



Centrum voor Wiskunde en Informatica

ANNUAL *REPORT*

'91

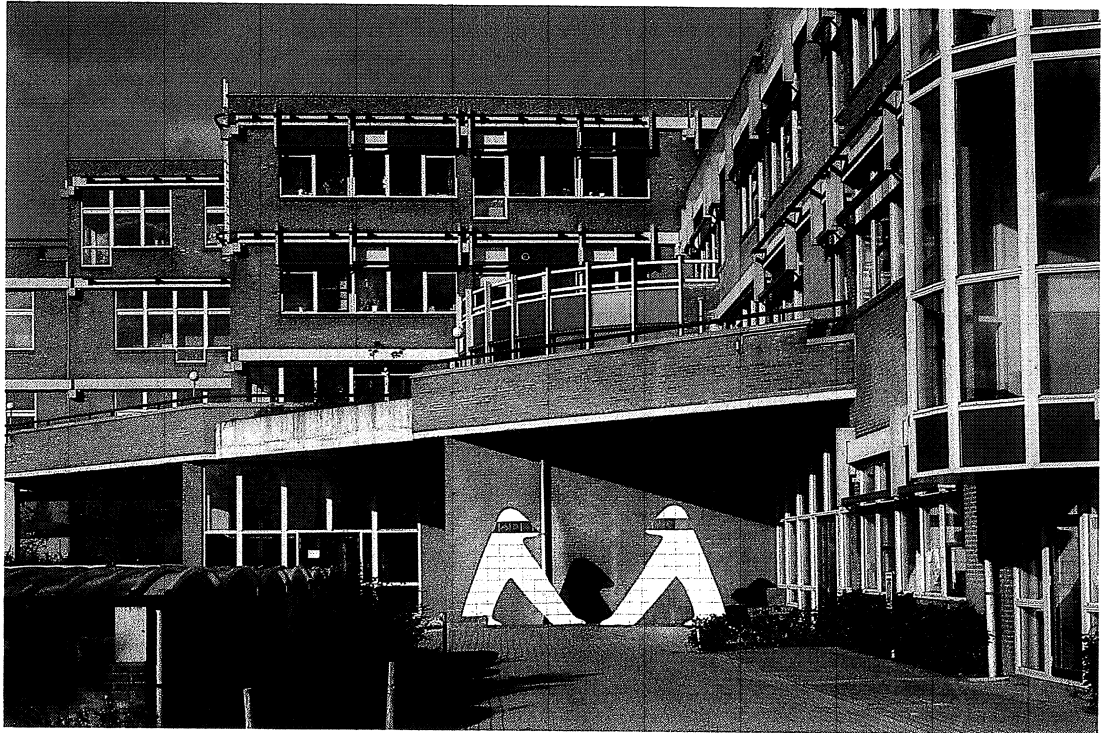


Centrum voor Wiskunde en Informatica

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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).

Board of Directors

P.C. Baayen (scientific director)
G. van Oortmerssen (managing director)

ERCIM



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

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

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, multimedia 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

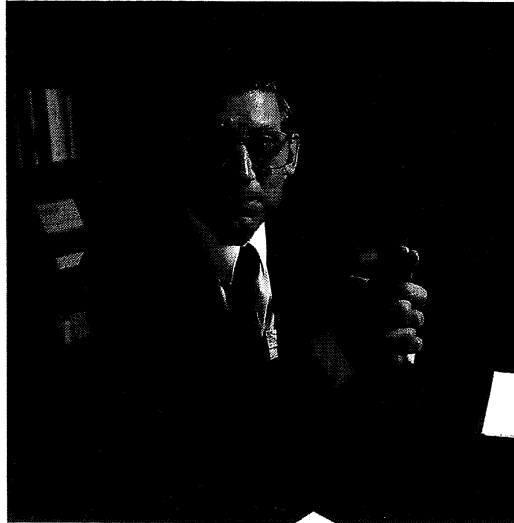
From the very start in 1988, when ERCIM (European Research Consortium for Informatics and Mathematics) was established at

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.

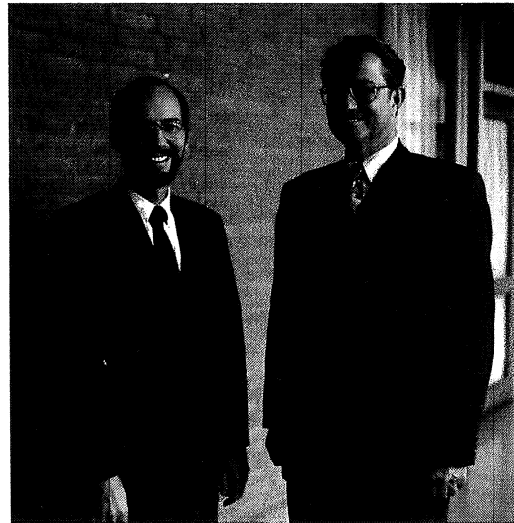
With an eye to formal status within the European Community, in 1991 ERCIM applied for registration as a European Economic Interest Group (EEIG). The ERCIM Bureau opened in April, for the first three years it will be based in Paris (INRIA Rocquencourt). Proof of ERCIM's European dimension was confirmed 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.

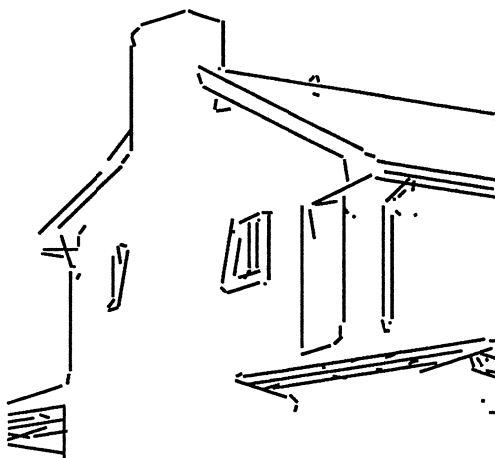
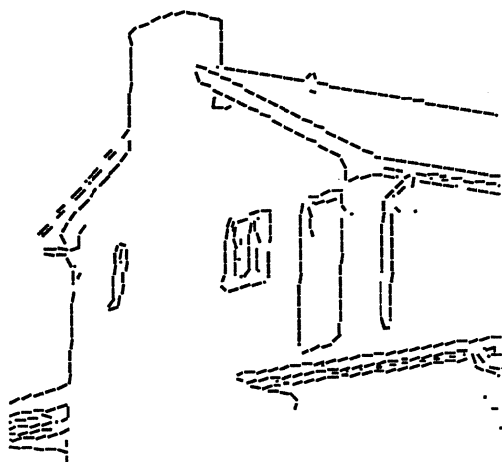
The fundamental research into communication and interaction between processes, which are important in massive parallel and distri-

buted 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 Interna-*

tional 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

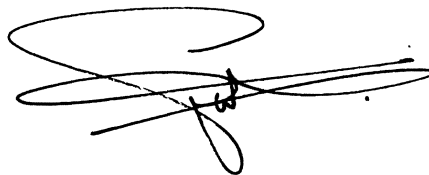
CWI welcomed many researchers for longer or shorter periods during 1991. Several scientific policy bodies also expressed interest in the institute and sent delegations during the report year. Among these were the Dutch parliament's permanent committees for Economic Affairs, Education, and Scientific 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.

