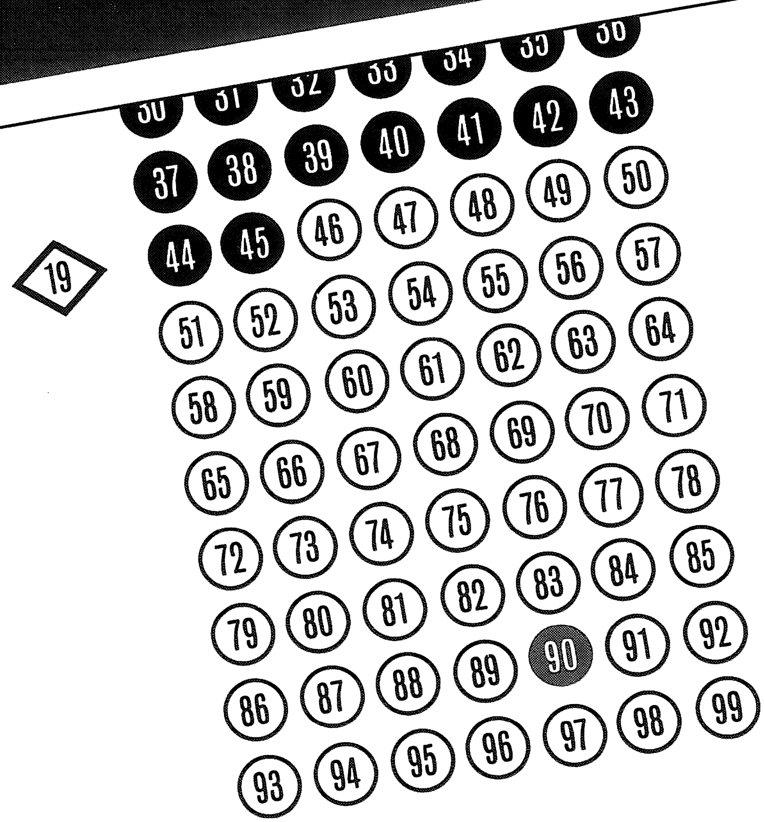
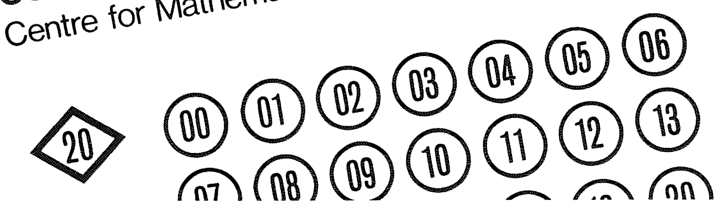
ANNUAL REPORT



CWI

Centrum voor Wiskunde en Informatica

Centre for Mathematics and Computer Science



CWI

ANNUAL REPORT 1990

Centrum voor Wiskunde en Informatica
Centre for Mathematics and Computer Science

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

The Stichting Mathematisch Centrum was founded on February 11 1946, as a non-profit institution aiming at the promotion of mathematics, computer science, and their applications. It is sponsored by the Dutch Government through the Netherlands organization for scientific research (NWO).

Board of Directors

P.C. Baayen (scientific director)
J. Nuis (management director)

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

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Contents

Introduction

Policy
The year 1990 was a time of difficult decisions for CWI. On the one hand, effects of the foregoing period of expansion - particularly in informatics - had included widening of research territory and international cooperation (ESPRIT, ERCIM). On the other, 1989 brought confrontation with a number of limiting factors. The Policy Document 1990-1995 of NWO, The Netherlands organization for scientific research, our main source of grants, announced an 'intermission in growth' for the exact sciences lasting up to 1994. Conversion of support under the government's Information Technology Promotion Plan (INSP), which ended in 1989, into a permanent NWO grant proved far from spontaneous. The INSP grant had amounted to Dfl. 2 million per year, and major effort was required to avoid a substantial decline in funding. Parallel with these developments, the emphasis of the European Community's ESPRIT programme shifted more towards applications; CWI was involved in several ESPRIT programmes, but this new trend was meshed less well with our research profile. Added to this, income from outside commissions was also below expectations in 1990.

Bearing these considerations in mind, and remembering that CWI's financial situation is likely to remain problematic in the longer term, the Board of Directors decided to take far reaching measures. These comprised both practical economies and stringent examination of scientific activities. In recent years, CWI research had been very highly rated on some occasions by international committees. Their recommendations stressed concentration of research and human resources on fewer projects, increased emphasis on fundamental, application oriented subjects, and closer contacts with business and industry. The visiting committees also advised clearer profiling of CWI vis-a-vis research at the university.

Against this background, an internal CWI committee was tasked with careful evaluation and examination of ongoing research and proposals for the coming years' Scientific Programme. Based on this committee's findings, the Board of Directors identified 22 research groups for priority support. A total of five large scale and strategically important Common Research Themes were then positioned over and across the groups - several of which contribute to one particular research theme. Both mathematicians and computer scientists contribute to the five themes: image processing, multimedia, mathematics and the environment, computational geometry, and scientific visualization. To the great disappointment of all concerned, the previously mentioned financial developments will mean that it is not possible to proceed with all research activities. The decision has now been taken to end several of them during 1991; the subjects concerned are in analysis and mathematical physics, mathematical statistics and probability, ergonomic aspects of computer systems, distributed systems and the independent research in the field of numerical software (with the exception of computer aided number theory).

Alongside the Scientific Programme for 1991, and the long-term plans 1992-1996, which details selected research, we have also responded to NWO's request by establishing a CWI Business Plan; this profiles CWI in the nineties taking account of the above-mentioned factors, and covers choice of research, financial parameters, a strategic approach to commissions, as well as definite activity plans and monitoring thereof. A special mention deserves to be made of the marketing team set up in late 1989, this unit is tasked with securing commissions from business and industry. Further, CWI's supporting sectors will also be subject to efficiency surveys in 1991.

ERCIM
The year under review was also marked by the start of a broad range of activities under the ERCIM programme, just as envisaged in 1988 by the founders of this European cooperative project by national research bodies in the fields of informatics and (applied) mathematics.

In political terms, the focus was on widening the consortium from its three founding members - GMD (Germany), INRIA (France) and CWI (The Netherlands). In

European Research Consortium for Informatics and Mathematics

ERCIM

November, the Rutherford Appleton Laboratory (RAL) of Great Britain joined as the fourth ERCIM member, and agreement was reached on the admission of Portugal represented by INESC (Instituto de Engenharia de Sistemas e Computadores). Contacts were also initiated with CNR of Italy (Consiglio Nazionale delle Ricerche). Further moves were made to formalise ERCIM at a European level, whereby consideration is being given to formation of a European Economic Interest Group (EEIG). One of the conditions for this is that ERCIM has its own offices, and it has been decided to base these in Paris for the first three years.

The *joint* workshops have always been a core activity of ERCIM. Two were organized in 1990, the first in April at GMD in St Augustin and the second in November at CWI in Amsterdam. Both workshops dealt with three themes; in April: System & Control Theory, Multimedia Document Production & Distribution, and Operating Systems; and in November: Computer Algebra, Mathematical Aspects of Image Processing, and High Speed Networking. The themes were selected for their expected major roles in Europe of the nineties, and the rich breeding ground offered here by the ERCIM partners. Of the some tens of researchers who participated in each workshop theme, there were a growing number from non-ERCIM bodies.

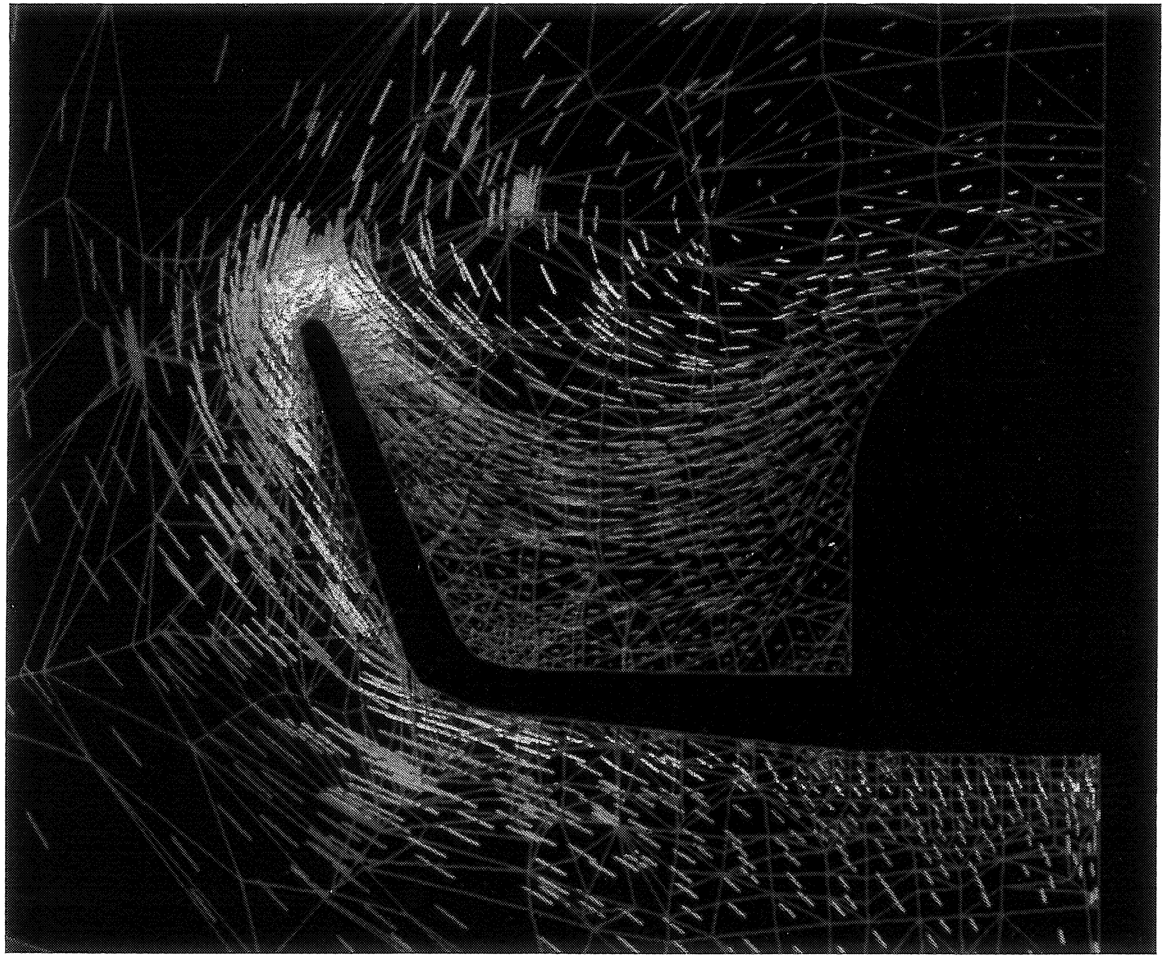
The ERCIM *fellowship programme* started up in 1990. The first round of three Ph.D. level fellowships for young researchers went to Michal Haindl (Czechoslovakia), Eric Rutten (France) and Alexander Malyshev (USSR). Each of them will spend six month periods at three different ERCIM institutes. This familiarises the candidates with the European situation while ERCIM contributes to the mobility of research personnel. A second round of four scholarships was started before the end of the year.

