.*

BS-R9122 M.C.J. VAN PUL. *Simulations on the Jelinski-Moranda model of software reliability.*

BS-R9123 M.C.J. VAN PUL. *Software reliability and the bootstrap.*

BS-R9129 L.G. BARENDREGT, M.C.J. VAN PUL. *An analytical solution to the consistency problem for the Littlewood model in software reliability.*

Other publications

J. VAN DEN BERG (1991). *On the Number of Non-Dominated Paths.* Preprint, December.

J. VAN DEN BERG, H. KESTEN (1991). *Inequalities for the Time Constant in First-Passage Percolation.* Preprint Cornell University, August 1991.

A.L.M. DEKKERS (1991). *On Extreme-Value Estimation.* Ph.D. thesis, Erasmus University Rotterdam.

K. DZHAPARIDZE et al. (1991). *Study of Switching Behaviour of TV-viewers.* Interim Report, 201 pages.

Department of Numerical Mathematics

NW 1: **Discretization of evolution problems**

Papers in Journals and Proceedings

J.G. BLOM, H. BRUNNER (1991). Algorithm 689 - Discretized collocation and iterated collocation for nonlinear Volterra integral equations of the second kind. *ACM Trans. Math. Software 17*, 167-177.

P.J. VAN DER HOUWEN (1991). Block Runge-Kutta methods. K. STREHMEL (ed.). *Numerical Treatment of Differential Equations*, Proceedings of Fifth International Seminar NUMDIFF-5, Halle, May 22-26, 1989, Teubner-Texte zur Mathematik 121, 68-80.

P.J. VAN DER HOUWEN, J. MOOIMAN, F.W. WUBS (1991). Numerical analysis of time-dependent Boussinesq models. *Int. J. Num. Meth. Fluids 13*, 1235-1250.

P.J. VAN DER HOUWEN, B.P. SOMMEIJER (1991). Iterated Runge-Kutta methods on parallel computers. *SIAM J. Sci. Stat. Comput. 12*, 1000-1028.

P.J. VAN DER HOUWEN, B.P. SOMMEIJER (1991). Block Runge-Kutta methods on parallel computers. *ZAMM 72*, 3-18.

P.J. VAN DER HOUWEN, B.P. SOMMEIJER, NGUYEN HUU CONG (1991). Stability of collocation-based Runge-Kutta-Nyström methods. *BIT 31*, 469-481.

W.H. HUNDSDORFER (1991). Local and global order reduction for some LOD schemes. K. STREHMEL (ed.). *Numerical Treatment of Differential Equations*, Proceedings of Fifth International Seminar NUMDIFF-5, Halle, May 22-26, 1989, Teubner-Texte zur Mathematik 121, 225-233.

W.H. HUNDSDORFER, B.I. STEININGER (1991). Convergence of linear multistep and one-leg methods for stiff nonlinear initial value problems. *BIT 31*, 124-143.

E.D. DE GOEDE (1991). Stabilization of a time integrator for the 3D shallow water equations. *Int. J. Num. Meth. in Fluids 12*, 475-490.

E.D. DE GOEDE (1991). A time splitting method for the three-dimensional shallow water equations. *Int. J. Num. Meth. in Fluids 13*, 519-534.

E.D. DE GOEDE (1991). 3D shallow water model on the CRAY Y-MP4/464. *Proceedings of the Sixth Int. Workshop on the Use of Supercomputers in Theoretical Science*, Antwerp, 107-114.

E.D. DE GOEDE (1991). On the numerical treatment of the advective terms in 3D shallow water models. *Proceedings of the 2nd Int. Symposium on High Performance Computing*, Montpellier, 491-502.

R.A. TROMPERT, J.G. VERWER (1991). A static-regridding method for two-dimensional parabolic partial differential equations. *Appl. Numer. Math. 8*, 65-90.

J.G. VERWER, W.H. HUNDSDORFER, B.P. SOMMEIJER (1991). Convergence properties of the Runge-Kutta-Chebyshev method. K. STREHMEL (ed.). *Numerical Treatment of Differential Equations*, Proceedings of Fifth International Seminar NUMDIFF-5, Halle, May 22-26, 1989, Teubner-Texte zur Mathematik 121, 273-284.

Reports

NM-R9101 P.J. VAN DER HOUWEN, B.P. SOMMEIJER, K. STREHMEL. *Smoothed Runge-Kutta methods in the method of lines.*

NM-R9103 P.J. VAN DER HOUWEN, B.P. SOMMEIJER, NGUYEN HUU CONG. *Parallel diagonally-implicit Runge-Kutta-Nyström methods.*

NM-R9104 P.J. VAN DER HOUWEN, B.P. SOMMEIJER. *Parallel solution of Burgers equation.*

NM-R9105 J.G. VERWER, R.A. TROMPERT. *Local uniform grid refinement for time-dependent partial differential equations.*

NM-R9106 E.D. DE GOEDE. *3D shallow water model on the CRAY Y-MP4/464.*

NM-R9108 A.S. VASUDEVA MURTHY, J.G. VERWER. *Solving parabolic integro-differential equations by an explicit integration method.*

NM-R9109 E.D. DE GOEDE. *Numerical methods for the 3D shallow water equations on vector and parallel computers.*

NM-R9110 E.D. DE GOEDE. *On the numerical treatment of the advective terms in 3D shallow-water models.*

NM-R9112 P.A. ZEGELING, J.G. VERWER, J.C.H. VAN EIJKEREN. *Application of a moving-grid method to a class of 1D brine-transport problems in porous media.*

NM-R9114 P.J. VAN DER HOUWEN, B.P. SOMMEIJER. *Analysis of parallel diagonal-implicit iteration of Runge-Kutta methods.*

NM-R9116 P.J. VAN DER HOUWEN. *Parallel step-by-step methods.*

NM-R9117 B.P. SOMMEIJER. *Parallel-iterated Runge-Kutta methods for stiff ordinary differential equations.*

NM-R9119 E.D. DE GOEDE. *A numerical model of the Northwest European Continental Shelf on the CRAY Y-MP2E.*

Other publications

J.C.H. VAN EIJKEREN, P.A. ZEGELING, S.M. HASSANIZADEH (1991). *Practical use of SPRINT and a Moving-Grid Interface for a Class of 1D Non-Linear Transport Problems*, RIVM Report nr. 959101001.

J. MOOIMAN (1991). *Boussinesq Equations Based on Positive Definite Hamiltonian*, Delft Hydraulics Report.

J. MOOIMAN (1991). *Comparison Between Measurements and a Boussinesq Model for Wave Deformation by a Shoal*, Delft Hydraulics Report.

NW 2: **Boundary-value problems, multigrid and defect correction**

Papers in Journals and Proceedings

P.W. HEMKER, J. MOLENAAR (1991). An adaptive multigrid approach for the solution of the 2D semiconductor equations. W. HACKBUSCH, U. TROTTENBERG (eds.). *Multigrid Methods III*, International Series of Numerical Mathematics, 98, Birkhäuser Verlag, Basel.