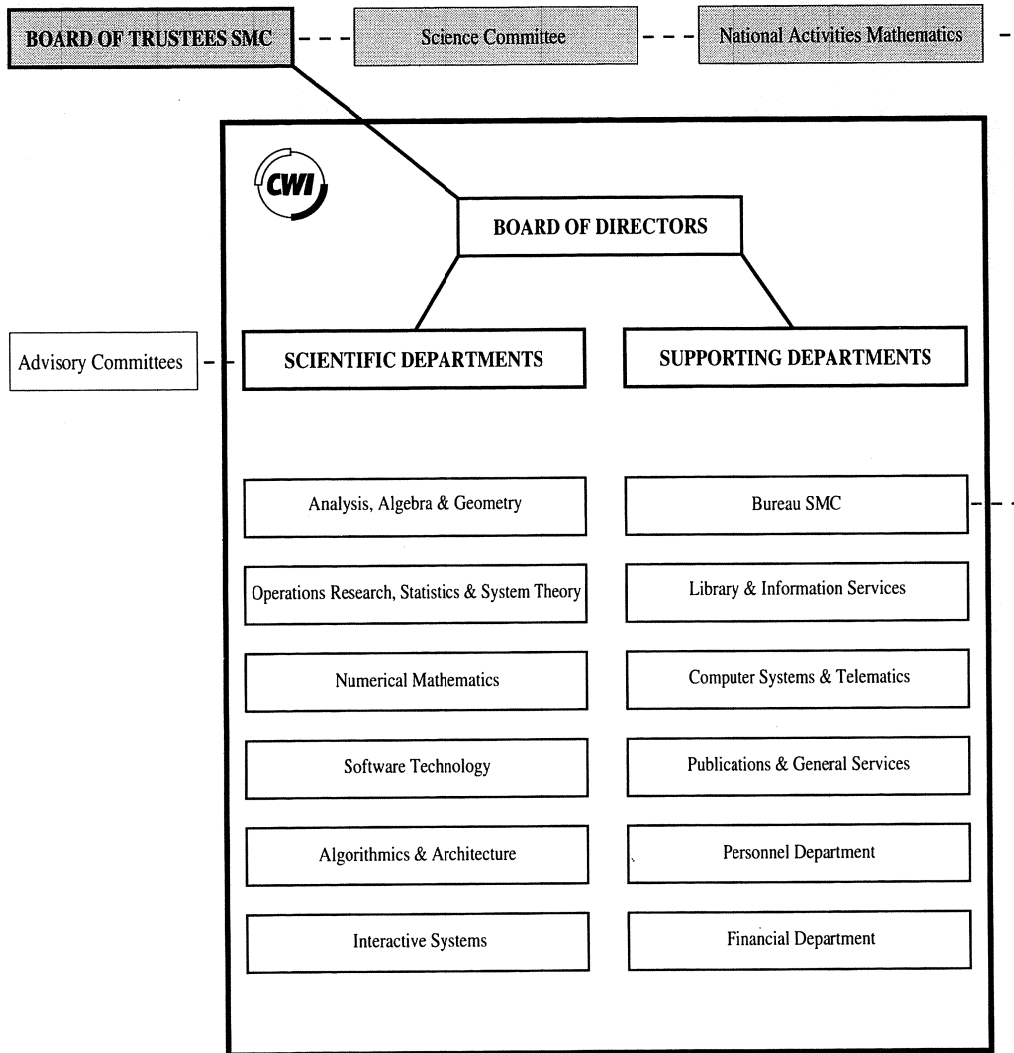
SMC is administered by a Board of Trustees. Actual administration is delegated to the Board of Directors of SMC, which is also responsible for CWI. A Science Committee advises the Board of Trustees on matters of research policy and organization involving both the National Working Parties and CWI. The 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 Ser-

vices, 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.

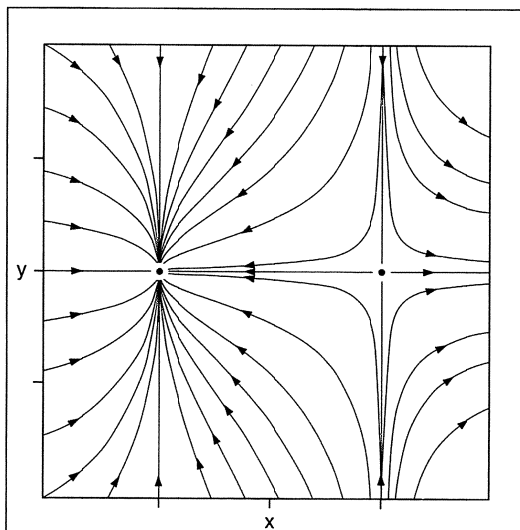
The idea is as follows. Consider a 'real life' system S (at the start of this century, S typically would be a mechanical system, but today one might also think of a chemical, biological, meteorological, ... system). Assume that S is stationary and deterministic, i.e., the laws governing the behaviour 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

of S is described by a point $x = (x_1, \dots, x_n) \in \mathbb{R}^n$. 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.

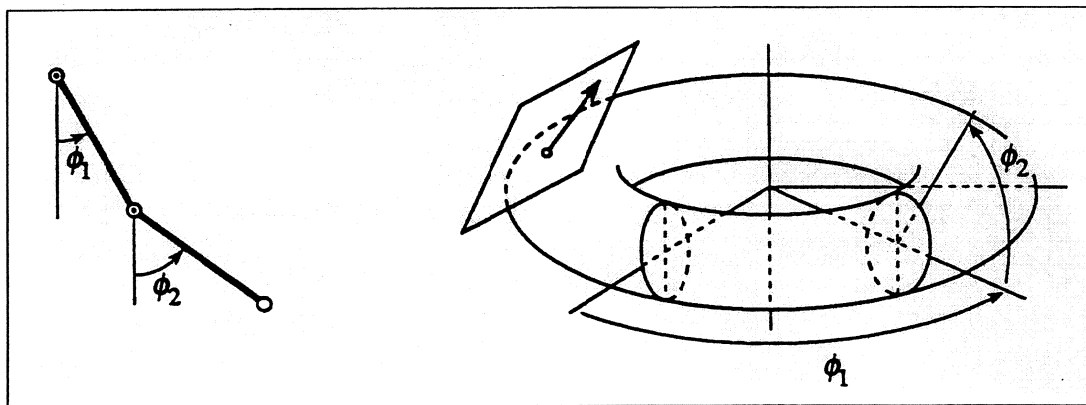
For this to be useful one needs a theory which, firstly, relates geometrical features of the phase portrait of S with significant physical features of S itself and, secondly, enables one to obtain a phase portrait for S without solving the equations describing S with all possible initial positions. Such 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,



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.



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., $x(t) \rightarrow A$ for $t \rightarrow \infty$? (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

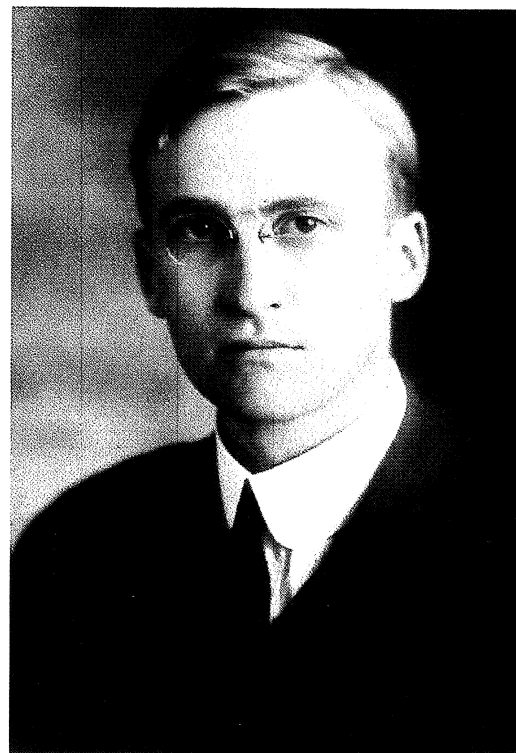
'irreducible' parts of a flow. Their frequent occurrence (many attractors are minimal) and complicated structure (a general classification is still lacking) make them interesting objects for further investigation.

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 indispensable 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.

Bronstein). 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 geodesic 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 chaotic 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.

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

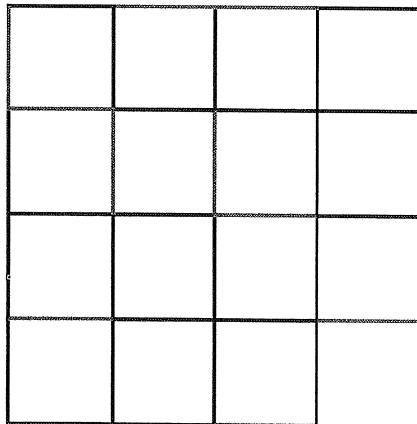


Figure 1
A 4x4 sponge with open (green) and closed (red) edges. The blue-coloured cells become wet if the sponge is surrounded by fluid.

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).

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

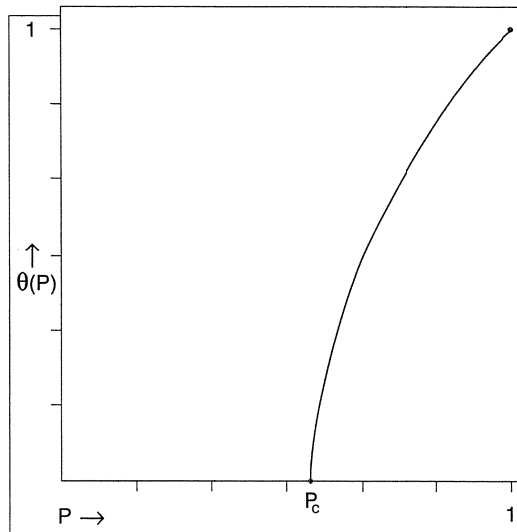


Figure 2

Typical shape of the graph of the percolation probability $\Theta(P)$. It is believed that $\Theta(P_c)=0$, 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.

making reasonable estimates. Other subjects of study are the speed of convergence of τ_n / n to μ , and the asymptotic ($t \rightarrow \infty$) 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).