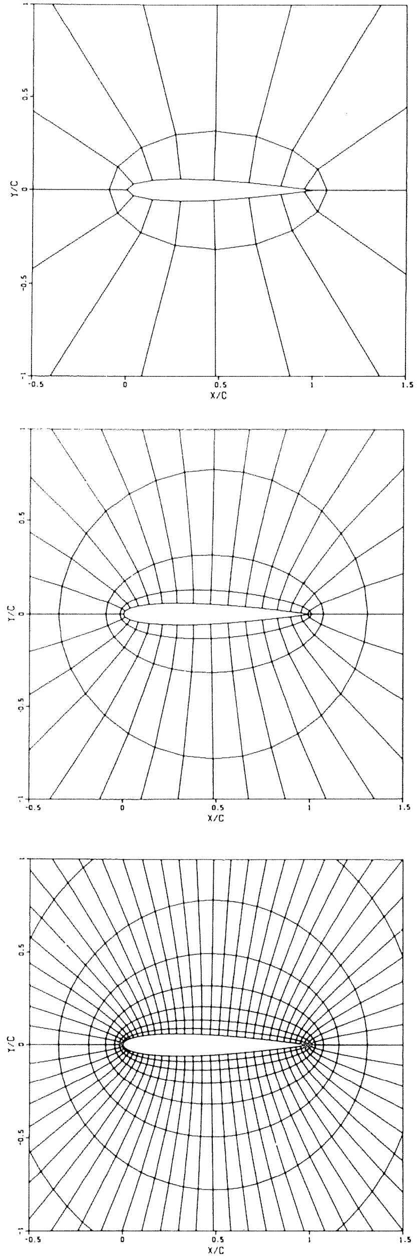
In November, CWI hosted the first ERCIM course for advanced researchers. The subject was 'Large Scale Parallel Scientific Computing' and most of the twenty participants were from abroad. In 1991, this same course, under the leadership of Herman te Riele (CWI), will also be given in Bonn and Paris. Funding has been secured under the European Community's COMETT II programme. Preparation is underway on other courses covering Parallel Computing, User Interfaces and Computational Fluid Dynamics.

April 1989 saw the first edition of a newsletter which has since undergone considerable development. The third of the 1990 editions carried the definitive name *ERCIM News,* and the new ERCIM logo. ERCIM News is now published three times a year, each print run of 6,000 is distributed in some 20 European countries as well as the United States and Japan. Most contributions come from ERCIM institutes but the aim is to encourage more outside contributors. ERCIM News reports on developments within ERCIM, activities at the research institutes, knowledge transfer, international contacts, conferences, workshops, courses, etc. Starting with the fifth issue (December 1990) each ERCIM News deals with a special theme, the first being Image Processing.

Projects

Despite the difficult situation and severe competition it is remarkable that CWI has succeeded in maintaining virtually the same level of involvement in European research programmes. It is so that the ESPRIT programme now offers a research institute such as CWI fewer openings than a few years ago. CWI now participates in five projects (ESPRIT II: *Atmosphere and GIPE II,* ESPRIT BRA: *Concur, Integration and Sema-*





The dynamics of fluids is studied (amongst others) in connection with the safety and economy of flying with heavier-than-air craft. Numerical solutions of the relevant flow equations are studied at CWI, partly in the European Hermes spaceshuttle project. CWI researchers successfully applied multigrid methods to provide efficient solutions to flow equations. Such methods use several scales of discretization interactively. Alongside a three-grid discretization for an aircraft wing section, the streamline distribution around a half cross-section of the Hermes spaceplane is also shown. Photo: Dassault.

graph); the contribution to *Tropics* came to an end. CWI's participation in the RACE (R&D in Advanced Communications technologies in Europe) projects *RIPE* and *SPECS* is being continued. As part of the BRITE EURAM programme, research was initiated into improved algorithms for solution of the Navier-Stokes equations using adaptive multigrid methods. There is considerable interest here from the aerospace industry in particular. CWI is also involved in the BCR project *Chebyshev Reference Software.* The European Commission's Community Reference Bureau (BCR) is tasked with simplifying methods of measurement and chemical analysis. Lastly, CWI participates in two projects supported by the SCIENCE programme: *Evolution Systems* (deterministic and stochastic evolution equations, control theory and mathematical biology) and *Combinatorial Optimization* (algorithmic methods for large and complex combinatorial optimization problems).

Details of some more projects follow below. The appointment as per 1st January 1991 of CWI project leader S.J. Mullender to a professorship at the Twente Technical University marked the ending of the Amoeba project at CWI. Amoeba is a distributed operating system developed in cooperation with the Free University of Amsterdam. The project also received support from the Open Software Foundation (OSF). Participation in the European Space Agency's *HERMES* space shuttle development project (application of adaptive multigrid methods to flow computations) was also rounded off in late 1990. Other projects ended during the course of the year were *PRISMA* (design of a parallel machine) and *FLAIR* (flexible automation) - both part of the Dutch national SPIN programme - and the NFI project *Cryptography and computer security.*

Following an uncertain start, research on *Image Processing* is now well underway. At CWI the particular focus is on reconstruction of dynamic images of the human heartbeat from NMR data (in cooperation with Philips Medical Systems), mathematical morphology (with Philips Research, Brussels, the TNO Institute for Sensory Physiology and the University of Amsterdam) and object recognition in images (statistical aspects of image recognition). Work also progresses on a software library in C^{++} for use in image processing.

The Computer Algebra project group developed the *LiE software package* for calculations on Lie groups. This is now available for several computer systems (VAX, SUN, IBM and compatible, Apple Macintosh).

Research into *natural languages* obtained the necessary reinforcement in 1990. The focus here is on semantic aspects, with special attention to non-monotonous reasoning and links with programming languages. This research is in close cooperation with the University of Utrecht's Institute for Language and Speech; other contacts include the Institute for Language, Logic and Information of the University of Amsterdam.

A further development has been coordination of Common Research Themes cutting right across the projects - and staffed by members of the groups. By their very nature, the themes concerned here are likely to have a major impact on every-day life in the future. The multidisciplinary approach to the problems produces clear synergetic effects. At present two themes: *Multimedia*, and *Mathematics and the Environment,* are in their initial phase, and two others: *Computational Geometry* and *Scientific Visualization* are being prepared.

New commissions

1990 saw intensified activity to secure new commissions. Research related to social issues has been part of CWI's mission since foundation. Naturally, such activities must fit within the conditions for fundamental application oriented research set by the charter of SMC.

At the end of the year there were some 70 ongoing contacts with companies and (government) bodies. Some of these are long-standing but a substantial number were generated during the year under review. Around 20% of the contacts involve current commissions, mainly in the areas of operations research, statistics and numerical mathematics.

Several long standing consultation projects: *PLATO* (platform allocation stands at Schiphol Airport, dating from 1986) *Basis Levels Coastal Area* (statistical research for the Tidal Waters Section of the Public Works department, since 1984), are now in the final phase and will be rounded off in 1991. Other statistical commissions were carried out for the Dutch broadcasting organization NOS (viewing figures), the Amsterdam Pedologic Institute (vulnerable periods for children) and the Province of Gelderland (ground water levels). Numerical consultations included the modeling of ground water flows and three-dimensional shallow water equations.

As part of the programme to intensify contacts with business and industry, CWI received delegations from ESTEC and the PTT, and made a return visit to ESTEC. Also notable here is the agreement reached with Shell KSEPL whereby a number of young researchers would be placed at CWI, with all costs borne by Shell.

International cooperation
In 1990, CWI signed cooperative agreements with the Tata Institute of Fundamental Research (Bombay) and the Steklov Institute of Mathematics (Moscow/Leningrad). Both agreements envisage short-term exchanges of researchers. And so, the following autumn saw a visit to CWI by Prof. A.N. Shiryaev (Steklov), who gave a series of lectures on 'Comparison and convergence of statistical experiments'. CWI also exchanged letters of intent with institutes in Tokyo, Prague and Budapest. Contacts on statistical aspects of image analysis were established with the Australian Commonwealth Scientific and Industrial Research Organization (CSIRO).

Another visitor was Prof. J.-L. Lions, member of the Collège de France. In January he gave two lectures entitled 'Problèmes mathématiques liés à l'environnement' on mathematical models and their control for large scale (global) physical, chemical and biological phenomena.

In November, CWI received a visit from Prof. J.A. Feldman, director of the International Computer Science Institute (ICSI) of Berkeley. ICSI was set up in 1986 as a joint project by the computer science department of the University of California and GMD (Germany). Starting in 1990, ICSI also receives support from Switzerland, Italy and a number of US sources. Like CWI, ICSI is an institute for fundamental research.

During the summer, Prof. P.C. Baayen, CWI's Scientific Director, returned the 1989 visit by Prof. Hsien Chung Meng, member of the National Science Council of Taiwan. Prof. Baayen went on from Taiwan to address GMD's annual 'Schlosstag' on 'The Importance of Parallelism in Computing for future European Information Technology Research'.

Lastly, P.J. Veerkamp (IS department) worked for six months in Prof. T. Tomiyama's group at the University of Tokyo; prof. Tomiyama had himself spent almost three years at CWI.

Conferences and courses
Once again in 1990, in line with the aimed for reinforcement of our centre function, there was an increase in the number of conferences, courses, workshops, colloquia, etc., organized by CWI. A description of just a few of the many events follows.