B. KOREN (1991). A computational tool for analyzing strong viscous-inviscid interactions in gasdynamics. A.G. TENNER (ed.). *Proceedings of the CP90 Europhysics Conference on Computational Physics*, Amsterdam, 1990, World Scientific, Singapore, 395-399.

B. KOREN (1991). Low-diffusion rotated upwind schemes, multigrid and defect correction for steady, multi-dimensional Euler flows. W. HACKBUSCH, U. TROTTENBERG (eds.). *Multigrid Methods III*, International Series of Numerical Mathematics, 98, Birkhäuser Verlag, Basel, 265-276.

B. KOREN, P.W. HEMKER (1991). Multi-dimensional upwind schemes, multigrid and defect correction for accurate and efficient Euler flow computations. W. BERRY, B. BATTRICK (eds.). *Aerodynamics for Space Vehicles*, European Space Agency, Noordwijk, 129-134.

B. KOREN, P.W. HEMKER (1991). Damped, direction-dependent multigrid for hypersonic flow computations. *Appl. Numer. Math. 7*, 309-328.

B. KOREN, P.W. HEMKER (1991). Defect correction and nonlinear multigrid for steady Euler equations. W.G. HABASHI, M.M. HAFEZ (eds.). *Advances in Computational Fluid Dynamics*, Cambridge University Press, Cambridge.

B. KOREN, H.T.M. VAN DER MAAREL (1991). Analysis of transonic shock configurations by a solution-adaptive multigrid technique. *Prel. Proceedings of the Fourth International Symposium on Computational Fluid Dynamics*, Davis, California, 640-645.

H.T.M. VAN DER MAAREL, B. KOREN (1991). Spurious, zeroth-order entropy generation along a kinked wall. *Int. J. Numer. Meth. Fluids 13*, 1113-1129.

J. MOLENAAR (1991). A two-grid analysis of the combination of mixed finite elements and Vanka-type relaxation. W. HACKBUSCH, U. TROTTENBERG (eds.). *Multigrid Methods III*, International Series of Numerical Mathematics, 98, Birkhäuser Verlag, Basel.

Reports

NM-R9102 J. MOLENAAR. *A two-grid analysis of the combination of mixed finite elements and Vanka type relaxation.*

NM-R9107 P.W. HEMKER, B. KOREN. *Efficient multi-dimensional upwinding for the steady Euler equations.*

NM-R9111 R.R.P. VAN NOOYEN. *An improved accuracy version of the mixed finite element method for a second order elliptic equation.*

NM-R9115 J. MOLENAAR. *Adaptive multigrid applied to a bipolar transistor problem.*

NM-R9118 J. MOLENAAR. *Multigrid for semiconductor device simulation: cell-centered or vertex-centered multigrid?*

NM-R9122 H.T.M. VAN DER MAAREL. *Adaptive multigrid for the steady Euler equations.*

NM-N9101 B. KOREN. *Report on a window-on-science trip.*

Other publications

H. DECONINCK, P.W. HEMKER, CH. HIRSCH, M. NAPOLITANO, P. LARSEN (1991). *Solution Adaptive Navier-Stokes Solvers with Grid Decoupled Upwind Schemes and Multigrid Acceleration.* BRITE/EURAM Progress Report, Von Karman Institute, Rhode St. Genese.

B. KOREN (1991). *Multigrid and Defect Correction for the Steady Navier-Stokes Equations, Application to Aerodynamics*, CWI Tract 74, CWI, Amsterdam.

B. KOREN (1991). *Upwind Schemes versus Centered Schemes, a One-Sided View.* Note prepared for Seminar Numerieke Advectie at the University of Utrecht, CWI, Amsterdam.

B. KOREN (1991). *Extension of a Multi-D Upwind Scheme.* Note prepared for Seminar Numerieke Advectie at the University of Utrecht, CWI, Amsterdam.

NW 3: Large-scale computing

Papers in Journals and Proceedings

R.P. BRENT, G.L. COHEN, H.J.J. TE RIELE (1991). Improved techniques for lower bounds for odd perfect numbers. *Math. Comp. 57*, 857-868.

A. IVIĆ, H.J.J. TE RIELE (1991). On the zeros of the error term for the mean square of $|\zeta(\frac{1}{2}+it)|$. *Math. Comp. 56*, 303-328.

H.J.J. TE RIELE (1991). A new lower bound for the de Bruijn-Newman constant. *Numer. Math. 58*, 661-667.

H.J.J. TE RIELE, W.M. LIOEN, D.T. WINTER (1991). Factorization beyond the Googol with MPQS on a single computer. *CWI Quarterly, Vol. 4, No. 1*, 69-72.

D.T. WINTER (1991). Floating-point attributes in Ada. *Ada Letters, Vol. XI, No. 7*, 244-273.

Reports

NM-R9113 A.N. MALYSHEV. *Parallel aspects of some spectral problems in linear algebra.*

NM-R9120 H.J.J. TE RIELE. *On the history of the function $M(x)\sqrt{x}$ since Stieltjes.*

NM-R9121 D.R. HEATH-BROWN, W.M. LIOEN, H.J.J. TE RIELE. *On solving the Diophantine equation $x^3+y^3+z^3=k$ on a vector computer.*

NM-R9123 W.M. LIOEN, D.T. WINTER. *Solving large dense systems of linear equations on systems with virtual memory and with cache.*

Other publications

H. BOENDER, M.P.A. SELLINK (1991). *De Multipolynomiale Kwadratische Zeefmethode*, final essay, CWI, Amsterdam.

H.J.J. TE RIELE, T.J. DEKKER, H.A. VAN DER VORST (eds.) (1991). *Selected Papers CWI-IMACS Symposia on Parallel Scientific Computing, Amsterdam, The Netherlands,* Three Special Issues of the journal Applied Numerical Mathematics: Vol. 7, Nr. 5, June 1991; Vol. 8, Nr. 2, September 1991, Vol. 9, Spring 1992.

Department of Software Technology

AP 1: Semantics

Papers in Journals and Proceedings

P. AMERICA, J.J.M.M. RUTTEN (1991). A layered semantics for a parallel object-oriented language. J.W. DE BAKKER, W.P. DE ROEVER, G. ROZENBERG (eds.). *Proceedings REX/FOOL Workshop on the Foundations of Object-Oriented Languages,* LNCS 489, Springer-Verlag, 91-123 (also to appear in FAC).

J.W. DE BAKKER (1991). Comparative semantics for flow of control in logic programming without logic. *Information and Computation, Vol. 94,* 123-179.

J.W. DE BAKKER, J.J.M.M. RUTTEN (1991). Concurrency semantics based on metric domain equations. G.M. REED, A.W. ROSCOE, R.F. WACHTER (eds.). *Topology and Category Theory in Computer Science,* Oxford University Press, 113-151.

J.W. DE BAKKER, E.P. DE VINK (1991). CCS for OO and LP. S. ABRAMSKY, T.S.E. MAIBAUM (eds.). *Proceedings TAPSOFT 1991,* LNCS 494, Springer-Verlag, 1-28.