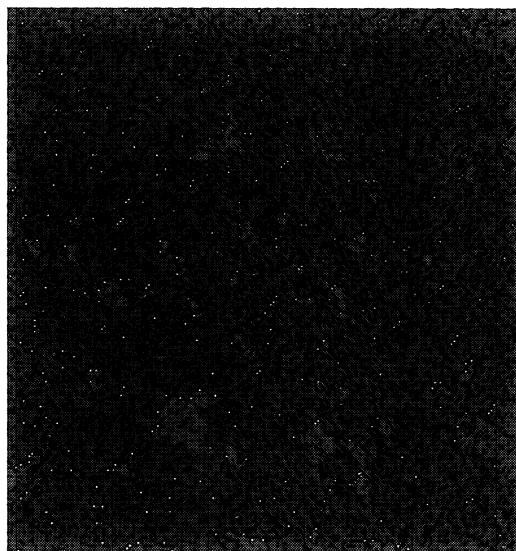
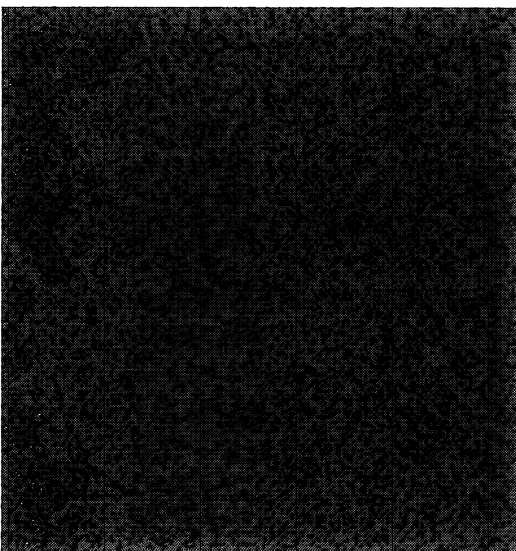


Figure 3:

(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.

	1			
		1		
		4	2	1
		1		
	3	2	1	
			2	
			1	

(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

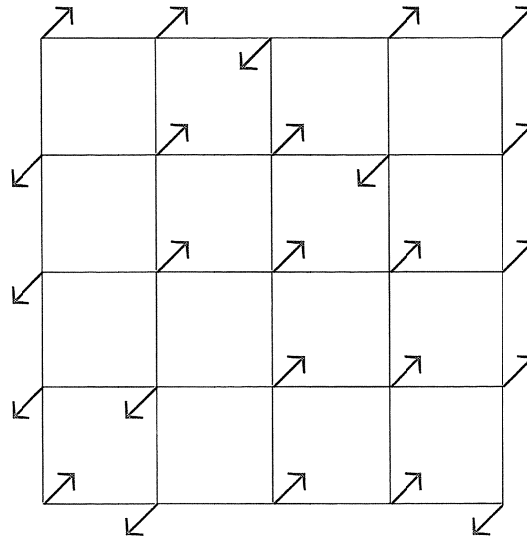


Figure 4: One of the 2^{25} possible configurations of a 5x5 spin system.

↗ denotes +1
↖ denotes -1

of the order n edges with time coordinate in A .

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 $\sim 1 \text{ cm}^2$). Each IC contains about one million devices (size $\sim 5 \mu\text{m}^2$). 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.

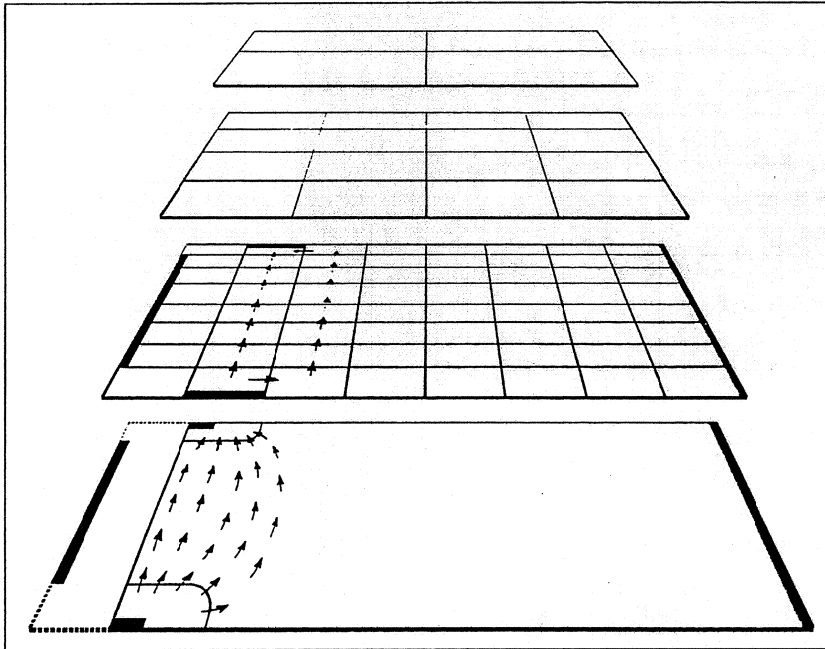
that point for the variables associated with that point, whereas all other variables are kept fixed. This is done for all grid points (one 'sweep'). As a result the solution 'relaxes' to a new solution, after which the procedure is repeated. Examples of commonly used relaxation methods are Jacobi or 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.



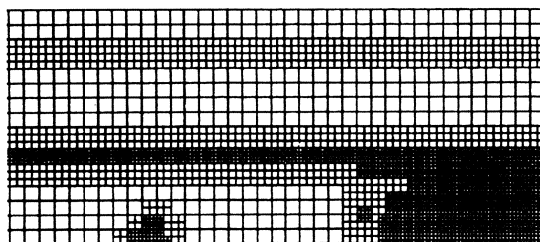
Application of multigrid methods can substantially speed up the numerical solution of semiconductor equations. The semiconductor device (bottom, arrows indicate electric currents) is covered with a hierarchy of increasingly coarser grids (here drawn as separate levels on top of each other). During the 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:

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

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

$$(3 + 5) \cdot (1 + 2) \rightarrow (3 + 5) \cdot 3 \rightarrow 3 \cdot 3 + 5 \cdot 3 \rightarrow 9 + 5 \cdot 3 \rightarrow 9 + 15 \rightarrow 24.$$

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,

دسته بچ هر اربعه و عشرون الترتیب المالک

مثال جدید از ضلع بیضی و موضوعه آن و التسطیح و معصا ز طول التسطیح مختلفا
 صلح حده و قدر علمنا ان طولہ عشره من العید لان کل سطح مربع متساوی الاضلاع
 و الزوايا فان اجزاء ضلعہ مضروبنا و واحد حده ذلك السطح و ليس جزاه فلما
 قال بل و اجد عشرین بعد عشره جزاه علمنا ان طول ضلع حده عشره اعداد
 لان ضلع حده جزا المالک یعنی ضلع حده مضربین علی سطحه و قدرنا ان حده
 مثل سطح حده و قدرنا ان حده ط مثل سطح حده و قدرنا ان حده ط علی اسمائه
 مثل سطح حده علی حده ط لیس فی التسطیح فصا حده ط مثل حده ط و جزا سطح مربع
 متساوی الاضلاع و الزوايا و هو سطح مربع و قدرنا ان حده ط حده ط حده و اضلاعه
 مثلہ سطحه اذا حده و عشرون و هو ما اجمع من ضرب نصف الاضلاع فی مثلها و هو
 حده و حده لیس حده و عشرون و قدرنا ان حده ط حده ط حده ط و هو الزوايا
 التي یوزع علی المالک تعطفنا من سطح حده ط حده ط الذي هو اجزاء ضلع حده ط
 بی سطحه و واحدنا من حده ط حده ط و هو مثل حده ط حده ط لان حده ط حده ط
 حده ط و فصل حده ط حده ط و هو مثل حده ط حده ط حده ط حده ط حده ط حده ط
 ط افسر لنا ان سطحه ط حده ط حده ط حده ط حده ط حده ط و هو واحد و عشرون
 و قدرنا ان سطحه ط حده ط حده ط حده ط حده ط حده ط حده ط حده ط حده ط حده ط
 هذا و اجد و عشرون بقولنا سطحه ط حده ط حده ط حده ط حده ط حده ط حده ط حده ط
 و واحد و عشرون و هو لیس حده ط حده ط حده ط حده ط حده ط حده ط حده ط حده ط
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 المالک ادرت علیه و اجد و عشرون حده ط حده ط حده ط حده ط حده ط حده ط حده ط حده ط
 عشره اجزایه و منه حده ط حده ط حده ط حده ط حده ط حده ط حده ط حده ط حده ط حده ط
 و ذلك ما اردنا ان نس