The 4th ACM conference on *Supercomputing* drew 150 participants to Amsterdam. The same number took part in *CONCUR'90,* the first of a series of conferences on concurrency organized at the initiative of the ESPRIT project CONCUR. A record 180 visitors from Belgium, Holland and Luxembourg came to discuss the advancement of research activities and cooperation at the annual *Benelux meeting on System and Control Theory.* There was also considerable interest for the *FOOL* workshop on the foundations of object oriented languages, organized under the auspices of the European Association for Theoretical Computer Science (as part of REX, Research and Education in Concurrent Systems). This event, which attracted 120 participants, was part of a national computer science programme in which CWI participates with the universities of Leiden and Eindhoven. CWI also had considerable input in two

Eurographics workshops on *Object oriented Graphics* and *Intelligent CAD systems.* Europe's first workshop on logic in artificial intelligence, *JELIA 1990,* was so successful that a follow-up is assured. The European space shuttle development project *HERMES* brought some fifty European specialists in computational aerodynamic to a meeting at CWI. Our expertise in multigrid methods has contributed to this project for several years now. The meeting also attracted considerable publicity. Another fifty researchers, mainly Europeans, took part in a workshop on *Functional-analytic Methods for Structured Populations.* The workshop was part of a European Commission SCIENCE project. Several tens of experts - academics and from the private sector - took part in a two-day state-of-the-art workshop on *Multimedia.* This theme is the subject of one of CWI's Common Research Themes. Five one-day symposiums on *Parallel Scientific Computing* were jointly organized in cooperation with Delft Technical University, the University of Amsterdam and the International Association for Mathematics and Computers in Simulation (IMACS). The proceedings will be published in a special number of the IMACS journal 'Applied Numerical Mathematics'. There was also considerable interest in a seminar on *Lie groups.* Finally, this year's theme for the traditional vacation course for mathematics teachers was *Number Theory.*

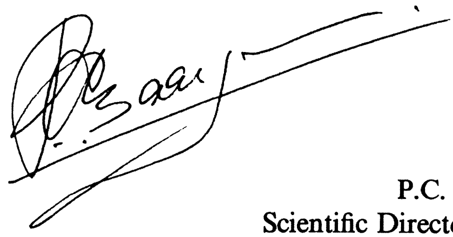
Miscellaneous
Some more events deserve to be mentioned.

The publication by Prentice Hall of the *ABC Programmer's Handbook* by L.J.M. Geurts, L.G.L.T. Meertens and S. Pemberton marked the completion of a 15 year development. The ABC programming language (previously known as B) was designed at CWI; it can be described as: interactive, structured, simple, powerful, user-friendly, compact and readable. Many of the ideas springing from ABC are being used in a Views follow-up project.

A new *CRAY Y-MP4 supercomputer* was installed at the Academic Computing Services Amsterdam (SARA) towards the end of 1990. CWI is one of the founders of SARA. The supercomputer will serve as a national research facility; a separate foundation has been established for this purpose.

CWI has always had strong links with the academic research community. This is evidenced by the professorships awarded to several senior staff members, three in 1990: P.W. Hemker to the chair of industrial mathematics at the University of Amsterdam; J.H. van Schuppen to the chair of system and control theory at Groningen University (and directorship of the National Network for System and Control Theory); and D.J.N. van Eijck to the chair of logical aspects of computational linguistics at Utrecht University (Research Institute for Language and Speech). Furthermore, J.W. de Bakker was elected to membership of the Academia Europaea.

CWI went through a difficult year - the difficulties affecting research as well as support and management. Reconsideration of our future tasks did not necessitate any change in CWI's basic mission, as laid down for example in the Policy Document 1988-1993. We expect to be able to deal with the challenges of the 1990's by concentration of our research efforts, intensification of our research contacts with outside parties (e.g. industry) and by emphasis on efficient support. I have full confidence in CWI's staff carrying out our programme for the near future.



P.C. Baayen
Scientific Director CWI

Organization

The Centre for Mathematics and Computer Science (CWI) is the research institute of the Stichting Mathematisch Centrum (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 Stichting Informatica Onderzoek in Nederland (SION), an 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 NWO about CWI's research programme in computer science.

SMC also finances research projects at Dutch universities. These projects are organized in eight national working parties in the following fields:

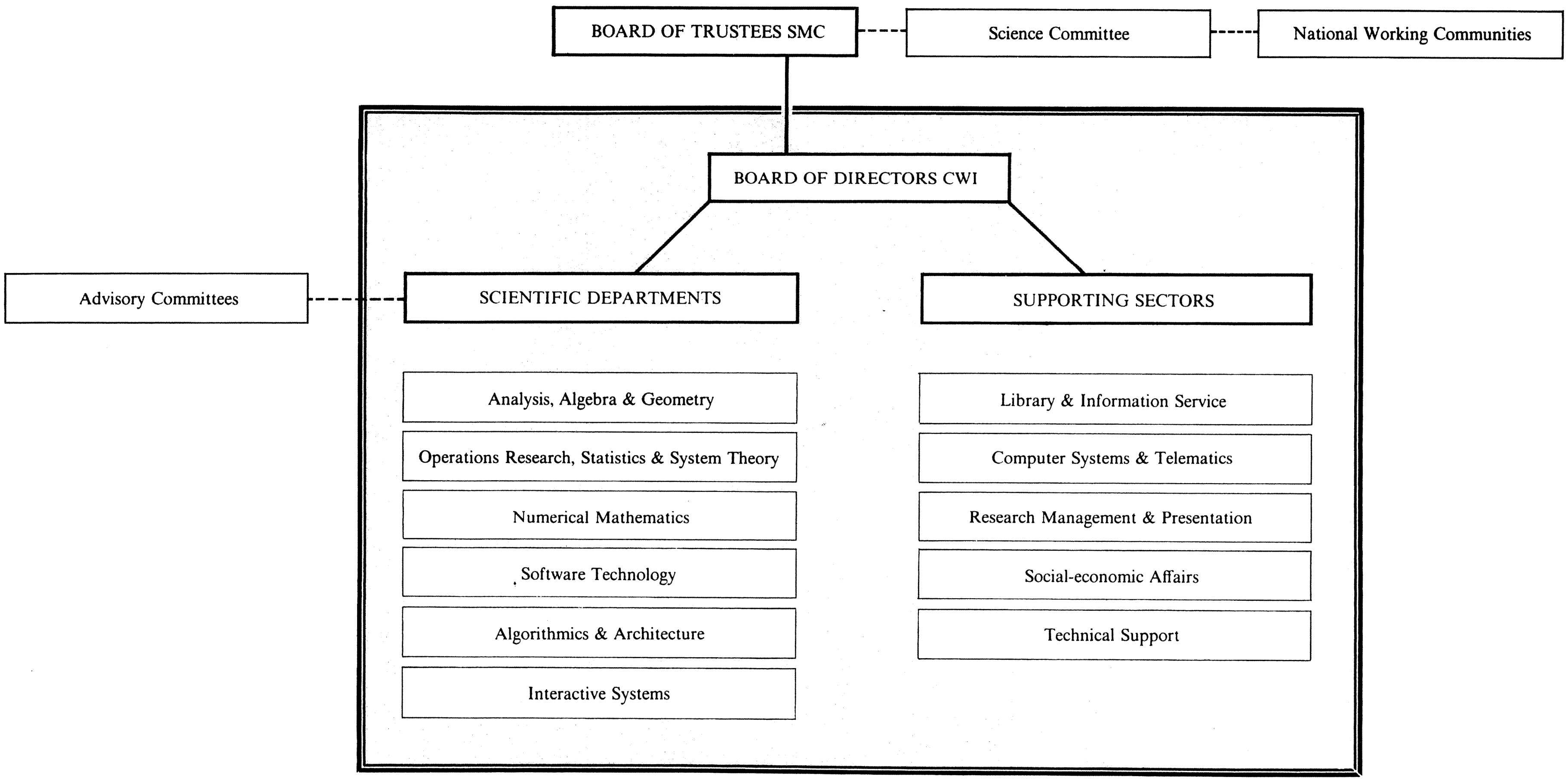
- Numerical mathematics;
- Stochastics;
- Discrete mathematics;
- Operations research and system theory;
- Analysis;
- Algebra and geometry;
- Logic and foundations of mathematics;
- Mathematical physics.

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

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 will be 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 Common Research Themes cutting right across the departmental research groups - and staffed by members of these groups.

By international standards CWI might appear relatively small and incapable of involvement in the full range of major developments in mathematics and computer science. However, size can be deceptive. By its very nature CWI, with its close knit research units supported by state-of-the-art computer facilities and a well stocked library, is ideally equipped to handle the dynamic and interdisciplinary demands of present day research.



Organizational chart: the Stichting Mathematisch Centrum SMC and its research institute, the Centrum voor Wiskunde en Informatica (Centre for Mathematics and Computer Science) CWI.

M. Hazewinkel (head of department)
G. Alberts
A.E. Brouwer
A.M. Cohen
O. Diekmann
M.S. Dijkhuizen
F.G. Greiner
F.C.A. Groen (advisor)
J.A.P. Heesterbeek
H.J.A.M. Heijmans
P. Hofstee
H. Inaba
T.H. Koornwinder
M.A.A. van Leeuwen
J. van de Lune
J.A.J. Metz (advisor)
J.M.A.M. van Neerven
A.B. Olde Daalhuis
J.B.T.M. Roerdink
S.N.M. Ruijsenaars
N.M. Temme
J. de Vries
M. Zwaan

COMPUTER ALGEBRA

Introduction
The rise of computer algebra is a direct consequence of the phenomenon that now, as never before, mathematics can be done quite successfully with a computer as the main tool, rather than the classic pencil and paper.

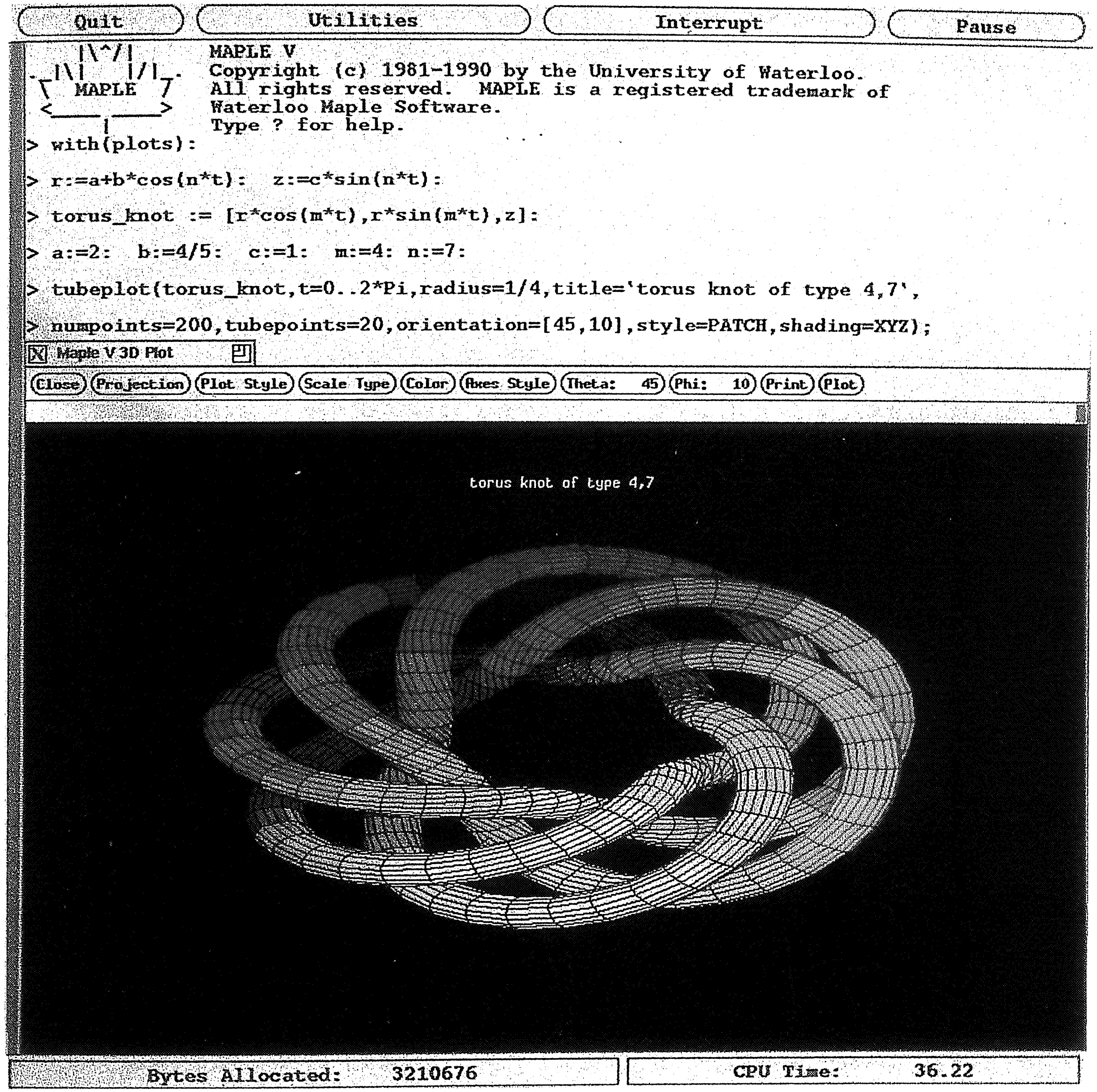
The rapid development in computers toward work stations with huge memory capacities and graphic interfaces has cleared the road for software packages that perform all the standard routines of calculus and algebra (simplification of symbolic expressions, expansion of product expressions into sums without brackets, integration and differentiation of elementary and not so elementary functions, normal form presentation of rational functions, and so on).