J.W. DE BAKKER, E.P. DE VINK (1991). Rendez-vous with metric semantics. E.H.L. AARTS, J. VAN LEEUWEN, M. REM (eds.). *Proceedings PARLE91,* LNCS 506, Springer-Verlag, 27-57.

J.W. DE BAKKER, J.H.A. WARMERDAM (1991). Four domains for concurrency. *Theoretical Computer Science 90,* 127-149.

F.S. DE BOER, J.N. KOK, C. PALAMIDESSI, J.J.M.M. RUTTEN (1991). The failure of failures: towards a paradigm for asynchronous communication. J.C.M. BAETEN, J.F. GROOTE (eds.). *Proceedings CONCUR '91,* LNCS 527, Springer-Verlag, 111-126.

F.S. DE BOER, J.N. KOK, C. PALAMIDESSI, J.J.M.M. RUTTEN (1991). Semantics for Concurrent Logic Programming Languages. *Theoretical Computer Science 86,* 3-34.

F.S. DE BOER, C. PALAMIDESSI (1991). A fully abstract model for concurrent constraint programming. S. ABRAMSKY, T.S.E. MAIBAUM (eds.). *Proceedings TAPSOFT 1991,* LNCS 494, Springer-Verlag, 296-319.

F.S. DE BOER, C. PALAMIDESSI (1991). Embedding as a tool for language comparison: on the CSP hierarchy. J.C.M. BAETEN, J.F. GROOTE (eds.). *Proceedings CONCUR '91,* LNCS 527, Springer-Verlag, 127-141.

F. VAN BREUGEL (1991). Comparative semantics for a real-time programming language with integration. S. ABRAMSKY, T.S.E. MAIBAUM (eds.). *Proceedings TAPSOFT 1991,* LNCS 493, Springer-Verlag, 397-411.

J.M. JACQUET, L. MONTEIRO (1991). Extended Horn clauses: the framework and some semantics. J.C.M. BAETEN, J.F. GROOTE (eds.). *Proceedings CONCUR '91,* LNCS 527, Springer-Verlag, 281-297.

Reports

CS-R9102 F.S. DE BOER, C. PALAMIDESSI. *Embedding as a tool for language comparison.*

CS-R9117 F.S. DE BOER. *A proof theory for the language POOL.*

CS-R9118 P.M. AMERICA, F.S. DE BOER. *A proof theory for a sequential version of POOL.*

CS-R9119 P.H.M. AMERICA, F.S. DE BOER. *A proof theory for process creation.*

CS-R9147 F.S. DE BOER, J.N. KOK, C. PALAMIDESSI, J.J.M.M. RUTTEN. *The failure of failures in a paradigm for asynchronous communication.*

CS-R9135 J.W. DE BAKKER, E.P. DE VINK. *Rendezvous with metric semantics.*

CS-R9136 J.W. DE BAKKER, E.P. DE VINK. *CCS for OO and LP.*

CS-R9148 J.J.M.M. RUTTEN. *Hereditarily-finite sets and complete metric spaces.*

Other publications

J.W. DE BAKKER, W.P. DE ROEVER, G. ROZENBERG (eds.) (1991). *Proceedings REX School/Workshop on Foundations of Object-Oriented Languages,* Noordwijkerhout, May/June 1990, LNCS 489, Springer, 442 pages.

J.W. DE BAKKER, J.J.M.M. RUTTEN (eds.) (1991). *Deliverables Second Year and Periodic Progress Report,* ESPRIT Basic Research Action Integration, June.

F.S. DE BOER (1991). *Reasoning about Dynamically Evolving Process Structures: a Proof Theory for the Object-Oriented Language POOL.* Ph.D. thesis, Free University Amsterdam.

A. ELIËNS (1991). *DLP: a Language for Distributed Logic Programming.* Ph.D. thesis, University of Amsterdam [jointly with AP 3].

AP 2: **Concurrency and real time systems**

Papers in Journals and Proceedings

J.C.M. BAETEN, J.A. BERGSTRA (1991). Recursive process definitions with state operator. *Theoretical Computing Science 82 (2),* 285-302.

J.C.M. BAETEN, J.A. BERGSTRA (1991). Design of a specification language by abstract syntax engineering. L. FEIJS, J.A. BERGSTRA (eds.). *Proceedings METEOR Workshop Methods based on Formal Specifications,* LNCS 490, Springer-Verlag, 363-395.

J.C.M. BAETEN, J.A. BERGSTRA (1991). *Real time process algebra,* Extended abstract in Proceedings Computing Science in the Netherlands 1991; also in Formal Aspects of Computing, 3, 142-188.

J.C.M. BAETEN, J.A. BERGSTRA (1991). Real space process algebra. J.C.M. BAETEN, J.F. GROOTE (eds.). *Proceedings CONCUR'91,* LNCS 527, Springer-Verlag, 96-110; to appear in FACS.

J.C.M. BAETEN, J.A. BERGSTRA, S. MAUW, G.J. VELTINK (1991). A process specification formalism based on static COLD. L. FEIJS, J.A. BERGSTRA (eds.). *Proceedings METEOR Workshop Methods based on Formal Specifications,* LNCS 490, Springer-Verlag, 303-335.

R.N. BOL, J.F. GROOTE (1991). The meaning of negative premises in transition systems specifications. J. LEACH ALBERT, B. MONIEN, M. RODRIGUEZ ARTALEJO (eds.). *Proceedings ICALP 91,* Madrid, LNCS 510, Springer-Verlag, 481-494.

J.F. GROOTE, A. PONSE (1991). μCRL: a base for analysing processes with data. E. BEST, G. ROZENBERG (eds.). *Proceedings 3rd Workshop on Concurrency and Compositionality*, Goslar, GMD-studien 191 & Hildesheimer Informatik-Bericht 6/91, 125-130.

J.F. GROOTE, A. PONSE (1991). Process algebra with guards (combining Hoare logic with process algebra). J.C.M. BAETEN, J.F. GROOTE (eds.). *Proceedings CONCUR'91,* LNCS 527, Springer-Verlag, 235-249.

A.S. KLUSENER (1991). Completeness in real time process algebra. J.C.M. BAETEN, J.F. GROOTE (eds.). *Proceedings CONCUR'91,* LNCS 527, Springer-Verlag, 376-392.

H. KORVER (1991). Computing distinguishing formulas for branching bisimulation. K.G. LARSEN, A. SKOU (eds.). *Proceedings 3rd CAV 1991,* Aalborg, report IR91-4/5, Aalborg University, 376-392.