Part of the 9th century Arabic work 'al-Jabr wa l-muqabala' by the great mathematician al-Khwarizmi (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:

$$\begin{aligned} ((S \cdot x) \cdot y) \cdot z &\rightarrow ((x \cdot z) \cdot (y \cdot z)) \\ ((K \cdot x) \cdot y) &\rightarrow x \\ (I \cdot x) &\rightarrow x \end{aligned}$$

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 ‘ \cdot ’ 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.

$$\begin{array}{c} \underline{((SI)I)((SI)I)} \\ \downarrow \\ \uparrow \quad \underline{(I((SI)I))(I((SI)I))} \\ \downarrow \\ \underline{((SI)I)I((SI)I)} \end{array}$$

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

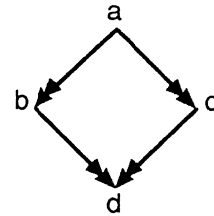
Since rewriting is a non-deterministic procedure (i.e. sometimes different parts of a term can be rewritten), rewriting sequences starting from the same term may lead to quite different terms. Fortunately, the famous Church-Rosser theorem for λ and CL states that any two ‘diverging’ rewritings of the 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.

$$\begin{aligned} \text{add}(x, \text{zero}) &\rightarrow x \\ \text{add}(x, \text{succ}(y)) &\rightarrow \text{succ}(\text{add}(x, y)) \\ \text{mult}(x, \text{zero}) &\rightarrow \text{zero} \\ \text{mult}(x, \text{succ}(y)) &\rightarrow \text{add}(x, \text{mult}(x, y)) \end{aligned}$$

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 authoritative 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.

$0 < 0$	\rightarrow	false
$0 < S(x)$	\rightarrow	true
$S(x) < 0$	\rightarrow	false
$S(x) < S(y)$	\rightarrow	$x < y$
$S(x) - S(y)$	\rightarrow	$x - y$
$0 - x$	\rightarrow	0
$x - 0$	\rightarrow	x
$gcd(x, y)$	\rightarrow	$gcd(x - y, y) \Leftarrow y < x \twoheadrightarrow$ true
$gcd(x, y)$	\rightarrow	$gcd(x, y - x) \Leftarrow x < y \twoheadrightarrow$ true
$gcd(x, x)$	\rightarrow	x

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

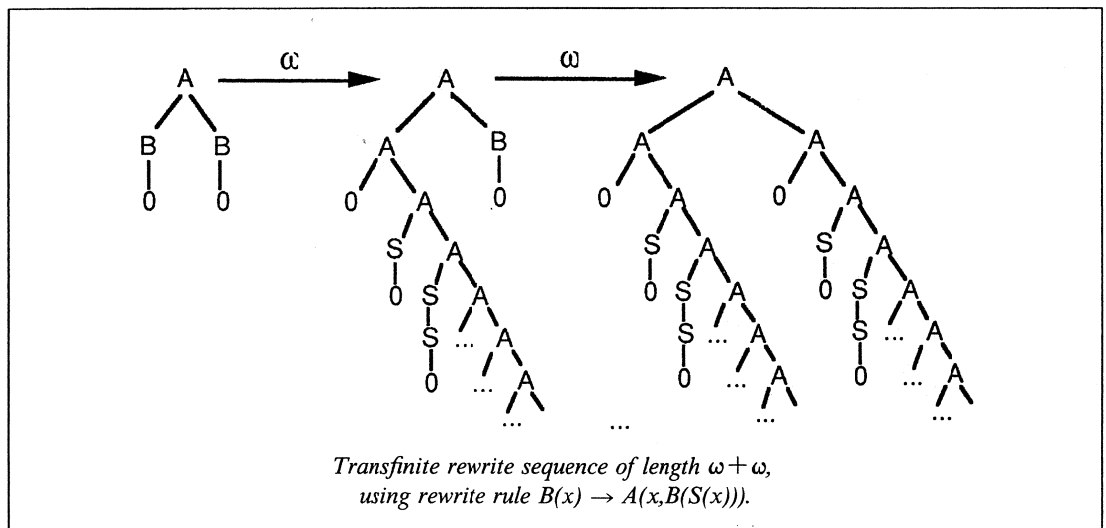
Finally, the research group studying algebraic and syntactic methods explicitly focuses on term rewriting systems. This group has operated mainly in the framework of two ESPRIT Basic Research Actions: Integration and Semagraph. The first programme aimed at the integration of the paradigms of logic programming, 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.



Constructive Algorithmics

Introduction

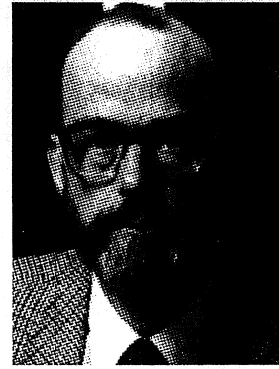
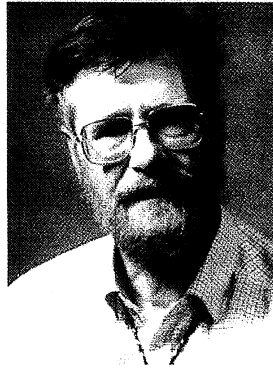
Two prominent concerns in program design and implementation are correctness and efficiency. Given the formal specification of a programming problem, it is required to construct an efficient program satisfying the requirements listed in the specification. Efficient programs are usually complex, containing 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.

$$\begin{aligned}
 & (x-a)(x+a) \\
 = & \\
 & x(x+a) - a(x+a) \\
 = & \\
 & x^2 + xa - ax - a^2 \\
 = & \\
 & x^2 - a^2.
 \end{aligned}$$

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

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

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 $(A^*, \# , \square, \tau)$, is an initial element in the category of monoids enriched with an operation with type A . A^* is the set of lists, $\# : A^* \times A^* \rightarrow A^*$ is the associative operator that concatenates two lists, with as identity

element the empty list \square , and $\tau : A \rightarrow A^*$ 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^* . $*$ is a postfix operator that is defined on types as well as functions. Given a function f , f^* satisfies

$$f^*[a,b,c] = [fa,fb,fc].$$

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 $X_{\#} / \cdot \tau^*$ 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

$$\uparrow / \cdot \times / \cdot X_{\#} / \cdot \tau^*.$$

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

$$\uparrow / \cdot \times / \cdot X_{\#} / \cdot \tau^*.$$

= claim

$$\times / \cdot \uparrow / \cdot.$$

Here is the formal derivation of this equality.

$$\uparrow / \cdot \times / \cdot X_{\#} / \cdot \tau^*$$

= Fusion, \times / \cdot is $(X_{\#}, X_{\times})$ -fusable

$$\uparrow / \cdot X_{\times} / \cdot \times / \cdot \tau^*$$

= map-distributivity (twice)

$$\uparrow / \cdot X_{\times} / \cdot (\times / \cdot \tau)^*$$

= $\oplus / \cdot \tau = id$ for all operators \oplus

$$\uparrow / \cdot X_{\times} / \cdot id^*$$

= $id^* = id$ (twice)

$$\uparrow / \cdot X_{\times} /$$

= Cross-law, (\uparrow, \times) is a dioid

$$\times / \cdot \uparrow / \cdot.$$

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.

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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 UNIXTM. 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*.

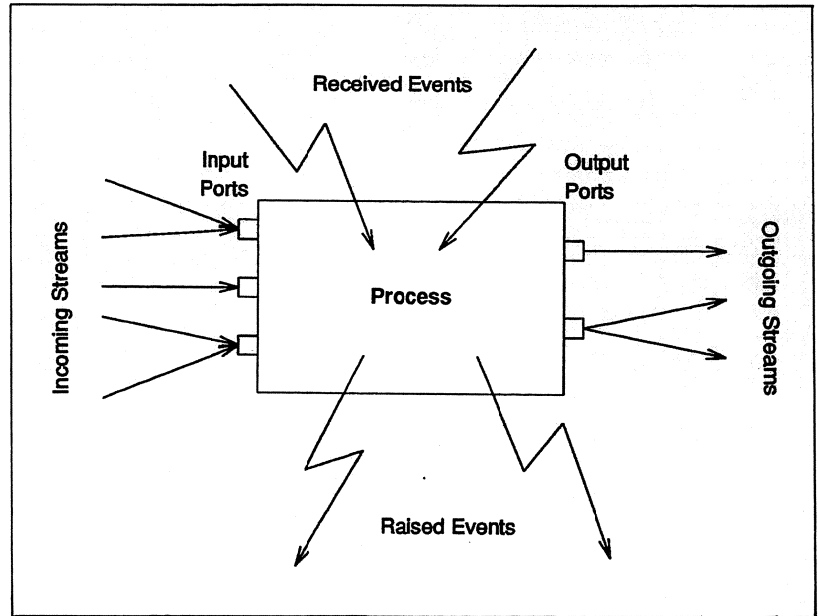
A manifold changes its connection pattern as a result of observing in its environment *events* in which it is interested. As such, events are the principal control mechanism in MANIFOLD, which makes it an event-driven programming system.