One might wonder why the word 'algebra' does not reappear in the above description of computer algebra. The reason is that most mathematical disciplines, like analysis, geometry and topology, have symbolic expressions that can be simplified with algebraic rules; and so, indeed the use of computer algebra stretches far beyond the pure algebraic territory.

The focus on these new interactions between mathematics and computers has given rise to the construction of software packages dealing with the treatment of symbolic mathematical expressions. These activities form the core of what has initially been understood to be computer algebra. During the last few years, however, quite a few mathematicians have been inspired by the new possibilities which have arisen, and have developed algorithms in mathematics to perform the computations needed in their discipline (and quite frequently also implemented in a software package). Thus the initial - technological - definition of computer algebra tends to broaden so as to encompass the algorithmic approach to mathematics itself.

Of these theoretical aspects of computer algebra, a division can be made into - roughly speaking - four main areas of active research: Differential Equations, Computational Number Theory, Computational Group Theory and Effective Commutative Algebra (algebraic geometry, polynomial systems solving, etc.).

Computational group theory
At CWI, computational number theory was in the picture before it was considered part of computer algebra. As an outgrowth of these activities, a large (101-digit) so-called 'more wanted' number has recently been factorized on the new Dutch national supercomputer (a CRAY Y-MP4, installed in December at the Amsterdam Academic Computing Centre SARA). The main area of research in the project group Algebra, Discrete Mathematical Structures and Computer Algebra, to be described here, is Computational Group Theory. It is of interest to CWI because of its tradition in groups and geometries, notably the geometries of Lie type and the subgroups of groups of exceptional Lie type. In this



Modern computer algebra systems bundle all aspects of scientific computation: numerics, symbolics and graphics. The picture shows a torus knot of type (7,4), produced by the software package Maple.

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context, algorithms have been developed to efficiently deal with Weyl groups, e.g. to enumerate their orbits in the reflection representations, and to handle questions such as decompositions of (symmetric) tensors and reductions of representations to subgroups for complex semisimple Lie groups. In writing these algorithms, a vast amount of known theory and existing formulae have been taken into account.

LiE

However, computer algebra also deals with the design and implementation of such algorithms. To try out the difficulties in such an enterprise and to put the results of the aforementioned activities into use for other mathematicians, a software package, named LiE, has been built at CWI; it incorporates most of the standard facts one might wish to draw from the reference books and tables in the field. For instance, it contains the routines to compute with Young tableaux known by the names Littelwood-Richardson and Robinson-Schensted.

Although some of the earlier computer algebra packages (viz. REDUCE and Schoonschip) originated in Europe, most of the recent ones (such as Maple, Mathematica and Scratchpad II) for general purposes come from North America. Conversely of the packages oriented towards more specific areas of research, a fair amount come from Europe. LiE is an example of such a package. It is of interest to mathematicians and physicists studying Lie group representations, and attempts to provide the best possible results. To give an indication, we mention here that the fifth symmetric tensor of the irreducible 3875-dimensional representation of the exceptional Lie group of type E_8 has been successfully completed, showing (among other facts) that the space of group invariant quintic forms has dimension 3.

Despite the shortage of staff the project group has attacked several other topics.
To mention a few:
- all of the construction problems of finite subgroups of the complex Lie group of type E_6 have now been settled (joint work with Wales) as well as some of the conjugacy questions that were left open;
- the interpretation (first noted by B. Sturmfels in the case of GL_n) of the straightening law in classical invariant theory as a special instance of the Gröbner bases theory - one of the main tools in computational commutative algebra (with R.H. Cushman);
- a new treatment of Zelevinsky's work on 'pictures' putting the above-mentioned algorithms on Young tableaux in a unified perspective.

CAN
Much of the project group's energy, however, has gone into organizing the national Expertise Centre CAN. This centre aims at providing the necessary aid to researchers and students at universities and schools, as well as researchers and engineers in industry, who wish to use computer algebra. CAN is developing into a location where anyone can make enquiries about computer algebra in general or about new developments or new packages (both commercial and non-commercial ones), be assisted in how to use a package, compute on one of the more powerful machines available at the centre, obtain support in solving a problem when using the computer, consult other people affiliated with the centre, and so on. Apart from the tasks emanating from these activities, policies have been set out to approach high schools and industry. In this vein, the Centre CAN will assist in producing work sheets for education in mathematics by use of computer algebra packages, and will generate a number of case studies of computer algebra use in industry, showing its cost effectiveness.

PROJECTS

The following information is given for each project: a short description, the start-up year, research staff (project leader in italic) and cooperating institutions.

Algebra, discrete mathematical structures and computer algebra
The project concerns both 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.

A.M. Cohen, A.E. Brouwer, M.A.A. van Leeuwen.

Univ. Nijmegen, Univ. Rotterdam, Free Univ. Brussels, Univ. Michigan, Univ. Eindhoven, Cal. Tech. Pasadena, UC Santa Cruz, Free Univ. Amsterdam, Imperial College, Univ. Cambridge, Inst. of System Studies Moscow.

Analysis and mathematical physics
This project involves (aspects of) harmonic analysis on homogeneous spaces, special functions, quantum groups, q-special functions, integrable dynamical systems, and topological dynamics and some of the manifold interrelations between these topics. There are four subprojects.
- Analysis on semisimple Lie groups and

symmetric spaces and the connection with special functions. (1972)
T.H. Koornwinder, M. Dijkhuizen.
Univ. Leiden, Univ. Nijmegen, Univ. Delft, Univ. Groningen, Univ. Amsterdam, Univ. Leuven, Univ. Wisconsin, Univ. London, Japan, Univ. Tunis.

- Lie Algebras, Hopf algebras and integrable dynamical systems. (1982)
  M. Hazewinkel.
  Univ. Amsterdam, Univ. Twente, UCLA, Univ. Utrecht, MGU Moscow, LOMI Leningrad.
- Relativistic and quantum integrable systems. (1986)
  S.N.M. Ruijsenaars.
  Univ. Amsterdam, Australia.
- Dynamical systems. (1976)
  J. de Vries.
  Univ. Delft, Univ. Maryland, Univ. Tel-Aviv.

Nonlinear analysis and biomathematics
Analysis of ordinary, partial and functional differential equations and integral equations which correspond to mathematical descriptions of biological processes. Development of a general mathematical modelling methodology, in particular for the dynamics of structured populations. (1975)
O. Diekmann, F.G. Greiner, J.A.P. Heesterbeek, H.J.A.M. Heijmans, H. Inaba, J.A.J. Metz, J.M.A.M. van Neerven.

Univ. Leiden, Univ. Delft, Univ. of Tech. Helsinki, Free Univ. Amsterdam, Univ. Calgary, Univ. of Strathclyde Glasgow, Univ. Tübingen, Kyoto Sangyo Univ., Univ. Hiroshima, Univ. Arizona, Georgia Inst. of Technology, Univ. München.

Asymptotics
This project includes research on asymptotic expansions of integrals and differential equations, and solving problems on analysis and asymptotics (with numerical aspects) from physics, biology, and statistics. (1975)
N.M. Temme, A.B. Olde Daalhuis.

Univ. Winnipeg, Univ. Knoxville, Univ. Maryland.

Image processing and reconstruction
- Research on mathematical aspects of image processing and reconstruction by means of mathematical and numerical analysis, mathematical statistics and computer science;
- Development of algorithms and software;
- Contact with medical investigators, biologists and physicists, as well as with laboratories. (1985)

J.B.T.M. Roerdink, F.C.A. Groen, H.J.A.M. Heijmans, P. Hofstee, M. Zwaan.
Philips Medical Systems Best, Univ. Nijmegen, Univ. Delft, IZF-TNO Soesterberg, Philips Research Lab. Brussels, Harvard Univ., Ecole Normale Supérieure des Mines Paris.

Miscellaneous
- Classical analysis and number theory. (1972)
  This project concerns the study of problems of a (numerical/analytical) number-theoretic nature.
  J. van de Lune.
  Bell Labs, Free Univ. Amsterdam.
- History of mathematization.
  History of mathematical activity in the Netherlands over the period 1945-1960, in particular the history of founding the Mathematical Centre and of setting up the study course of Mathematical Engineer. Both events are being considered on the one hand in the general history context of their time, on the other hand against the background of the preceding development in the relation between mathematics and application. (1988)
  G. Alberts, M. Hazewinkel.
  Univ. Twente, Univ. Amsterdam.

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

OVERLOAD CONTROL

Introduction
In a modern technological society new services like data communication and video networks are becoming increasingly important. The main part of today's communication, however, is still carried by the telephone network. Usually we do not realize how much we rely on this means of communication, until the network is temporarily not available. Such an unavailability can be caused by technical failures or by a demand for telephone services that exceeds the capacity of the network and the exchanges. The latter situation is called overload and the problems that it may cause are of great concern to telephone companies.

The effect of overload can be disastrous. In the spring of 1988 a TV call-in show caused a total breakdown of the Dutch telephone network for one and a half hours. A similar situation occurred after the 1989 earthquake that hit Northern California. The Bay Area telephone network almost broke down, not because of earthquake damage, but because of an overload due to incoming calls. Since a considerable amount of revenue may be lost during overload, it is of great interest for telephone companies to prevent the occurrence of such situations.