A. PONSE (1991). Process expressions and Hoare's logic. *Information and Computation, Vol. 95, No. 2,* 192-217.

Reports

CS-R9103 J.C.M. BAETEN, J.A. BERGSTRA. *Process algebra with signals and conditions.*

CS-R9106 A.S. KLUSENER. *Completeness in real time process algebra.*

CS-R9108 H.P. KORVER. *The current state of bisimulation tools.*

CS-R9120 R.J. VAN GLABBEEK, W.P. WEIJLAND. *Branching time and abstraction in bisimulation semantics.*

CS-R9121 H.P. KORVER. *Computing distinguishing formulas for branching bisimulation.*

CS-R9130 G.J. AKKERMAN, J.C.M. BAETEN. *Term rewriting analysis in process algebra.*

CS-R9131 J.C.M. BAETEN, J.A. BERGSTRA. *Real space process algebra.*

CS-R9137 J.F. GROOTE, H. HÜTTEL. *Undecidable equivalences for basic process algebra.*

CS-R9138 J.F. GROOTE, A. PONSE. *Proof theory for μCRL.*

CS-R9140 J.C.M. BAETEN, J.A. BERGSTRA. *The state operator in real time process algebra.*

CS-R9144 A.S. KLUSENER. *Abstraction in real time process algebra.*

CS-R9145 A.S. KLUSENER. *Deriving a code generator for an executable subset of COLD from its operational semantics.*

CS-R9149. W.J. FOKKINK. *Normal forms in real time process algebra.*

CS-R9151 J.F. GROOTE. *A short proof of the decidability of bisimulation for normed BPA-processes.*

Other publications

J.C.M. BAETEN, J.A. BERGSTRA (1991). *The State Operator in Real Time Process Algebra.* Progr. report P9104, University of Amsterdam.

J.C.M. BAETEN, J.A. BERGSTRA (1991). *Asynchronous Communication in Real Space Process Algebra.* Progr. report P9106, University of Amsterdam.

J.C.M. BAETEN, J.F. GROOTE (eds.) (1991). *Proceedings CONCUR'91*, LNCS 527, Springer-Verlag.

J.F. GROOTE (1991). *Process Algebra and Structured Operational Semantics.* Ph.D. thesis, University of Amsterdam.

H.P. KORVER (1991). *The Current State of Bisimulation Tools.* Progr. report P9101, University of Amsterdam.

H. KORVER (1991). *An Algorithm to Produce Distinguishing Formulas for Branching Bisimulation.* Progr. report P9103, University of Amsterdam.

AP 3: **Extensible programming environments**

Papers in Journals and Proceedings

A. VAN DEURSEN (1991). An algebraic specification of the static semantics of Pascal. J. VAN LEEUWEN (ed.). *Proceedings Computing Science in the Netherlands*, SION, 150-164.

P. KLINT (1991). A meta-environment for generating programming environments. J.A. BERGSTRA, L.M.G. FEIJS (eds.). *Algebraic Methods II: Theory, Tools and Applications,* Lecture Notes in Computer Science, Springer-Verlag, 105-124.

E.A. VAN DER MEULEN (1991). Deriving incremental implementations from algebraic specifications. *Second International Conference on Algebraic Methodology and Software Technology,* (AMAST), Ohio, USA, May 22-25.

J. REKERS, J.W.C. KOORN (1991). Substring parsing for arbitrary context-free grammars. *SIGPLAN Notices, Vol. 26, No. 5,* 59-66 (also appeared in *Proceedings of the Second International Workshop on Parsing Technologies, Association for Computational Linguistics*, 218-224).

Reports

CS-R9124 J. HEERING, P. KLINT, J. REKERS. *Lazy and incremental program generation* (revised version).

CS-R9129 A. VAN DEURSEN. *An algebraic specification of the static semantics of Pascal.*

CS-R9150 J. HEERING. *Implementing higher-order algebraic specifications.*

CS-R9153 J. REKERS. *Generalized LR parsing for general context-free grammars.*

CS-R9158 P. KLINT. *Lazy scanner generation for modular lexical grammars.*

CS-R9159 E.A. VAN DER MEULEN. *Fine-grain incremental implementation of algebraic specifications.*

Other publications

A. ATIE, I. ATTALI, J. CHAZARAIN, D. CLEMENT, D. DARDAILLER, M.H.H. VAN DIJK, M.C. GIBOULOT, L. HASCOET, P.R.H. HENDRIKS, P. DE JAGER, W. JONKER, P. KLINT, J.W.C. KOORN, A. LE HORS, F. MONTAGNAC, E.A. VAN DER MEULEN, G. POPOVITCH, V. PRUNET, J. REKERS, F. THOMASSET, H. WALTERS, A. WAMMES, J. WESTER (1991). *Third Review Report of ESPRIT Project 2177 (GIPE II),* January.

M. ALT, U. ASSMANN, J. VAN BRUMMEN, A. DESPLAND, D. DETERDING, H. EMMELMANN, C. FERDINAND, R. FORTIER, V. GOETCHERIAN, N. HAINES, M. JOURDAN, J. KAMPERMAN, P. KLINT, C. KOUTSOUMALIS, M. MAZAUD, C. MELDRUM, T. MUELLER, N. ROQUES, G. SANDER, M. SCHOOREL, A. SIZER, F. THOMASSET, F. TIP, W. WAKKER, H. WALTERS, R. WILHELM (1991). *First Review Report of ESPRIT Project 5399 (COMPARE).*

P.R.H. HENDRIKS (1991). *Implementation of Modular Algebraic Specifications.* Ph.D. thesis, Programming Research Group, University of Amsterdam.

AP 4: **Algebraic and syntactic methods**

Papers in Journals and Proceedings

K.R. APT, R.N. BOL, J.W. KLOP (1991). An analysis of loop checking mechanisms for logic programs. *Theoretical Computer Science 86,* 35-79.

N. DERSHOWITZ, J.-P. JOUANNAUD, J.W. KLOP (1991). Open problems in rewriting. R.V. BOOK (ed.). *Proceedings Rewriting Techniques and Applications,* Como, Italy, 1991, LNCS 488, Springer-Verlag, 445-456.

J.R. KENNAWAY, J.W. KLOP, M.R. SLEEP, F.J. DE VRIES (1991). Transfinite reductions in orthogonal term rewriting systems. R.V. BOOK (ed.). *Proceedings Rewriting Techniques and Applications,* Como, Italy, 1991, LNCS 488, Springer-Verlag, 1-12.

J.W. KLOP, A. MIDDELDORP (1991). Sequentiality in orthogonal term rewriting systems. *J. Symbolic Computation 12,* 161-195.

J.W. KLOP, R.C. DE VRIJER (1991). Extended term rewriting systems (invited paper). S. KAPLAN, M. OKADA (eds.). *Proceedings 2nd Intern. CTRS (Conditional and Typed Rewriting Systems),* LNCS 516, Springer-Verlag, 26-50.

A. MIDDELDORP (1991). Confluence of the disjoint union of conditional term rewriting systems. S. KAPLAN, M. OKADA (eds.). *Proceedings 2nd Intern. CTRS (Conditional and Typed Rewriting Systems),* LNCS 516, Springer-Verlag, 295-306.

A. MIDDELDORP, Y. TOYAMA (1991). Completeness of combinations of constructor systems. R.V. BOOK (ed.). *Proceedings Rewriting Techniques and Applications,* Como, Italy, 1991, LNCS 488, Springer-Verlag, 188-199.