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.

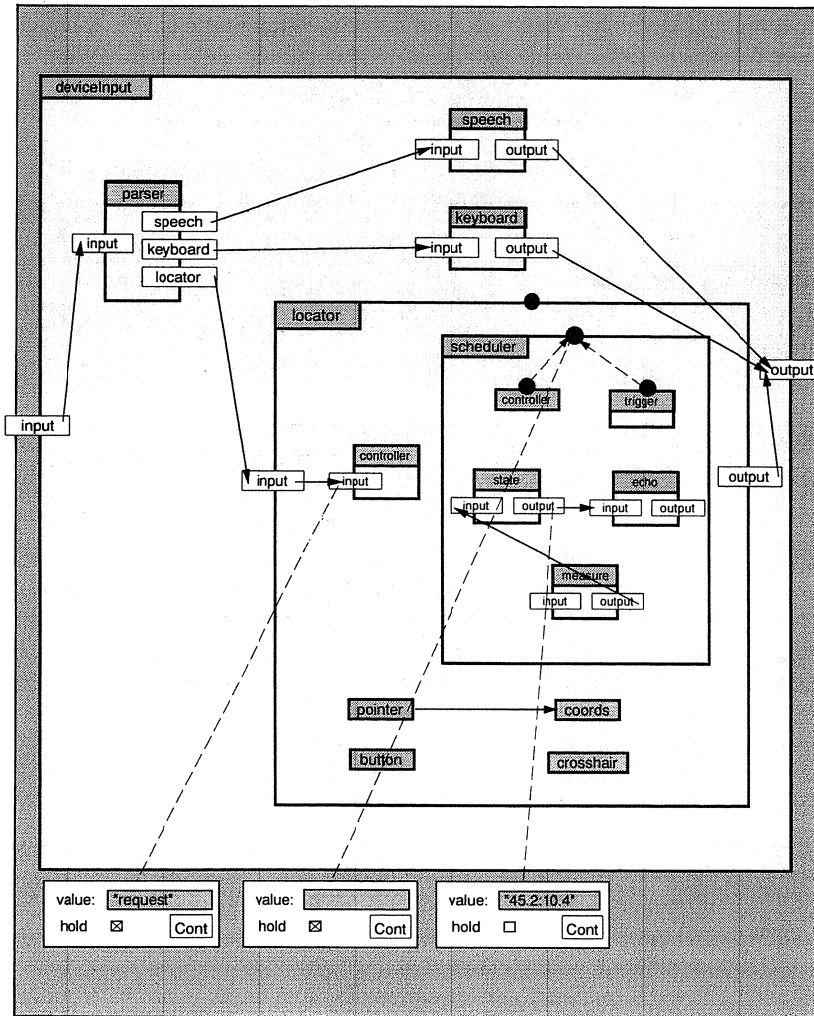
The interconnections between the ports of processes are made with streams of information units between two ports. Streams are constructed and removed dynamically. The units of information exchanged through ports and streams, are *passive* pieces of information which are produced and consumed at the two 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.

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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.

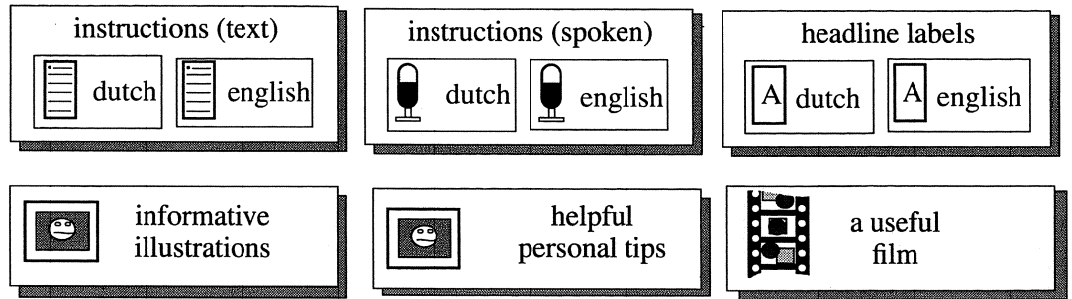
To put CMIF in perspective, consider the current state of multimedia computing. According to the sales and marketing literature produced by most computer vendors, multimedia computing is a solution in search of user-generated problems. Facilities currently exist that allow even modest personal computers 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.

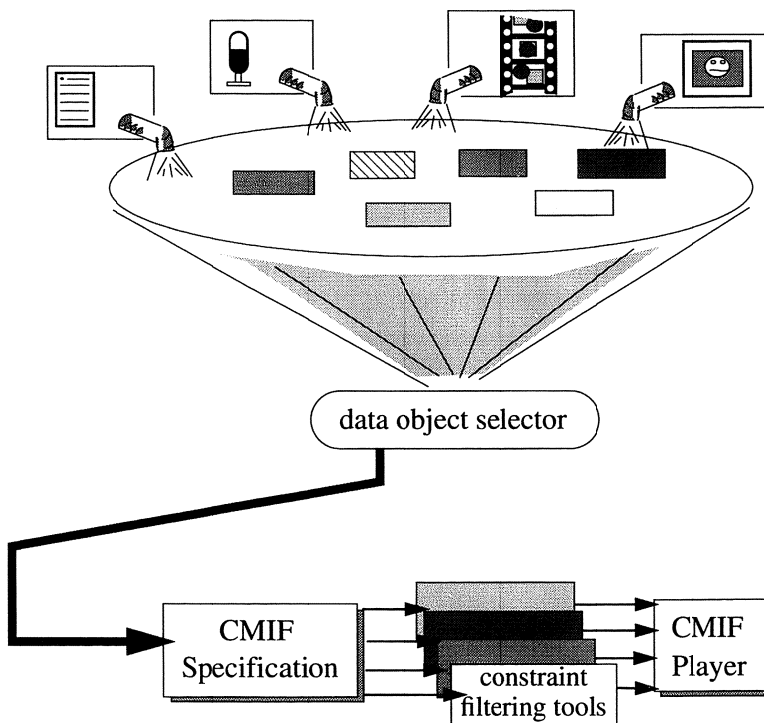
Defining and manipulating CMIF documents

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 2
Making a CMIF multimedia document.



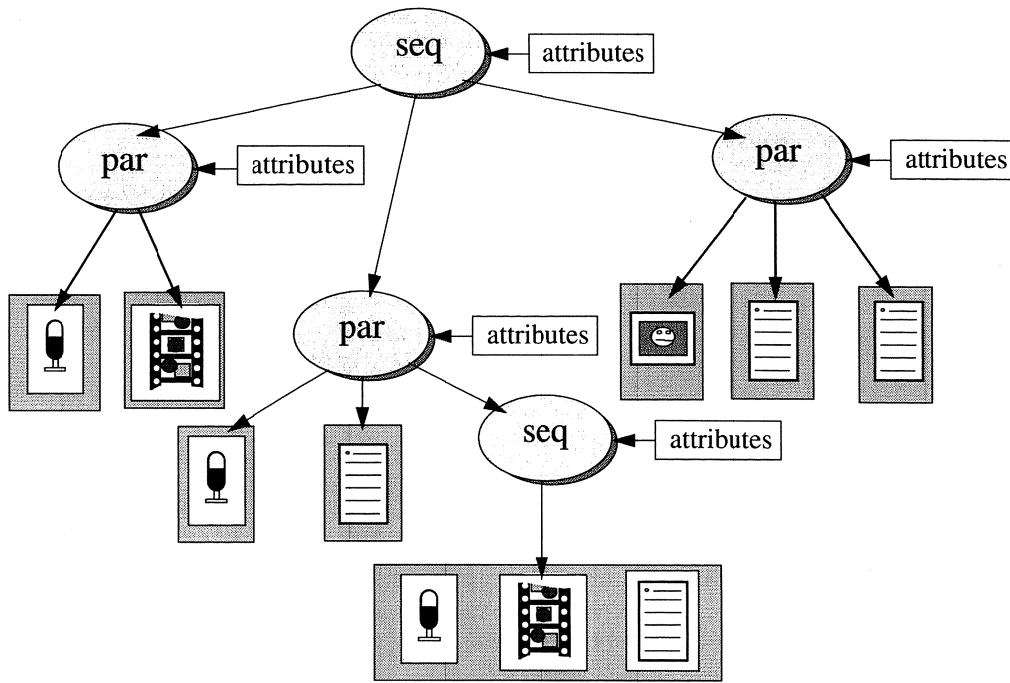


Figure 3
The CMIF hierarchy specification.

teristics of a (potentially large) data set can be manipulated in an efficient manner. Second, it contains an encoding of the runtime 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.)