Current research in communication networks
Overload control of telephone exchanges is just one of the current research topics in communication networks; more are likely to emerge with the advent of new electronics technologies and the introduction of the *Integrated Services Digital Network* (ISDN). Among current and future research topics are admission control, routing problems and load balancing.

SPC telephone exchanges
Most modern *Stored Program Controlled* (SPC) exchanges are powerful digital computers running a dedicated operating system that is specially designed to maintain telephone communication. Most of the resources in an SPC are expensive and thus scarce, so it is important to determine the capacity of resources needed under nominal operating conditions. Since the demand for service of the exchange fluctuates, this capacity is not likely to be sufficient for all situations, but it is an economically justifiable choice. It appears, however, that some control action is needed to guarantee a certain service level of the exchange in overload. Observations have revealed that exchanges under overload conditions exhibit a sharp decrease in the effective call handling capacity to unacceptably low levels. Therefore some form of overload control must be implemented.

Design of an SPC

Before a new exchange is installed, a study is made of the volume and type of traffic that the exchange must handle. An SPC is configured to make its call handling capacity large enough to deal with call requests under nominal load. Since traffic fluctuates, SPC's are usually dimensioned to use 80% of their design capacity when offered a (constant) nominal load. In this way enough room is left to cope with small short term fluctuations.

The capacity for nominal conditions is determined in the following way. Most telephone companies use nominal timing specifications to relate traffic volume to design capacity. In the United States' telephone network, for instance, one of the requirements is that the probability of *dial tone delay* - the time that elapses between the moment a subscriber lifts the receiver and the generation of a dial tone - exceeding 3 seconds is smaller than 0.01.

With these guidelines it is possible to determine the design capacity for an exchange. Under a slightly varying nominal load it is then guaranteed that all call requests can be handled and that delays are sufficiently small. In practice, however, one can experience large deviations from the nominal load. If the actual load exceeds the design capacity, then we speak of overload.

When the demand for service is larger than the design capacity several nominal specifications will no longer be met. Because of this violation a number of tasks for the processor will encounter long delays and hence will not complete successfully. The call request of which such a task forms part will not result in a connection, and all the work that the processor has done (for this call request) can be considered wasted. If no precautions are taken, this waste can lead to even longer delays and to more wastage of capacity. In the ultimate situation the exchange might end up in not completing any call requests at all. This phenomenon of a sharp increase of delays and decrease of the call handling capacity is called *congestion.* This behaviour means that some means of control is needed to prevent congestion of an SPC in an overloaded environment.

A queueing model

At CWI a research project, funded by the Dutch Technology Foundation (STW), was performed with the aim of developing design tools for overload control. A simple model that captures real life SPC behaviour is depicted in Figure 1. In the model requests for connections are represented as customers who require service from the server. The server models the processor of the exchange. When a subscriber lifts the receiver to dial a connection, we represent this in the model by the arrival of a customer. The service of a customer models all the work that has to be done to build the connection (dial tone generation, digit analysis, etc.). When the connection is established, the main part of the work for the processor is done, so in the model we then consider the service of the customer completed and the customer leaves the queue.

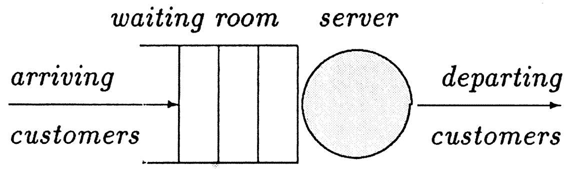


Figure 1: a queueing model without overload control.

At the moment when a customer arrives a deadline is set for his service completion. This represents the maximum time the subscriber is willing to wait for the build up of the connection. Expiration of the deadline corresponds to the moment the subscriber puts the receiver back on-hook. In the model, however, the customer will always wait until his service is completed, but if this happens when his deadline has already expired, we consider this a non-successful service completion. The processor time spent on this customer is wasted, since no connection and hence no revenue for the telephone company are made. In an actual exchange the same wastage can occur.

It is not difficult to predict what happens if

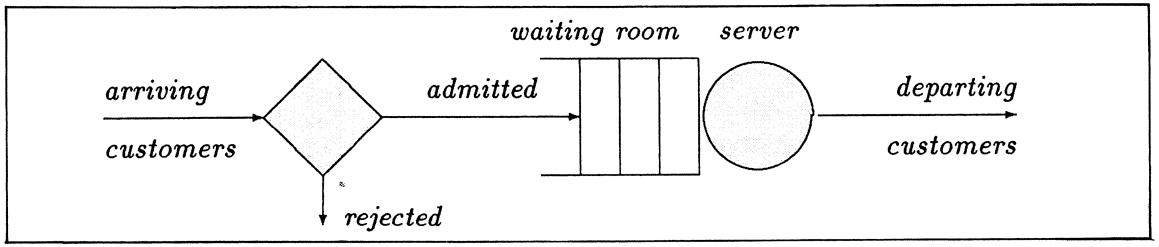


Figure 2: a queueing model with overload control.

there is a high demand for service. After a short while there will be a large number of customers waiting for service and most customers will not have their service completed in time. In practice this means that the processor is spending all of its capacity on useless work.

Control

The performance of this model can be improved significantly by introducing an admission control algorithm or policy as in Figure 2. The admission control allows the exchange to refuse to help new customers, by preventing them from entering the queue. In practice this can be implemented by denying a calling subscriber the dial tone and thus a connection. The problem now is how to operate the admission control.

From the point of view of both the operating telephone company and its users it is optimal to maximize the number of successful service completions. This quantity is usually referred to as *goodput,* the throughput of successful or 'good' customers. It is easy to see that we have to take care of the following trade-off. If the control algorithm rejects too many customers, the processor may be idling for a considerable fraction of the time that could be used for (successfully) serving customers. On the other hand, if too many customers are admitted then a large fraction of these customers will abandon their call request prematurely, thus reducing the goodput.

With optimal stochastic control theory we can show that the admission policy that maximizes goodput for a large class of cost criteria, is a so-called threshold policy. Effectively this means that new customers will be rejected, when the number of customers waiting equals the threshold value. If the threshold is not yet met, new customers are admitted. A striking advantage of a threshold admission policy is its simplicity, which ensures that it can be implemented in the SPC software with negligible effort. From a numerical point of view the computation of the right value for the threshold is no problem either.

In Figure 3 the effect of threshold policies is depicted. Note that if the threshold k is large, goodput will drop to zero when the offered load increases. It is remarkable that a threshold value of around 6 appears a good choice regardless of the offered load. We call this *robustness* of the optimal threshold with respect to the load and this is an invaluable property in practical applications. The service demand can fluctuate quite drastically and robustness means that it is not necessary to adjust the threshold with varying loads. Besides, it might appear extremely difficult to find the actual value of the load.

Elaborate model

A more elaborate model was also investigated as part of the CWI project. In the model, depicted in Figure 4, two arrival streams of customers represent call requests and operator tasks, respectively. Operator tasks are issued by the operator of the exchange and are not directly related to call request processing. They are necessary, however, to guarantee correct operation of the exchange, so part of the processor capacity has to be available at any time to perform these tasks.

In the model we consider admission control policies that admit or reject call requests and operator tasks with the objective to optimize goodput. In addition we want the algorithm to treat call requests and operator tasks in a

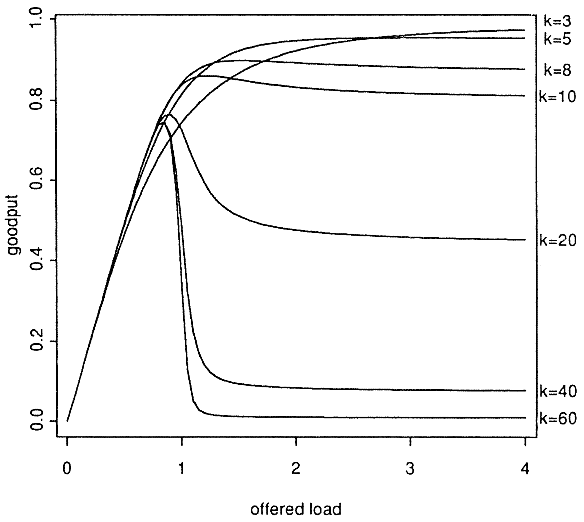


Figure 3: performance of a model without control; k = maximum number of calls to be admitted.

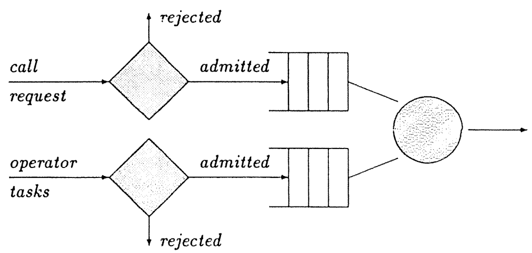
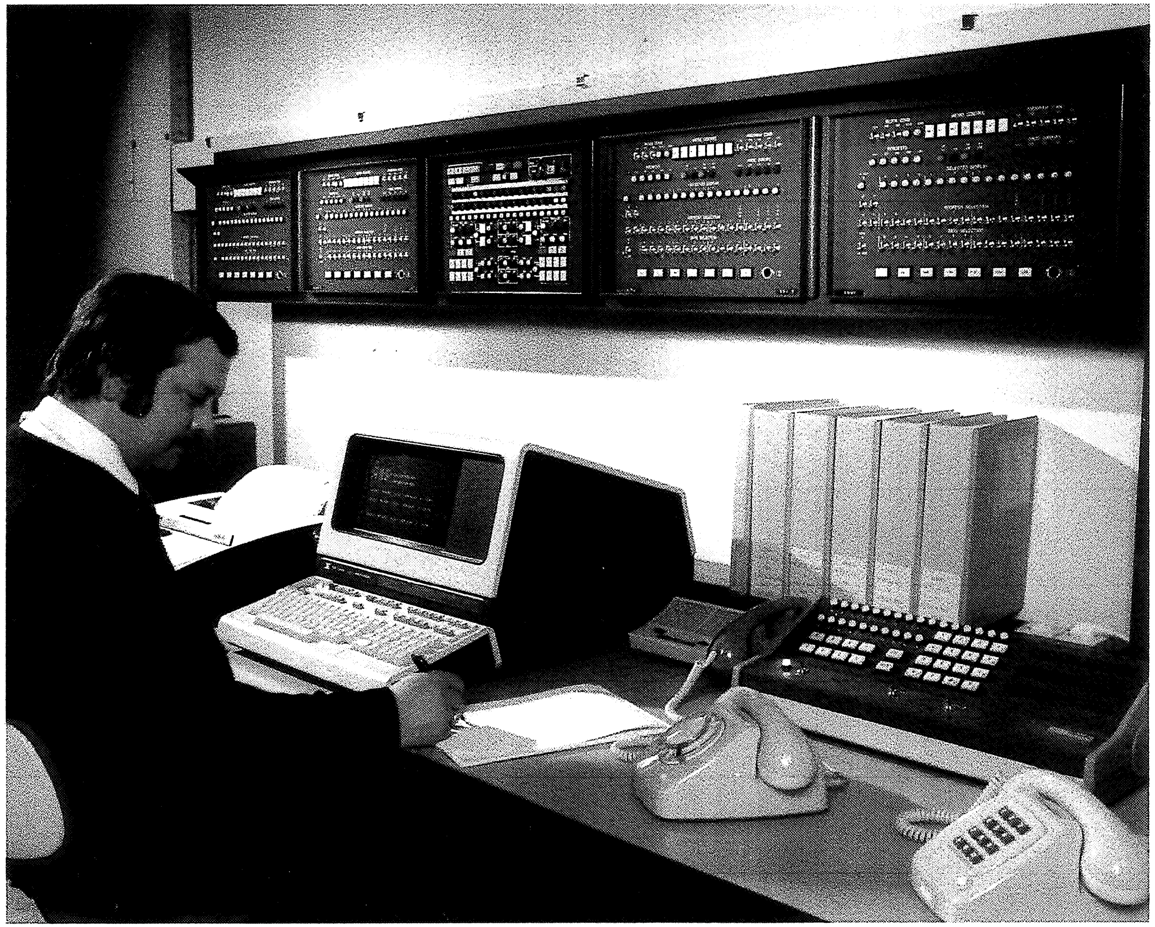


Figure 4: a queueing model for call request and operator task processing.