Reports

CS-R9105 A. MIDDELDORP. *Modular properties of conditional term rewriting systems.*

CS-R9107 J.W. KLOP, R.C. DE VRIJER. *Extended term rewriting systems.*

CS-R9114 N. DERSHOWITZ, J.-P. JOUANNAUD, J.W. KLOP. *Open problems in rewriting.*

CS-R9115 D.J.N. VAN EIJCK, F.-J. DE VRIES. *Dynamic interpretation and Hoare deduction.*

CS-R9146 Y. TOYAMA. *Strong sequentiality of left-linear overlapping term rewriting systems.*

CS-R9154 A. MIDDELDORP, E. HAMOEN. *Counterexamples to completeness results for basic narrowing.*

CS-R9155 D.J.N. VAN EIJCK, F.-J. DE VRIES. *A sound and complete calculus for update logic.*

CS-R9156 J.W. KLOP, A. MIDDELDORP, Y. TOYAMA, R.C. DE VRIJER. *A simplified proof of Toyama's theorem.*

CS-R9160 A. MIDDELDORP, M. STARČEVIĆ. *A rewrite approach to polynomial ideal theory.*

Other publications

J.R. KENNAWAY, J.W. KLOP, M.R. SLEEP, F.J. DE VRIES (1991). *Finite Orthogonal Graph Rewriting is Adequate for Rational Orthogonal Term Rewriting,* Semagraph deliverable, Nijmegen.

J.R. KENNAWAY, J.W. KLOP, M.R. SLEEP, F.J. DE VRIES (1991). *Event Structures and Orthogonal Term Graph Rewriting,* Semagraph deliverable, Nijmegen.

AP 5: **Logic and language**

Papers in Journals and Proceedings

K.R. APT, M. ABADI, B. ALPERN, N. FRANCEZ, S. KATZ, L. LAMPORT, F.B. SCHNEIDER (1991). Preserving liveness: comments on 'Safety and Liveness from a Methodological Point of View'. *Information Processing Letters 40,* 141-142.

K.R. APT, M. BEZEM (1991). Acyclic programs. *New Generation Computing 9, No. 3+4,* 335-363.

K.R. APT, R.N. BOL, J.W. KLOP (1991). An analysis of loop checking mechanisms for logic programs. *Theoretical Computer Science 86,* 35-79.

K.R. APT, E.R. OLDEROG (1991). Introduction to program verification. E.J. NEUHOLD, M. PAUL (eds.). *IFIP State-of-the-Art Reports: Formal Description of Programming Concepts,* Springer-Verlag, 363-430.

K.R. APT, E.R. OLDEROG (1991). Using transformations to verify parallel programs. *Algebraic Methods II: Theory, Tools and Applications,* LNCS, Springer-Verlag, 55-81.

K.R. APT, D. PEDRESCHI (1991). Proving termination of general Prolog programs. *Proceedings International Conference on Theoretical Aspects of Computer Software,* LNCS 526, Springer-Verlag, 265-289.

R.N. BOL (1991). Loop checking and negation. J. VAN EIJCK (ed.). *Logic in AI,* LNCS 478, Springer-Verlag, 121-138.

J. VAN EIJCK (1991). The dynamics of description. *Computational Linguistics in the Netherlands; Papers from the First CLIN-meeting,* Utrecht, OTS Working Papers, 33-58.

J. VAN EIJCK (1991). Quantification and partiality. *Generalized Quantifier Theory and Applications,* Dutch Network for Language, Logic and Information, 49-84.

J. VAN EIJCK (1991). Quantification. A. VON STECHOW, D. WUNDERLICH (eds.). *Handbook of Semantics,* Walter de Gruyter, 459-487.

J. VAN EIJCK, F.J. DE VRIES (1991). Dynamic interpretation and Hoare deduction: Extended abstract. *Proceedings from Semantics and Linguistic Theory I,* volume 10, Cornell Working Papers in Linguistics, 65-84.

Reports

CS-R9111 K.R. APT, D. PEDRESCHI. *Proving termination of general Prolog programs.*

CS-R9115 D.J.N. VAN EIJCK, F.-J. DE VRIES. *Dynamic interpretation and Hoare deduction,* submitted for publication.

CS-R9134 R.N. BOL. *Loop checking in partial deduction.*

CS-R9143 D.J.N. VAN EIJCK. *The dynamics of description.*

CS-R9152 D.J.N. VAN EIJCK. *Quantification and partiality.*

CS-R9155 D.J.N. VAN EIJCK, F.-J. DE VRIES. *A sound and complete calculus for update logic.*

CS-R9157 M.I. KANOVICH. *Fast theorem proving in intuitionistic propositional logic.*

Other publications

K.R. APT, E.-R. OLDEROG (1991). *Verification of Sequential and Concurrent Programs,* Texts and Monographs in Computer Science, Springer-Verlag, 441 + xvi pages.

R.N. BOL (1991). *Loop Checking in Logic Programming.* Ph.D. thesis, University of Amsterdam, 199 + viii pages.

J. VAN DER DOES, J. VAN EIJCK (eds.) (1991). *Generalized Quantifier Theory and Applications,* Dutch Network for Language, Logic and Information.

J. VAN EIJCK (1991). *Tussen Taal en Betekenis.* Inaugural speech as professor of logical aspects of computational linguistics at the University of Utrecht.

J. VAN EIJCK (ed.) (1991). *Logic in AI / European Workshop JELIA '90 / Amsterdam, The Netherlands, September 1990 / Proceedings,* Lecture Notes in Artificial Intelligence 478, Springer-Verlag.

Department of Algorithmics and Architecture

AA 1: **Algorithms and complexity**

Papers in Journals and Proceedings

A. BLUM, T. JIANG, M. LI, J. TROMP, M. YANNAKAKIS (1991). Linear approximation of shortest superstrings. *Proceedings 23rd ACM Symp. Theory of Computing,* New Orleans, 328-336.

P. CLOTE, E. KRANAKIS (1991). Boolean functions, invariance groups and parallel complexity. *SIAM Journal on Computing, Vol. 20, No. 3,* 553-590.

G. KISSIN (1991). Upper and lower bounds on switching energy in VLSI. *J. Assoc. Comp. Mach. 38,* 222-254.

E. KRANAKIS (1991). Visibility in integer lattices. *Proceedings 3rd IEEE Conference on Parallel and Distributed Processing,* Dallas, Texas.

E. KRANAKIS, D. KRIZANC (1991). Computing boolean functions on anonymous hypercubes. *Proceedings 3rd IEEE Conference on Parallel and Distributed Processing,* Dallas, Texas.

M. LI, J. TROMP, P.M.B. VITÁNYI (1991). How to share concurrent wait-free variables. *J. Assoc. Comp. Mach.,* under revision.

M. LI, P.M.B. VITÁNYI (1991). Learning simple concepts under simple distributions. *SIAM J. Comput, Vol. 20, No. 5,* 911-935.

M. LI, P.M.B. VITÁNYI (1991). Combinatorics and Kolmogorov complexity. *Proceedings 6th IEEE Structures in Complexity Theory Conference,* Chicago.

M. LI, P.M.B. VITÁNYI (1991). A brief introduction to Kolmogorov complexity and its applications. WU WEN-TSUN, CHENG MIN-DE (eds.). *Chinese Mathematics into 21st Century,* Peking University Press, Peking, China, 67-84.

J.T. TROMP (1991). How to construct an atomic variable. *Distributed Computing,* under revision.