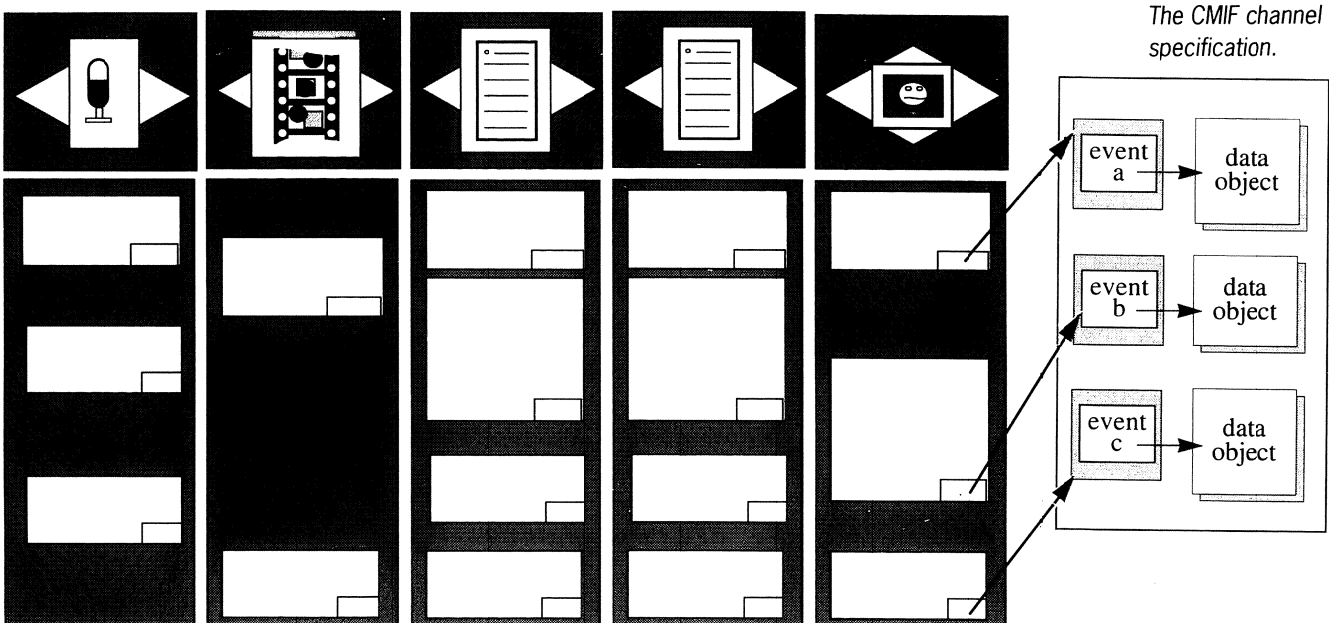


Figure 4
The CMIF channel specification.

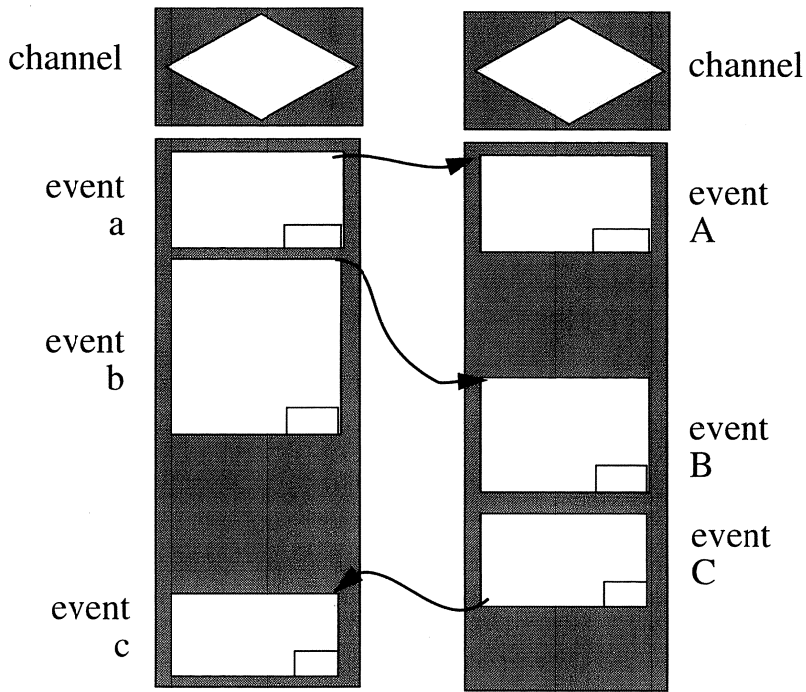


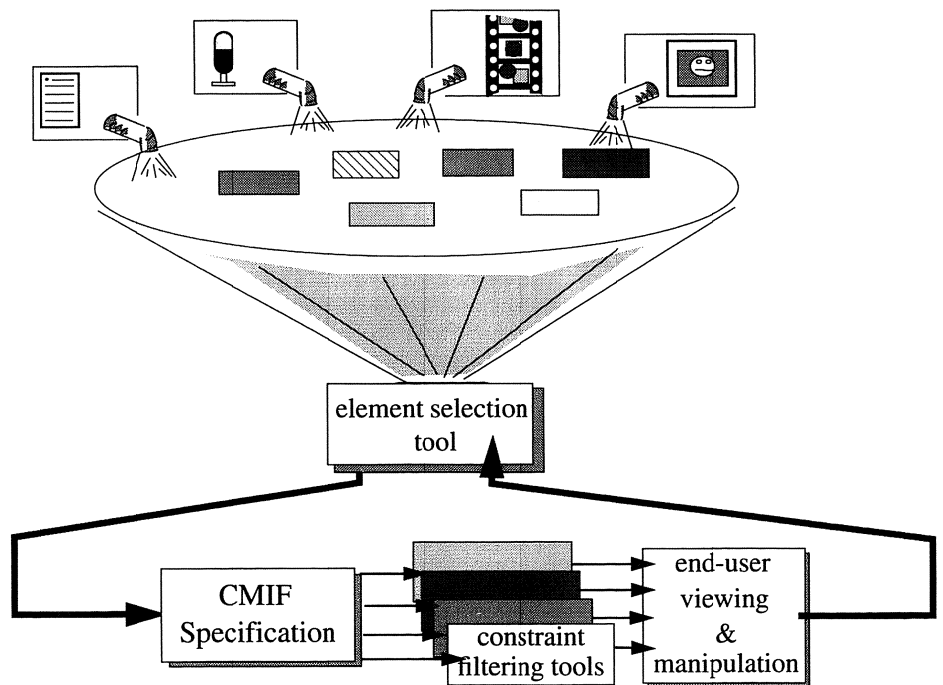
Figure 5
Explicit inter-channel
synchronization.

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.



Channel Specification: film, voice, label, nl_txt, eng_txt, pic, form

Receipt:
 Datum : 27 november 1991 (14:32:29)
 Kopprijs: 16,37 cent
 Koop: Max Havelaar koffie (Residentie: f 13,30 / 1000 gr),
 Kringloop filterzakjes 'no. 2' (of '102'),
 Melkcupjes,
 Suiker.