Modern telephone exchanges work with admission control. Without control, effective capacity during overload sharply decreases (see Fig.3). Taking into account the dynamics of the processor load and the stochastic character of the communication process, CWI has constructed effective control algorithms (research supported by the Technology Foundation STW).
Photo: Philips Telecommunication.

fair manner. The algorithm also has to be robust against service demand fluctuations. The class of policies we are considering are feedback control algorithms, which means that the decision of admission or rejection is based on information about the processor queue.

Several classes of feedback admission policies have been investigated. It appears that under small service demands *sharing policies* are to be preferred: the total sum or weighted sum of call requests and operator tasks must be below a threshold. In overload it is better to use a *partitioning policy:* separate thresholds are used for the different customer types.

PROJECTS

The following information is given for each project: a short description, the start-up year, research staff (project leader in italic) and cooperating institutions.

Combinatorial optimization and algorithmics
Combinatorial optimization and algorithmics is the mathematical investigation of problems and algorithms involving the arrangement, grouping, ordering or selection of discrete objects. The subjects are:

- Design and analysis of algorithms (1973);
- Polyhedral methods (1983);
- Multicommodity flows and VLSI-layout (1989);
- Computational geometry (1989);
- Parallel computations (1982);
- Multi-criteria machine scheduling problems (1985);
- Interactive planning methods (1983);
- Model and algorithm representation and manipulation (1988).

A. Schrijver, A.M.H. Gerards, J.A. Hoogeveen, B.J.B.M. Lageweg, J.K. Lenstra, S.L. van de Velde, H. Oosterhout, B. Veltman.

Univ. Rotterdam, Univ. Tilburg, Eötvös Lorand Univ. Budapest, MIT Cambridge, Univ. Augsburg, Univ. California Berkeley, Univ. Pennsylvania, Bell Communications Research, Morristown NJ, IBM Research, Yorktown Heights (NY), Univ. Grenoble, Univ. Pittsburgh, Univ. Waterloo, Univ. Eindhoven, Cornell Univ., Ithaca NY, Univ. Montréal, Univ. Amsterdam, Univ. Texas, Oxford Univ.

Analysis and control of information flows in networks
The project concerns the mathematical modeling, analysis and control of information flows in computer systems and telecommunication networks. The subjects are:

- Analysis of mathematical queueing models (1981);
- Performance analysis of communication systems (1983);
- Performance analysis of computer systems (1985);
- Reliability and availability of networks (1987).

O.J. Boxma, J. van den Berg, J.L. van den Berg, J.W. Cohen, F.A. van der Duyn Schouten, W.P. Groenendijk, P. Wartenhorst.

Univ. Rotterdam, Free Univ. Amsterdam, Univ. Tilburg, KSLA, PTT Research

Leidschendam, AT&T Bell Laboratories, IBM Forschungslaboratorium Zürich, IBM Tokyo Research Laboratory, INRIA, Univ. Tel-Aviv.

System and control theory
System and control theory aims at formulating and analyzing dynamical systems as models for dynamic phenomena, and solving control and prediction problems. The subjects are:

- Deterministic system theory (1984);
- Stochastic system theory (1978);
- Systems with a generalized state space (1988);
- Control of discrete event systems (1990);
- Control-theoretic computations for element models (1990).

J.H. van Schuppen, M. Hazewinkel (CWI, AM), M. Kuijper, J.M. Schumacher, P.R. de Waal (STW), J.W. van der Woude (Shell fellow).

Univ. Twente, Univ. Groningen, Philips Telecomm. Hilversum, Univ. California Berkeley, Univ. Gent, Univ. Padua.

Image analysis
This project is concerned with mathematical and statistical aspects of the analysis of digital images and related spatial data. The aims of the project are to apply probabilistic models and statistical techniques to obtain new algorithms and assess the performance of existing ones.

- Stochastic geometry (theory and simulation) (1988);
- Applied spatial statistics and stereology (1989);
- Bayesian and likelihood-based image analysis (1989);
- Mathematical morphology and discrete image transforms (1990);
- Software development (1989).

A.J. Baddeley, R.D. Gill, R.A. Moyeed, M.N.M. van Lieshout, R. van der Horst (CWI-STO), B. Lisser (CWI-STO).

Free Univ. Amsterdam, Univ. Amsterdam, Univ. Delft, Univ. Leiden, CSIRO Australia, ITI-TNO, Univ. Aarhus, Bergakademie Freiberg.

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. As well as fundamental research, applications are considered, especially in consultation, cooperative projects and STW projects. The subjects are:

- Stochastic processes (1981);
- Semiparametric inference for filtered experiments (1988);
- Asymptotic methods and resampling techniques (1984);
- Applied statistics and consultation (1990).

R. Helmers, H.C.P. Berbee, J. van den Berg, K.O. Dzhaparidze, R.D. Gill, L.F.M. de Haan, A.L.M. Dekkers, D.M. Bakker, M.C.J. van Pul, R. van der Horst (CWI-STO).

Univ. Delft, Courant Inst., New York Univ., Cornell Univ., Steklov Math. Inst., Computing Centre, Univ. Helsinki, Univ. Pierre et Marie Curie, Limburg Univ. Centre (Belgium), Charles Univ. (Czechoslovakia), TU Dresden, Ministry of Public Works (RWS), The Royal Dutch Meteorological Inst. (KNMI), RIVM, Central Bureau of Statistics (CBS), INRIA Rocquencourt, Univ. Tbilisi.

Department of Numerical Mathematics

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

E.D. de Goede	R.R.P. van Nooyen	*programmers*:
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	*trainees*:
J. Mooiman		H. Boenders
		A. Sellink

ADAPTIVE GRID TECHNIQUES IN THE METHOD-OF-LINES

Introduction

Mathematical modelling of scientific and engineering problems frequently leads to time-dependent partial differential equations (PDEs). These equations normally represent physical laws, like conservation of mass, momentum or energy as they arise, e.g., in fluid and heat flow problems. For most realistic real life problems, these laws give rise to PDEs which are too complicated to solve by hand, in closed form, and one must therefore resort to numerical methods. As computers become more and more powerful, there is an increasing demand for advanced numerical methods for solving these complicated PDE problems. At CWI the numerical solution of evolutionary PDE problems is therefore an important research theme. Currently, much attention is devoted to the development of adaptive grid techniques to be used in combination with the so-called method-of-lines approach.

Method-of-lines

The primary idea of the method-of-lines approach is to extend numerical integration methods for time-dependent ordinary differential equations (ODEs) to PDEs and, most importantly, to exploit the sophisticated software developed in the ODE field. We note, in particular, the high state-of-the-art reached in software for the difficult 'stiff' ODEs (the solution of a set of stiff equations consists of components slowly and rapidly varying in time). The application of ODE methods is natural since the discretization of time-dependent PDEs commonly leads to an ODE system. This system can be huge as it emanates from discretizing the spatial partial derivatives on a grid covering the spatial domain of the PDE, mostly by finite-difference or finite-element type methods. This spatial discretization converts the PDE into this, frequently stiff, ODE system which is continuous in time and lives component-wise on 'lines in the temporal direction'. These lines are located at the points of the space grid. Along these lines the problem is then numerically integrated in time with a numerical ODE method, thus explaining the name method-of-lines. Very often this is accomplished by using an existing, well-developed stiff ODE code.

Numerical software packages

In fact, one of the main merits of the method-of-lines approach is that it has given important impetus to numerical software development in the field of PDEs. User-oriented, reliable software packages are available now for solving routinely wide classes of one-space (1D) dimensional problems, while similar packages are on the way for 2D and even 3D problem classes. The user of such a package is merely asked to provide the mathematical definition of his PDE problem, say by means of a FORTRAN routine, and to provide some numerical control parameters. The spatial discretization and numerical

$$\sum_{k=0}^{NPDE} C_{jk}(x, t, \underline{u}) \frac{\partial u_k}{\partial t} = \frac{\partial}{\partial x} X_j(x, t, \underline{u}, \frac{\partial \underline{u}}{\partial x}) + S_j(x, t, \underline{u}, \frac{\partial \underline{u}}{\partial x}) \quad \text{for } j = 1, \ldots, NPDE.$$

This formula represents the master form for the problem class of PDE systems that can be solved with the 1D moving-grid method implemented in the SPRINT package. This master form comprises a large variety of interesting applications. We have used the package for solving problems from combustion theory and chemical kinetics, porous media, biomathematics, etc.

integration are then carried out fully automatically, saving much human effort. Hence, for modelling purposes, these method-of-lines based packages are becoming increasingly popular. An example of such a package is SPRINT (Software for PRoblems IN Time), developed at the Shell research laboratory at Thornton, UK, and the University of Leeds. The main workhorse of SPRINT is the efficient Gear method for stiff ODEs.

Adaptive grid methods

Method-of-lines schemes are very suitable to integrate PDEs on fixed space grids, defined a priori for the whole interval of physical time. However, in applications where large changes in spatial activity can occur, like reaction fronts in combustion and steep fronts in flows through porous media, this a priori chosen fixed space grid can easily be chosen too coarse to represent the solution on the grid sufficiently accurate. The reason is that there is not always prior knowledge how thin or steep the front will be, or even at which particular point of time a front will emerge. To give an example, in heat flow problems encountered in modelling combustion processes in chemical mixtures, the temperature can show a very diverse behaviour. A notorious situation is encountered in a so-called hot spot problem. In such a problem heat is generated at a particular spot in the mixture, first causing the temperature to increase rather gradually, which is then followed by a very sudden ignition of the mixture at this spot. This ignition causes the temperature to rapidly increase near the spot and normally generates a thin reaction-temperature front in the mixture for later times.