Reports

CS-R9101 G. KISSIN, J. TROMP. *The energy complexity of threshold and other functions.*

CS-R9113 J. TROMP, P.M.B. VITÁNYI. *Randomized wait-free test-and-set.*

CS-R9125 M. LI, P.M.B. VITÁNYI. *Combinatorics and Kolmogorov complexity.*

CS-R9126 A. BLUM, T. JIANG, J.T. TROMP, M. JANNAKAKIS. *Linear approximation of shortest superstrings.*

CS-R9128 M. LI, P.M.B. VITÁNYI. *Optimality of wait-free atomic multiwriter variables.*

CS-N9101 M. LI, P.M.B. VITÁNYI. *An introduction to Kolmogorov complexity and its applications, Part I: Theory.*

M. LI, P.M.B. VITANYI. *Kolmogorov Complexity Arguments in Combinatorics.* ITLI Prep. Series, Computation and Complexity Theory, Techn. Rept. CT-91-01, University of Amsterdam.

M. LI, J. TROMP, P.M.B. VITÁNYI (1991). *How to Share Concurrent Wait-Free Variables (revised).* ITLI Prep. Series, Computation and Complexity Theory, Techn. Rept. CT-91-02, University of Amsterdam.

M. LI, P.M.B. VITÁNYI (1991). *Average Case Complexity under the Universal Distribution Equals Worst Case Complexity.* ITLI Prep. Series, Computation and Complexity Theory, Techn. Rept. CT-91-03, University of Amsterdam.

A. BLUM, T. TIANG, M. LI, J. TROMP, M. JANNAKAKIS (1991). *Linear Approximations of Shortest Superstrings.* ITLI Prep. Series, Computation and Complexity Theory, Techn. Rept. CT-91-26, University of Amsterdam.

Other publications

E. KRANAKIS (1991). *Primality and Cryptography,* Wiley-Teubner Series in Computer Science, B.G. Teubner (Stuttgart) and John Wiley and Sons (Chichester), 1986, 235 + xv pages.

AA 2: **Cryptology**

Papers in Journals and Proceedings

D. CHAUM (1991). Zero-knowledge undeniable signatures. I.B. DAMGÅRD (ed.). *Advances in Cryptology, EUROCRYPT '90,* Springer-Verlag, 458-464.

J.-H. EVERTSE, E. VAN HEYST (1991). Which new RSA signatures can be computed from some given RSA signatures? I.B. DAMGÅRD (ed.). *Advances in Cryptology, EUROCRYPT '90,* Springer-Verlag, 83-97.

T. OKAMOTO, K. OHTA, D. CHAUM (1991). Direct zero knowledge proofs of computational power in five rounds. *Advances in Cryptology, EUROCRYPT '91,* Springer-Verlag, to appear.
(a) Security Without Identification: Transaction Systems to Make Big Brother Obsolete, *Communications of the ACM, Vol. 28 No. 10,* October 1985, 1030-1044 (invited); (b) Revised version (in Dutch) *Informatie,* pp. 213, 1987. (c) Extended and revised version: Subti-

tled 'Card Computers to Make Big Brother Obsolete' (in German), *Informatik-Spektrum, Vol. 10,* 262-277, 1987; & *Datenschutz und Datensicherung, No. 1,* 1988, 26-41.

Reports

J.-H. EVERTSE, E. VAN HEYST (1991). *Which New RSA Signatures can be Computed from Some Given RSA Signatures?* Report W91-06, Mathematical Institute, University of Leiden.

AA *: **Computer systems and ergonomics**

Papers in Journals and Proceedings

LON BARFIELD, EDDY BOEVE, STEVEN PEMBERTON (1991). The Views user interface system. *Proceedings of the 1991 Computer Human Interaction Conference (CHI '91),* New Orleans, USA, ACM Press.

EDDY BOEVE (1991). Modelling interaction tools in the Views architecture. *First Moscow International Workshop on Human Computer Interfaces,* Moscow, USSR.

STEVEN PEMBERTON (1991). A short introduction to the ABC language. *SIGPLAN Notices, Vol. 26, No. 2,* 11-16.

STEVEN PEMBERTON (1991). Object-centred open user interfaces. *Second Eurographics Workshop on Object Oriented Graphics.*

STEVEN PEMBERTON (1991). Action through editing: uniform user interfaces. *First Moscow International Workshop on Human Computer Interfaces,* Moscow, USSR.

STEVEN PEMBERTON (1991). Everything you wanted to know about your C compiler but didn't know who to ask. *Proceedings NLUUG Autumn Conference,* Ede, The Netherlands.

STEVEN PEMBERTON (1991). Interoperability in an open architecture system. *Proceedings ECSCW 91 System Developers' Workshop,* Amsterdam, The Netherlands.

AA 4: **Databases**

Papers in Journals and Proceedings

C. VAN DEN BERG, M.L. KERSTEN (1991). Engineering a MMDBMS. *CWI Quarterly, Vol. 4, No. 4.*

C. VAN DEN BERG, M.L. KERSTEN (1991). Dynamic parallel query processing. *CWI Quarterly, Vol. 4, No. 4.*

M.L. KERSTEN (1991). Goblin, A DBPL designed for advanced database applications. *2nd Int. Conference on Database and Expert Systems Applications,* August 1991, Berlin.

M.L. KERSTEN, C. VAN DEN BERG (1991). Parallel processing of a class of geographical queries. *Proceedings Int. Workshop on Database Management Systems for Geographical Applications,* May 1991, Capri, Italy, 274-288.

M.L. KERSTEN (1991). The database research group at CWI. *CWI Quarterly, Vol. 4, No. 4.*

T.D. MEYLER, H.W. KUIL, E.S. GELSEMA, M.L. KERSTEN (1991). Providing interactive interoperability for the end-user. *Proceedings Int. Conf. on Interoperable Systems,* April 1991, Kyoto, Japan, 338-341.

S. PLOMP (1991). Lock latency in distributed systems. J. VAN LEEUWEN (ed.). *Proceedings Computing Science in the Netherlands,* SION, 453-467.

A.P.J.M. SIEBES (1991). EG, integration of the object-oriented and the deductive database paradigms. *CWI Quarterly, Vol. 4, No. 4.*

A.P.J.M. SIEBES, M.H. VAN DER VOORT, M.L. KERSTEN (1991). A framework for the formalisation of active objects. J. VAN LEEUWEN (ed.). *Proceedings Computing Science in the Netherlands,* SION, 484-498.

Reports

CS-R9112 C.A. VAN DEN BERG, M.L. KERSTEN, S. SHAIR-ALI. *Dynamic parallel query processing.*

CS-R9122 M.H. VAN DER VOORT, M.L. KERSTEN. *Facets of database triggers.*

AA 5: **Constructive algorithmics**

Papers in Journals and Proceedings

R.C. BACKHOUSE, P.J. DE BRUIN, G. MALCOLM, T.S. VOERMANS, J.C.S.P. VAN DER WOUDE (1991). Relational catamorphisms. B. MÖLLER (ed.). *Constructing Programs from Specifications,* 287-318.