Naam	NIEUW AANTAL	INKOPEN	Cedronken	Betaald	Te drinken	Saldo
Jack		2505	444,32	107	17,57	
Jansteen		541	107,69	91	14,93	
Guido		2308	405,26	86	14,02	
Eddy		1505	262,56	58	9,54	
Dfk		19	10,00	42	6,81	
Jh		149	28,89	29	4,75	
Sjoerd		1839	317,92	26	4,32	
Irv		413	74,98	17	2,73	
Frank		122	23,20	17	2,72	
JAN HODAAL		609	105,70	14	2,21	
Jt		204	36,63	12	1,99	
Lon		386	66,82	10	1,71	
Ocab		12	3,00	6	0,96	
Steven		385	65,09	3	0,53	
Sape		478	80,91	2	0,27	
Leonie		8	1,35	0	0,01	
Hk		53	8,69	0	-0,01	
Hans		1	0,00	0	-0,15	
Hines		1	0,00	0	-0,18	
Petero		2	0,00	0	-0,32	
Adrianb		2	0,00	0	-0,36	
Frankd		44	6,95	0	-0,42	
Hieke		45	6,57	0	-0,75	
Harja		874	147,73	0	-1,16	
Peterb		12	0,00	0	-1,96	
GHOSTS		3059	522,06	0	-2,14	
Carsl		1371	230,07	0	-2,78	
Laubert		460	74,06	0	-3,85	
Japie		245	34,70	0	-6,87	
TOTAL		17043	2959,65	820	61,92	

Text 1: Fresh coffee is put into the copper insulating can. This can has a lid that seems to pose problems to the average computer-scientist, with its two independent lly and always close it, fee will go cold.

Text 2: Als er verse koffie is zit die normaal gesproken in de koperkleurige koffiekkan die bij het apparaat staat. Het deksel van het apparaat is een wonder van vernunft, met twee onafhankelijke scharnieren. Let er dus op dat je het deksel weer goed sluit, anders heeft de volgende koude koffie.

Dagelijks gebruik

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

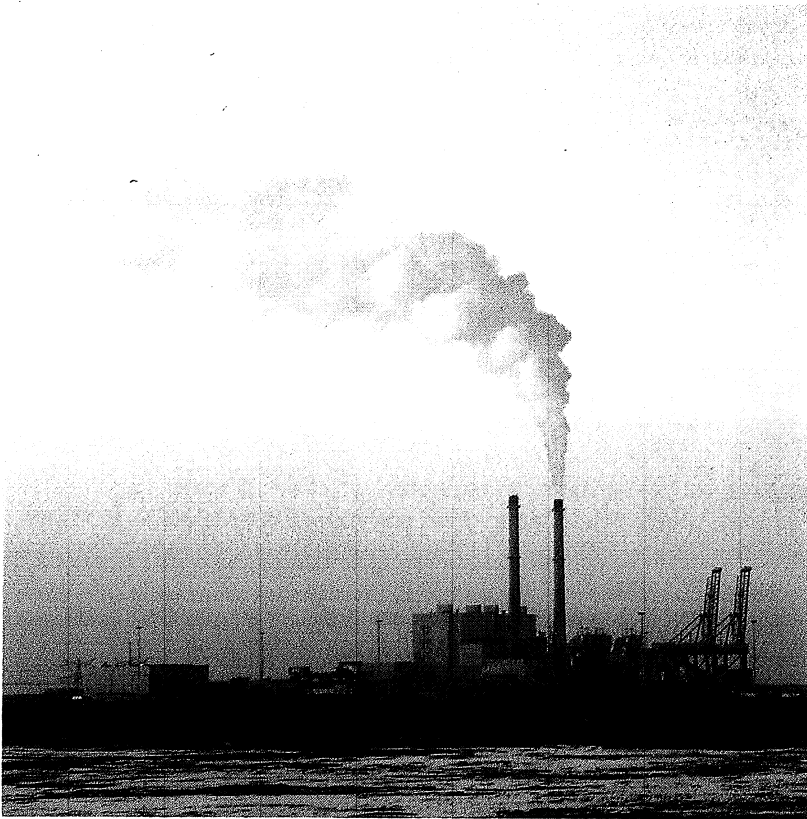
massive data handling, image reconstruction, inverse methods and parameter estimation, dynamical system theory and chaos, statistics, operations research, optimization and optimal control, and biomathematics.

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 super-model. 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 regriding 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 phenomena 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.

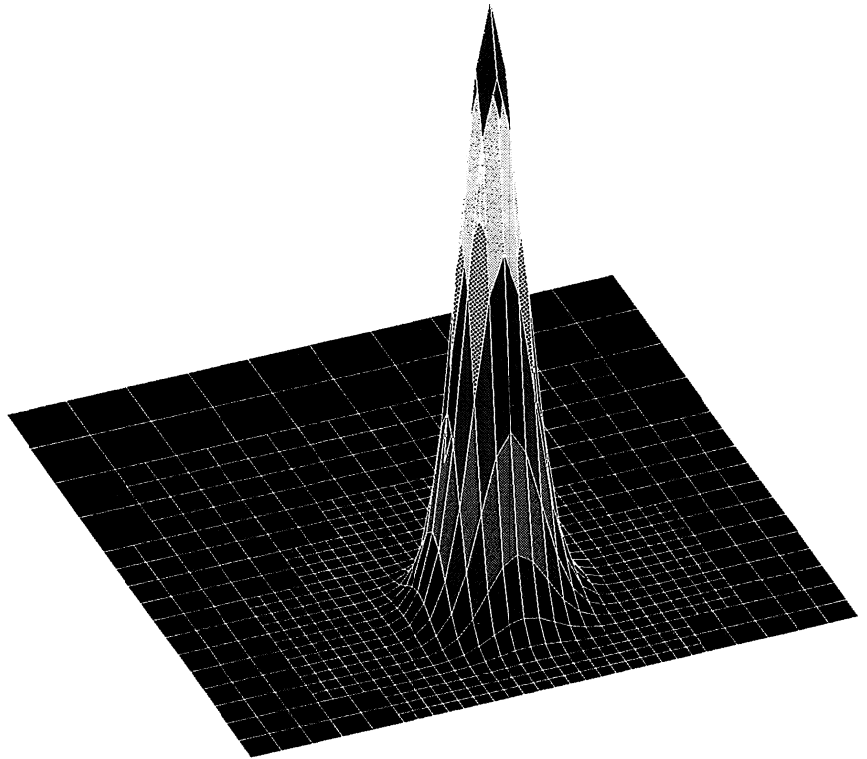
Algorithms for mathematical air pollution models

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 preconditioning 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, SO₂-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 simula-

tion 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 aerodynamicists.

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 Trailblazer modems

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

FINANCIAL AND OTHER DATA

FINANCES 1991

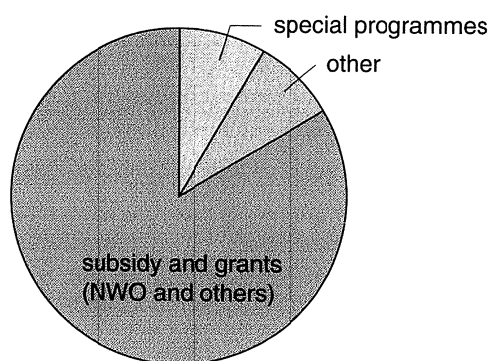
In 1991, SMC spent Dfl. 24.91 million, of which about Dfl. 2.05 million was allocated to research by the national working parties and Dfl. 22.86 million to CWI.

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).

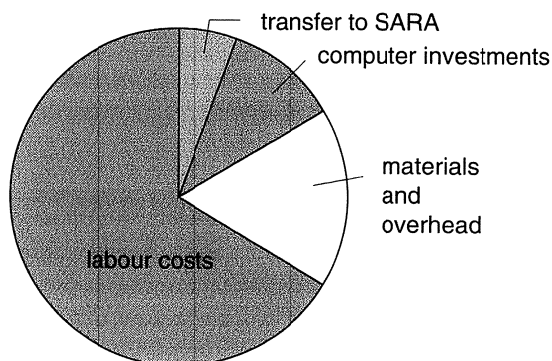
Finally, an amount of about Dfl. 1.99 million was obtained as revenues out of third-party-services, sponsorships and other sources.