A standard option of modern method-of-lines packages is to automatically adapt the step sizes in the temporal direction to the degree of activity in the solution. However, when working with a fixed spatial grid, the danger of insufficient solution. representation can only be overcome by choosing a very fine grid for the whole interval of time. This, unfortunately, can result in excessive computational costs. To give an example, integrations with thousands to millions of ODE components form no exception.

The idea of adaptivity in space can be employed to adequately resolve the local, fine-scale phenomena at reasonable computational costs. Adaptive grid methods compute numerical solutions on space grids which are dynamically adapted to the local solution at hand, by some form of local grid refinement. Of importance is that this local refinement takes place without user intervention. By a suitable local adaptation of the grid, it is often possible to work with considerably less grid points and therefore with less computational effort, resulting in faster and even more accurate computations.

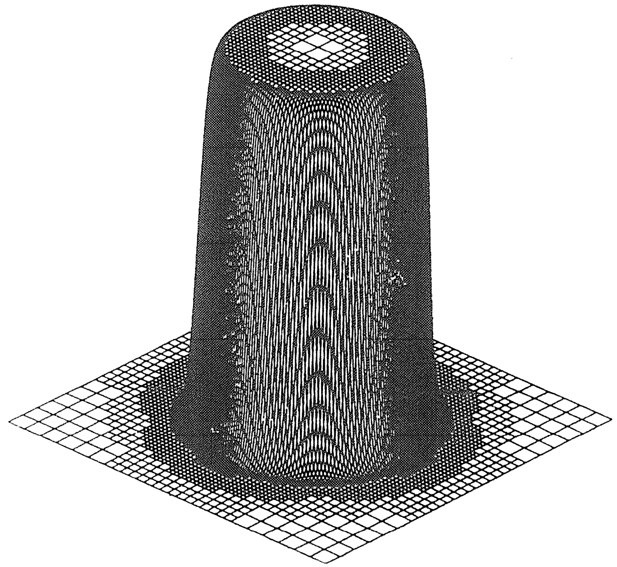
Research at CWI

For evolutionary PDE problems two main categories of adaptive grid methods can be distinguished. In the first category the grid moves in a continuous way, like in classical Lagrangian methods, while the discretization of the PDE and the grid selection algorithm are intrinsically coupled. Using some transformation of variables, the spatial grid points are defined as dependent variables of the independent variable time. The transformation is then taken into account by adding grid equation(s) to the Lagrangian PDE problem, the choice of which determines the transformation. The resulting extended system is then solved, using again a method-of-lines package.

In the second category of methods the space grid is adapted only at discrete times and no intrinsic coupling exists between the discretization of the PDE and the grid selection. Mathematically, the main difference between the two is that in the first category one attempts to solve, by a coordinate transformation, a problem with significantly less activity in both the spatial and temporal direction, and thus easier to solve numerically, while in the second category merely spatial activity is taken into account. During one or more time steps with the integration method, the grid remains in position here. In literature this type of grid adaptivity is commonly referred to as static (in time) regridding, whereas the first type is called dynamic (in time) regridding.

For general use, even in the well-ordered 1D-case, the dynamic regridding methods have proven to be surprisingly difficult. The difficulty arises from numerically solving the grid motion governing grid equations in a reliable way. But there is also considerable controversy concerning the many possibilities of transformation and implementation, even though only a few basic grid selection principles are around. At CWI two such principles have been studied in a joint project with the Shell research laboratory in Amsterdam (KSLA) and with financial support from the Dutch Technology Foundation STW. For 1D and 2D problems we have investigated methods based on moving-finite-elements, which underly the principle of residual minimization in the Galerkin sense. Furthermore, specifically for 1D problems, we have investigated methods based on moving-finite-differences underlying the principle of spatial equidistribution of a characteristic solution functional, such as arclength or curvature. We have successfully developed a 1D moving-grid method based on this equidistribution principle. This method has now been implemented in the SPRINT package and is applicable to a wide class of nonlinear PDEs.

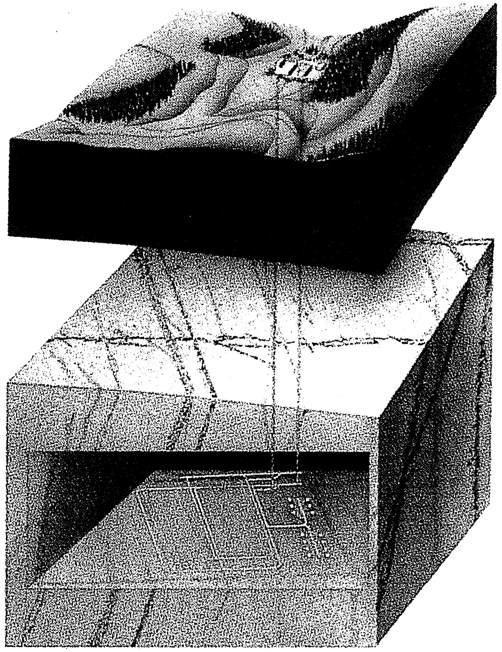
The advantage of the principle of static-regridding is that for a considerable part it is dimension free. One may as well develop such methods for 1D, 2D and 3D problems, using similar mathematical ideas concerning decisions on when and where refinement in the spatial domain of the PDE is needed. Our current research on static methods concentrates on what is commonly called local-uniform-grid-refinement (LUGR). In 1989 and 1990 we have developed a mathematical framework for LUGR methods, including convergence analysis, and built research codes for 2D problem classes. The considerable software effort here is due to the need of developing an efficient data structure. Our efforts aim at developing user-oriented LUGR codes which can be used to advantage for modelling purposes, as easily as existing single-grid method-of-lines packages.



Circular wave front computed with the LUGR code developed at CWI. The displayed grid shows four refinement levels.

Applications: mathematics and the environment

Generation of electricity by nuclear reactors gives rise to radioactive waste which must be disposed of safely. Some wastes contain only a low concentration of radioactive elements that decay quickly. Other wastes are highly



Schematic representation of deep disposal of high-level waste. Knowledge of groundwater movement and modelling of potential radionuclide transport in the geosphere will be required to evaluate safety.
Credit: NAGRA.

Mathematical formulation of a model for radionuclide transport in the geosphere.

(From 'The International INTRAVAL Project', OECD Paris.)

PROCESSES MODELLED IN THE GEOSPHERE

$$\underset{a}{\frac{\partial C_i}{\partial t}} = \underset{b}{-V\frac{\partial C_i}{\partial x}} + \underset{c}{D_L\frac{\partial^2 C_i}{\partial x^2}} \underset{d1}{- \lambda_i C_i} + \underset{d2}{\lambda_{i-1}C_{i-1}} + \underset{e}{D_e a\left.\frac{\partial C_i}{\partial z}\right|_{z=0}} \underset{f}{- \frac{\partial S_i}{\partial t}}$$

a) **The rate of change of the concentration of radionuclide i in the flowing liquid phase is dependent on the following processes:**

b) **Advection, which is governed by the Darcy velocity V; x is the distance from the near field-geosphere interface.**

c) **Dispersion-Diffusion, is governed by the dispersion coefficient D_L which is dependent on the interstitial water velocity. If the water velocity is 0, only diffusion of the radionuclides take place.**

d1, d2) **Radioactive decay chains take into account the radioactive decay of the nuclide i, and the formation of nuclide i from radioactive decay of the parent nuclide i-1. These terms are governed by the two decay constants λ_i and λ_{i-1}.**

e) **Matrix diffusion, is governed by the effective diffusivity, D_e, in the stagnant water in microfissures and pores in the rock matrix; a is the area of the surface of the rock matrix in contact with the flowing water per volume of flowing water and z is the distance from that surface.**

f) **Interaction with solid phase. This term takes into account sorption and desorption phenomena on the surface of the rock in contact with the flowing water. S_i represents the concentration of radionuclide i on the rock surface.**

radioactive and contain long-lived radioactive elements. Environmental protection demands the most advanced treatment and disposal techniques for these long-lived wastes, hence radioactive waste management programmes in OECD countries cover a wide range of activities. One such activity is INTRAVAL, an international project concerned with the use of mathematical models for predicting the potential transport of radioactive substances in the geosphere. Such models are used to help assess the long-term safety of radioactive waste disposal systems. Twenty-two organizations from twelve OECD countries participate in INTRAVAL. The main Dutch organization involved is our National Institute of Public Health and Environmental Hygiene (RIVM). In 1989 cooperation started between CWI and RIVM on numerical modelling in connection with the OECD project INTRAVAL.

Many types of geological formations show favourable characteristics for long-term isolation of radioactive wastes. Possible sites for The Netherlands, and Germany, are considered to be salt formations deep underground. In the event of escape of radioactive particles from such a repository, the most probable mechanism for their release to the biosphere is the transport via groundwater. Thus, safety prediction on deep disposal of radioactive waste in salt formations requires knowledge of groundwater movements near these salt formations and transport of particles with the groundwater. The mathematical equations which model such phenomena are so-called porous media equations. These are coupled, nonlinear time-dependent PDEs which, due their complexity, require advanced numerical methods for their solution.

The cooperation between CWI and RIVM is directed to developing user-oriented, accurate and efficient numerical methods and software for the specific porous media models encountered here. Characteristic for these models is that in a high salt concentration situation, e.g. near salt domes, large concentration gradients also prevail. In other words, the physical quantities to be computed - e.g. velocities, pressure, concentrations and temperature - will show a strong temporal and spatial activity, which directs us to consider the use of adaptive grid methods. Also of great importance are long time simulations, due to the low decay rate of the radioactive waste. Successful numerical 1D simulations, using the SPRINT package with the CWI moving-grid module, have already been carried out. However, two- and three-dimensional simulations are required in order to provide more definite conclusions. These are subject of further investigation.

PROJECTS

The following information is given for each project: a short description, the start-up year, research staff (project leader in italic) and cooperating institutions.

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. The subjects are:

- Stability and convergence (1978);
- Adaptive grid methods (STW) (1987);
- Static regridding methods (1989);
- 3D Shallow water equations (RWS) (1988);
- Boussinesq model (STW) (1988);
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P.J. van der Houwen, J.G. Verwer, W.H. Hundsdorfer, J. Mooiman, B.P. Sommeijer, J.G. Blom, E.D. de Goede, R.A. Trompert, P.A. Zegeling, Nguyen huu Cong.

Shell Research Amsterdam, Univ. Valladolid, Univ. Halle, Univ. Delft, Univ. Trieste, Univ. Liverpool, Hydrodynamic, Univ. Dundee, Univ. Leiden, Delft Hydraulics, Min. Public Works, RIVM.