H. BALSTERS, M.M. FOKKINGA (1991). Subtyping can have a simple semantics. *Theoretical Computer Science 87,* 81-96.

M.M. FOKKINGA (1991). An exercise in transformational programming—backtracking and branch-and-bound. *Science of Computer Programming, Vol. 16, No. 1,* 19-48.

M.M. FOKKINGA (1991). Datatype laws without signatures. J. VAN LEEUWEN (ed.). *Proceedings Computing Science in the Netherlands,* SION, 231-248.

M.M. FOKKINGA (1991). Calculate categorically! J. VAN LEEUWEN (ed.). *Proceedings Computing Science in the Netherlands,* SION, 211-230.

M.M. FOKKINGA, J.T. JEURING, L. MEERTENS, E. MEIJER (1991). A translation from attribute grammars to catamorphisms. *The Squiggolist, Vol. 2, No. 1,* CWI, 20-26.

M.M. FOKKINGA, L. MEERTENS (1991). Map-functor factorized. *The Squiggolist, Vol. 2, No. 1,* CWI, 17-19.

J.T. JEURING (1991). The derivation of hierarchies of algorithms on matrices. B. MÖLLER (ed.). *Constructing Programs from Specifications,* 9-32.

J.T. JEURING (1991). Incremental algorithms on lists. J. VAN LEEUWEN (ed.). *Proceedings Computing Science in the Netherlands,* SION, 315-335.

L. MEERTENS (1991). A neutral suggestion. *The Squiggolist, Vol. 2, No. 1,* CWI, 16.

L. MEERTENS, J. VAN DER WOUDE (1991). A tribute

to attributes. *The Squiggolist, Vol. 2, No. 1,* CWI, 10-15.

E. MEIJER, M.M. FOKKINGA, R. PATERSON (1991). Functional programming with bananas, lenses, envelopes and barbed wire. *Proceedings Functional Programming Languages and Computer Architecture FPCA 91,* August 1991, LNCS 523, Springer-Verlag, 124-144..

T.S. VOERMANS, J.C.S.P. VAN DER WOUDE (1991). Relational tupling. *Notes EURICS Workshop on Calculational Theories of Program Structure*, Hollum-Ameland.

J.C.S.P VAN DER WOUDE (1991). Plat-Etudes For Carel ende Elegance. W.H.J. FEIJEN, A.J.M. VAN GASTEREN (eds.). Van Oude Machines En Nieuwe Rekenwijzen, Academic Service, 229-237.

J.C.S.P. VAN DER WOUDE (1991). Atoms and extensionality, what's the point? *Notes EURICS Workshop on Calculational Theories of Program Structure*, Hollum-Ameland.

J.C.S.P. VAN DER WOUDE (1991). C4, general manipulative nonsense. *Notes EURICS Workshop on Calculational Theories of Program Structure*, Hollum-Ameland.

J.C.S.P. VAN DER WOUDE (1991). Free style spec wrestling II: preorders. *The Squiggolist, Vol. 2, No. 2,* CWI, 48-53.

Reports

CS-R9104 M.M. FOKKINGA, E. MEIJER. *Program calculation properties of continuous algebras.*

CS-R9132 M.M. FOKKINGA. *Calculate categorically!*

CS-R9133 M.M. FOKKINGA. *Datatype laws without signatures.*

Other publications

J.T. JEURING (editor-in-chief) (1991). *The Squiggolist, Vol. 2, No. 1,* CWI.

J.T. JEURING (editor-in-chief) (1991). *The Squiggolist, Vol. 2, No. 2,* CWI.

Department of Interactive Systems

IS 1: **Computer Graphics**

Papers in Journals and Proceedings

M. BAKKER (1991). Triangle sets in PHIGS PLUS: a valuable link with finite element modeling. *Computer Graphics Forum 10*, 61-65.

M. BAKKER (1991). At last an ISO C binding of GKS. *Computer Graphics Forum 10*, 249-254.

M. BAKKER (1991). Computer graphics standards. *CWI Quarterly, Vol. 3, No. 3,* 237-253.

D.C.A. BULTERMAN, R. VAN LIERE (1991). Multimedia synchronization and UNIX. *Proceedings 2nd Intl. Workshop on Network and Operating Systems,* Heidelberg.

D.C.A. BULTERMAN, G. VAN ROSSUM, R. VAN LIERE (1991). A structure for transportable, dynamic multimedia systems. *Usenix Summer Conference 1991,* Nashville.

V.C.J. DISSELKOEN (1991). Real-time quadratic shading. J. VAN LEEUWEN (ed.). *Proceedings Computing Science in the Netherlands,* SION, 165-181.

D.A. DUCE, R. VAN LIERE, P.J.W. TEN HAGEN (1991). Logical input devices - An outdated concept? R. TOOK (ed.). *Building Interactive Systems: Architectures and Tools*, Springer-Verlag.

M.A. GURAVAGE, E.H. BLAKE, A.A.M. KUIJK (1991). XInPosse: Structural Simulation for Graphics Hardware. *Proceedings 6th Eurographics Workshop on Graphics Hardware.*

J.A.K.S. JAYASINGHE, A.A.M. KUIJK, L. SPAANENBURG (1991). A display controller for an object-level frame store system. *Advances in Computer Graphics Hardware III,* EurographicSeminars, Springer-Verlag.

A.A.M. KUIJK (1991). Report on the 6th Workshop on Computer Graphics Hardware. *Computer Graphics Forum, Vol. 10, No. 4.*

A.A.M. KUIJK, R. VAN LIERE (1991). Architectures for interactive raster graphics. *CWI Quarterly, Vol. 3, No. 3,* 179-197.

Reports

CS-R9109 M. BAKKER. *Parametric surfaces in PHIGS PLUS: a new chance for patterning and hatching?*

CS-R9110 M. BAKKER. *Triangle sets in PHIGS PLUS: a valuable link with finite element modeling.*

CS-R9123 V.C.J. DISSELKOEN. *Real-time quadratic shading.*

CS-R9139 M. HAINDL. *Texture synthesis.*

Other publications

M. BAKKER (1991). *GKS/C, The Graphical Kernel System Language Bindings, Part 4: C,* ISO/IEC 8651-4, final text, December.

M. BAKKER (1991). *GKS-3D/C, The Graphical Kernel System for Three Dimensions Language Bindings, Part 4: C,* ISO/IEC 8806-4, final text, December.

M. BAKKER (1991). *GKS-New/C, The Graphical Kernel System Revision Language Bindings, Part 4: C,* initial draft, August.

E.H. BLAKE, P. WISSKIRCHEN (eds.) (1991). *Advances in Object-Oriented Graphics I,* EurographicSeminars, Springer-Verlag.

A.A.M. KUIJK (ed.) (1991). *Advances in Computer Graphics Hardware III,* EurographicSeminars, Springer-Verlag.

IS 2: **Interaction**

Papers in Journals and Proceedings

F. ARBAB, I. HERMAN (1991). MANIFOLD: A language for specification of inter-process communication. *Proceedings of the EurOpen Autumn Conference,* Budapest.