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

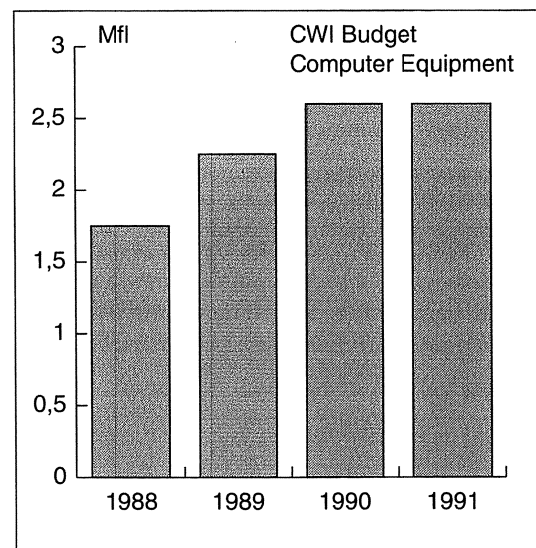
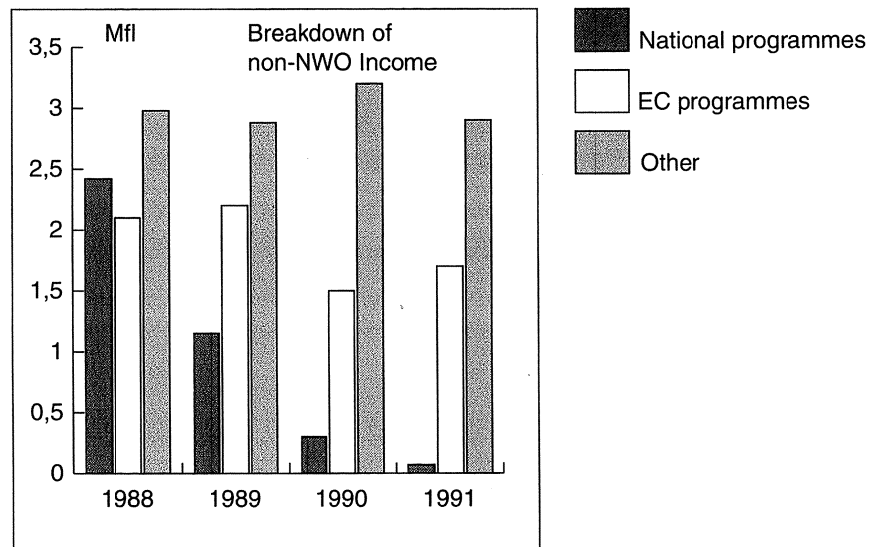
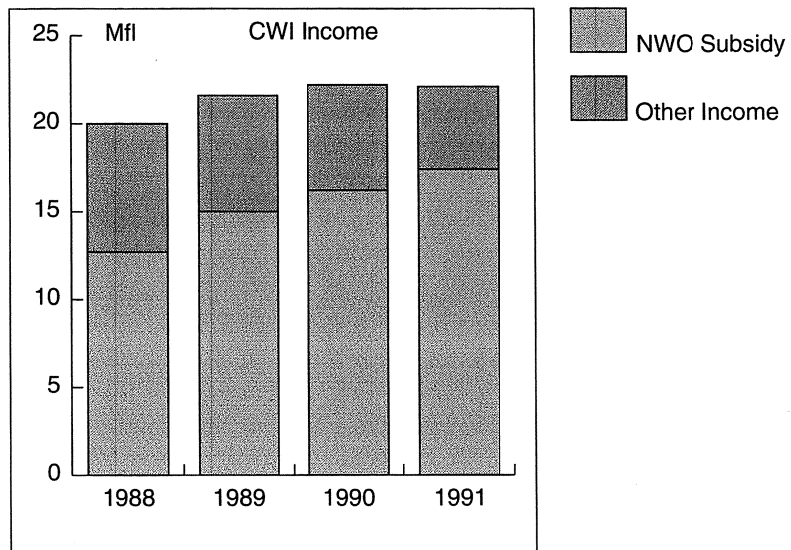


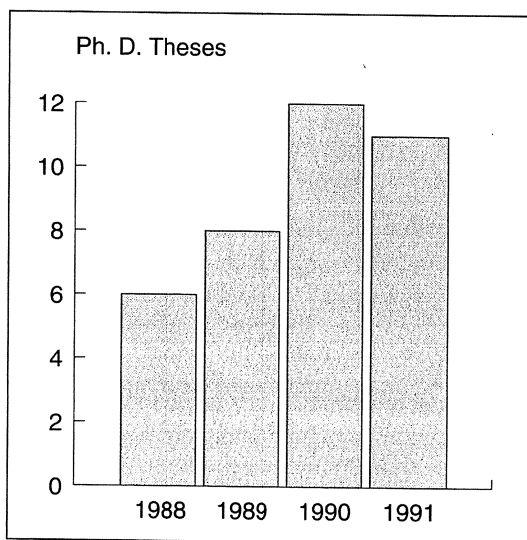
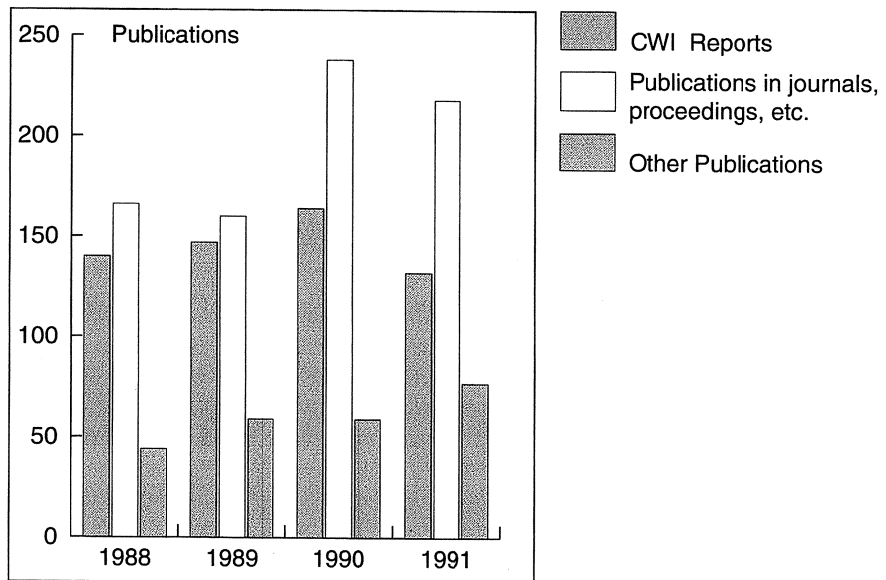
expenses CWI



	<i>national working parties</i>	<i>CWI</i>	<i>SMC</i>
	* 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





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
- Geometries 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 combina-
torial 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: Solu-
tion adaptive Navier-Stokes solvers with
grid-decoupled upwind schemes and mul-
tigrigrid acceleration
January 1990 - January 1992
Von Kármán Institute Brussels (main con-
tractor), 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 develop-
ment 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 pro-
gramming 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 Sys-
tems (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. Dzharidze

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

Operations Research, Statistics & System Theory

O.J. Boxma (head of department)

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

Numerical Mathematics

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

E.D. de Goede	R.R.P. van Nooyen	<i>programmers:</i>
P.W. Hemker	H.J.J. te Riele	J.G. Blom
W.H. Hundsdorfer	B.P. Sommeijer	W.M. Lioen
J. Kok	R.A. Trompert	M. Louter-Nool
B. Koren	J.G. Verwer	D.T. Winter
H.T.M. van der Maarel	H.A. van der Vorst (advisor)	P.M. de Zeeuw
A.N. Malyshev	P. Wesseling (advisor)	
J. Molenaar	P.A. Zegeling	
J. Mooiman		

Software Technology

J.W. de Bakker (head of department)

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

Algorithmics & Architecture

L.G.L.T. Meertens (head of department)

L.G. Barfield	M.L. Kersten	M.H. van der Voort
C.A. van den Berg	E. Kranakis	J.C.S.P. van der Woude
E.D.G. Boeve	S.J. Mullender (advisor)	
J.N.E. Bos	T.P. Pedersen	<i>programmers:</i>
D. Chaum	S. Pemberton	F. van Dijk
P. Clote	A. Plomp	A.J. Jansen
M.J. Coster	G. van Rossum	T.J.G. Krijnen
I.J.P. Elshoff	H. Shin	
M.M. Fokkinga	A.P.J.M. Siebes	<i>trainees:</i>
M.W. van der Ham	C.J.E. Thieme	G. Brands
E.J.L.J. van Heyst	J.T. Tromp	P.J.M. Veugen
R. Hirschfeld	N.Th. Verbrugge	
J.T. Jeuring	P.M.B. Vitányi	

Interactive Systems

P.J.W. ten Hagen (head of department)

F. Arbab	D.B.M. Otten	R.C. Veltkamp
E.H. Blake	J.L.H. Rogier	
C.L. Blom	M.M. de Ruiter	<i>programmers:</i>
V.C.J. Disselkoen	E.P.B.M. Rutten	M.A. Guravage
W. Eshuis	D. Soede	R. van Liere
M. Haindl	P. Spilling	
I. Herman	P.J. Veerkamp	<i>trainee:</i>
H.E. Klarenbosch	J. van der Vegt	I.Chr. Maurice
A.A.M. Kuijk		

Computer Systems & Telematics

D.C.A. Bulterman (head of department)

L. Hardman	<i>programmers:</i>
G. van Rossum	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-Luërsen (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)
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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. Moscovitz (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. KOORNWINDER (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.

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Department of Algorithmics and Architecture

AA 1: Algorithms and complexity

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