P.J.W. TEN HAGEN, D. SOEDE (1991). Assembling a user interface out of communicating processes. D.A. DUCE (ed.). *Proceedings of the Eurographics/Esprit Workshop on User Interfaces Management Systems and Environments,* EurographicSeminar Series, Springer-Verlag.

I. HERMAN (1991). Projective geometry and computer graphics. M. GRAVE, T.W. HEWITT, M. ROCH (eds.). *Advances in Computer Graphics IV,* EurographicSeminar Series, Springer-Verlag.

E. RUTTEN (1991). An imperative planning language: from temporal representation to real-time execution. *Proceedings of the 3rd IFAC International Workshop on Artificial Intelligence in Real-Time Control,* Napa/Sonoma, California.

E. RUTTEN (1991). A temporal representation for imperatively structured plans of actions. *Proceedings of the 5th Portuguese Conference on Artificial Intelligence, EPIA '91,* Albufeira, Portugal, Lecture Notes in Artificial Intelligence (LNCS) 541, Springer-Verlag.

D. SOEDE, F. ARBAB, I. HERMAN, P.J.W. TEN HAGEN (1991). The GKS input model in Manifold. *Computer Graphics Forum 10,* 209-224.

J. VAN DER VEGT (1991). Editing objects of a hierarchical structured drawing. G.C. VAN DER VEER (ed.). *Proceedings of the Conference 'Interacting with Computers: Preparing for the Nineties'.*

Reports

CS-R9127 D. SOEDE, F. ARBAB, I. HERMAN, P.J.W. TEN HAGEN (1991). *The GKS input model in Manifold.*

CS-R9142 F. ARBAB, I. HERMAN, P. SPILLING. *An overview of Manifold and its implementation.*

Other publications

G. GARCIA, I. HERMAN (eds.) (1991). *Advances in Computer Graphics VI,* EurographicSeminar Series, Springer-Verlag.

IS 3: **Intelligent CAD systems**

Papers in Journals and Proceedings

F. ARBAB (1991). Design object representation. H. YOSHIKAWA, F. ARBAB (eds.). *Intelligent CAD, III,* Elsevier Science Publishers.

F. ARBAB, I. HERMAN (1991). MANIFOLD: A language for specification of inter-process communication. *Proceedings of EurOpen Autumn Conference,* Budapest.

F. ARBAB, I. HERMAN (1991). MANIFOLD: A language for specification of inter-process communication. *Proceedings Computing Science in the Netherlands,* SION, 31-46.

P.J.W. TEN HAGEN (1991). Critique of the Seeheim Model. D.A. DUCE (ed.). *Proceedings of the Eurographics/Esprit Workshop on User Interface Management Systems and Environments,* EurographicSeminar Series, Springer-Verlag.

D.B.M. OTTEN, P.J.W. TEN HAGEN (1991). On the role of delegation and inheritance in object-oriented systems. H. YOSHIKAWA, F. ARBAB (eds.). *Intelligent CAD, III, Proceedings of the 3rd International IFIP WG5.2 Workshop on Intelligent CAD,* Elsevier Science Publishers.

J.L.H. ROGIER, D.B.M. OTTEN (1991). Retrospective creation of virtual alternative hierarchives. E.H. BLAKE, P. WISSKIRCHEN (eds.). *Advances in Object-Oriented Graphics,* EurographicSeminar Series, Springer-Verlag, 117-129.

D. SOEDE, F. ARBAB, I. HERMAN, P.J.W. TEN HAGEN (1991). The GKS input model in Manifold. *Computer Graphics Forum 10,* 209-224.

P.J. VEERKAMP (1991). On the development of an artifact and design description language. *CWI Quarterly, Vol. 3, No. 3,* 219-236.

P.J. VEERKAMP (1991). Qualitative reasoning about design objects. *5th International Conference on the Manufacturing Science and Technology of the Future,* Enschede, The Netherlands.

P.J. VEERKAMP, P.J.W. TEN HAGEN (1991). Qualitative reasoning about design objects. *Preprints of the 5th International Conference on the Manufacturing Science and Technology of the Future,* Enschede, The Netherlands.

R. VELTKAMP (1991). A quantum approach to geometric constraint satisfaction. *Proceedings of the Eurographics Workshop on Object Oriented Graphics,* to be published as Advances in Object Oriented Graphics II, EurographicSeminars, Springer-Verlag.

R. VELTKAMP (1991). Review of: M.E. Hohmeyer and B.A. Barsky. Rational continuity: parametric, geometric, and Frenet frame continuity of rational curves. *ACM Transactions on Graphics, (8),* 4 Oct. 1989, 335-359, for Computing Reviews, Vol. 32, page 433.

R. VELTKAMP (1991). Geometric constraint management with quanta. *IFIP TC5/WG5.2 Working Conference on Intelligent Computer Aided Design,* Columbus, Ohio.

R.C. VELTKAMP (1991). Scientific report on the 2nd Eurographics Workshop on Object Oriented Graphics. *Computer Graphics Forum, Vol. 10, No. 4,* December.

R. VELTKAMP, F. ARBAB (1991). Geometric constraint propagation with quantum labels. *Eurographics Workshop on Computer Graphics and Mathematics,* Genova, Italy.

Reports

CS-R9116 R.C. VELTKAMP. *2D and 3D object reconstruction with the γ-neighborhood graph.*

CS-R9127 D. SOEDE, F. ARBAB, I. HERMAN, P.J.W. TEN HAGEN. *The GKS input model in Manifold.*

CS-R9141 R.C. VELTKAMP, F. ARBAB. *Geometric constraint satisfaction.*

CS-R9142 F. ARBAB, I. HERMAN, P. SPILLING. *An overview of Manifold and its implementation.*

Other publications

P.J.W. TEN HAGEN, P.J. VEERKAMP (eds.) (1991). *Intelligent CAD Systems III: Practical Experiences and Evaluation.* Proceedings of the Third Eurographics Workshop on Intelligent CAD Systems, EurographicSeminars, Springer-Verlag.

H. YOSHIKAWA, F. ARBAB (eds.) (1991). *Intelligent CAD III: Selected Contributions from the Third IFIP WG5.2 Workshop on Intelligent CAD,* Osaka, Japan, Elsevier Science Publishers.

Department of Computer Systems & Telematics

CS 1: **Multimedia Kernel Systems**

Papers in Journals and Proceedings

D.C.A. BULTERMAN, G. VAN ROSSUM, R. VAN LIERE (1991). A structure for transportable, dynamic multimedia documents. *Proceedings of the Summer 1991 Usenix Conference,* Nashville, TN (USA), June 1991.

D.C.A. BULTERMAN, G. VAN ROSSUM, D.T. WINTER (1991). Multimedia synchronization and UNIX-or-If multimedia support is the problem, is UNIX the solution? *Proceedings of the 1991 EURopen Autumn Conference,* Budapest (Hungary), September 1991.

D.C.A. BULTERMAN, R. VAN LIERE (1991). Multimedia synchronization and UNIX. *Proceedings of the Second International Workshop on Network and Operating Systems Support for Digital Audio and Video,* Heidelberg (FRD), November 1991.