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. The subjects are:

- Defect correction techniques and theoretical background (1978);
- Singularly perturbed boundary value problems (1978);
- Adaptive methods in fluid dynamics (BRITE/EURAM) (1987);
- Multigrid techniques for the solution of the Euler and compressible Navier-Stokes equations (1983);
- Reliable and efficient methods for semiconductor device simulation equations (1987).

P.W. Hemker, B. Koren, H.T.M. van der Maarel, J. Molenaar, R.R.P. van Nooyen (IOP), P. Wesseling (advisor), P.M. de Zeeuw (STW).

NLR, Fokker, Univ. Delft, Univ. Twente, Philips CFT Eindhoven, Univ. Michigan, GMD St. Augustin, INRIA Sophia-Antipolis, Techn. Univ. Hamburg-Harburg, NAG Downers Grove (USA), TU Denmark, Univ. Bari, Free Univ. Brussels, Von Karman Inst. Rhode St. Genese.

Numerical software

1. *Development of numerical software in the programming language Ada.* (1981)
2. *Vector and parallel algorithms.*
   Study of existing and development of new numerical algorithms in order to exploit the special features of vector and parallel computers. Development and optimization of numerical software for vector and parallel computers (in particular NEC SX-2, CRAY Y/MP4, Alliant FX/4). (1984)
3. *Computational number theory.*
   Study of how vector and parallel processors can be used in an optimal way for the solution of those number-theoretical problems where modern computers and numerical techniques can play a vital role. (1976)

J. Kok (1), *H.J.J. te Riele* (2,3), H.A. van der Vorst, E.D. de Goede, B.P. Sommeijer, W.M. Lioen, M. Louter-Nool, D.T. Winter, H. Boender, A. Sellink.

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Y. Toyama
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J.H.A. Warmerdam

COMPUTATIONAL LINGUISTICS ON THE BORDERLINE OF LOGIC, LANGUAGE AND COMPUTATION

What is computational linguistics?
Formal language theory, as a branch of computer science, is concerned with the study of formal languages such as *Pascal, Prolog, LISP,* and various other formalisms designed for human-computer interaction. It has become clear in the past two decades, however, that the tools developed for the analysis of formal languages can fruitfully be applied to the study of natural languages such as English, Russian or Dutch. Recently, a new branch of linguistics has emerged which uses insights from formal language theory, empirical linguistics, and logic, with the overall aim to implement natural language understanding systems on computers. This new discipline is called computational linguistics.
Below a schematic view is given of a typical system for human-computer interaction by means of natural language:

NL sentence	keyboard → input	language engine	translation →	*representation of meaning*	→ application →	*answer or action.*

A system which supports voice interaction would have extra components for speech recognition and generation. In the scheme above these components are omitted. If written input is assumed, a natural language engine for English should be able to recognize a substantial fragment of grammatical written English sentences, and generate their literal meanings; it should also be able to generate grammatical English expressions on the basis of symbolic inputs from an application program. In the scheme it is assumed that the answers given by the system are displayed as English expressions on the screen. The language engine should contain an extensive lexicon for English, a set of grammar rules for a considerable fragment of English, and a set of translation rules matching the grammar rules for translating the English expressions into unambiguous formal expressions that represent their meanings and that can be handled by the application. Typical applications are expert systems or knowledge bases.

Fragments of English

Probably the best way of forming an accurate picture of what is involved in natural language processing is to develop a toy natural language application. In this contribution we aim to give you a basic idea of some aspects of designing a system for natural language understanding by developing a very simple toy fragment of natural language. The method of fragments has been first advocated in the work of Richard Montague (ref. 4). Our fragment will be a lot simpler still than the simplest Montague grammar fragment. We want to be able to process sentences like the following:

(1) *A woman smiles.*
(2) *John loves a woman.*
(3) *If a woman smiles, John loves her.*

These examples may seem embarrassingly simple, but they are not quite as trivial as may appear at first sight. Example (3) exhibits a logical puzzle that has bothered natural language researchers for a long time. If one compares examples (1) and (2) with (3), then it appears that the first two can be understood as statements about a particular woman, while the third seems to express a general statement about women. This poses a genuine problem for natural language understanding, for the process of building meaning representations for sentences has to proceed in a *compositional* fashion: the meaning of a complex expression of natural language is built from the meanings of its components. This compositionality requirement is one of the cornerstones of the enterprise of building meaning representations in a systematic way.

As the example sentences indicate, indefinite noun phrases such as *a woman* seem to require a meaning representation as existential expressions when they appear in simple contexts and a representation as universal expressions when they appear in the antecedents of *if then* contexts. A first attempt at solving this problem would use ordinary predicate logic. Take example (4).

(4) *If a woman smiles, John smiles.*

Here one can translate the noun phrase *a woman* using an existential quantifier and still get the right meaning: $\exists x(Wx \wedge Sx) \rightarrow Sj$. To the logician it is clear immediately that this expresses a universal statement: the existential quantifier occurs in a negative position, so the translation is equivalent to $\forall x((Wx \wedge Sx) \rightarrow Sj)$. Unfortunately, this obsertion does not work for example (3). A straightforward translation of (3) in predicate logic would yield $\exists x(Wx \wedge Sx) \rightarrow Ljx$. But this cannot be correct, for the variable x in Ljx is left unbound.

A systematic solution of this unbound variable problem becomes possible if one translates to a representation language where variable binding proceeds in a dynamic fashion, as in imperative programming languages; such a move was first proposed by J. Barwise in 1987. To make this work one has to replace existential quantifiers with indeterministic instructions for storing values with specified properties in the memory locations associated with variables. So instead of $\exists x(Wx \wedge \cdots)$ one writes $\eta x: Wx; \cdots$, with the intended meaning: 'fill location x with (a representation of) an object satisfying W and proceed with the $\cdots$ processing'. The switch to dynamic interpretation will make it necessary to relate dynamic meaning representations to the old fashioned static representations that can be expressed in predicate logic, for example. This problem has been addressed in the research in natural language analysis at CWI (ref. 1).

What we will do in the remainder of this contribution is give a very rudimentary sketch of the syntactic processing of natural language by means of a tool called *categorial grammar*. We will then show how the syntactic analysis can be used to build meaning representations in a dynamic representation language. Finally, we will discuss the problem of relating the dynamic representations to static representations phrased in ordinary predicate logic.

Categorial grammar

A categorial grammar is a grammar combined with a lexicon in such a way that the lexical information comprises virtually all the information one needs for syntactic processing. These grammars are called categorial because they proceed by assigning *categories* to expressions. Simple categories such as S for 'sentence', CN for 'common noun' and IV for 'intransitive verb' are taken as basic.

For our fragment we have the following expressions in basic categories: *smiles:IV, man:CN* and *woman:CN*. Next, a proper name can be viewed as an expression which combines with an intransitive verb to its right to form a sentence; in categorial notation: S/IV. So for our fragment: *John:S/IV*. The indefinite article combines with a common noun to form a noun phrase; noun phrases, as we have seen, have category S/IV, so we have: $a:(S/IV)/CN$. Transitive verbs combine with noun phrases to form intransitive verbs, which gives: *loves* $:IV/(S/IV)$. Finally, the sentential operator *if* takes an antecedent sentence and forms an expression which combines with a consequent sentence to form a new sentence, which gives: *if* $:(S/S)/S$.

The basic strategy for putting categorial expressions together is very simple: put an expression of category CAT_1/CAT_2 in front of an expression of category CAT_2 to form a new expression of category CAT_1. Thus, putting *John* $:(S/IV)$ in front of *smiles* $:IV$ gives *John smiles: S*, and so on.

Of course, this grammar is too simple as it stands. For example, the pronoun *her* will have the same category as any other noun phrase, namely S/IV, and this would enable the derivation of *her smiles: S*. To remedy this, it is customary to enrich the categories with *feature information*. For instance, if one assumes that a noun phrase has features for case, gender, number and a coreference index, the category for *her* could look like (S/IV):[$-$*nom*, *f*, *sg*, 213], to indicate that its case is not nominative, its gender is feminine, its number is singular, and it has coreference index 213 (which means that it is intended to be linked to an antecedent which also has index 213). This information can be used to enrich the category of noun phrases to force agreement in case and number with an intransitive verb phrase, as follows: (S/IV:[*Case*, *Number*]): [*Case*, _, *Number*, _]. The upper case letters are used to indicate feature constraints; _ indicates that any value will do for the feature at that position. If an item of this category combines with an IV with given features for case and number, then these features should agree. Enriching the category of *walks* to *IV:[nom, sg]* now blocks the derivation of *her walks*. It is possible to encode very complex and detailed information in syntactic features. It should also be noted that the ways in which complex categories can be formed can be made much more sophisticated. In the next section we will see how a procedure for building meaning representations can be hooked to a categorial grammar.

Toy Categorial

John_i	(S/IV[Case,sg]):[Case,sg,m,i]
her_i	(S/IV:[-nom,sg]):[-nom,f,sg,i]
smiles	IV:[nom,sg]
loves	(IV:[nom,sg]/(S/IV)):[-nom, _, _, _]
man	CN:[sg,m]
woman	CN:[sg,f]
a_i	((S/IV):[_ ,sg,Gender,i]/CN:[sg,Gender]
if	(S/S)/S

Building meaning representations

If a categorial grammar is given, meaning representations for the expressions recognized by the grammar can be given using the tools of lambda abstraction. The semantic operation corresponding to the syntactic combination of an expression of category CAT_1/CAT_2 and one of category CAT_2 will be the functional application of a typed lambda expression corresponding to the functor expression to a typed lambda expression corresponding to the argument. The basic categories provide the clue for the types of the corresponding semantic operations: S expressions should translate as formulae, IV and CN expressions as one-place predicates. Thus, an appropriate translation for *woman* is $\lambda x.Wx$, which does indeed denote a one place predicate. Similarly for IV expressions: *smiles* can be translated as $\lambda x.Sx$. Expressions of category S/IV must be lambda expressions that can can take things like $\lambda x.Sx$ as arguments, so an appropriate translation for *John* would be $\lambda X.Xj$, where X is a variable for one-place predicates. Given that we want to translate *a woman* as $\eta x:Wx;\cdots$, an appropriate translation for this noun phrase is $\lambda Y.\eta x:Wx;Yx$, which means that a can be translated as $\lambda X \lambda Y.\eta x:Xx;Yx$, and so on. If one wants to use the noun phrase indices to establish links of pronouns to their antecedents, individual variables with the same index must be used in the translations. These considerations are all taken into account in the example grammar with semantic component on the next page.

Toy Categorial Grammar with Semantic Component

John_i	(S/IV[Case,sg]):[Case,sg,m,i]	$\lambda X.(\eta v_i: v_i = j; Xv_i)$
her_i	(S/IV:[-nom,sg]):[-nom,f,sg,i]	$\lambda X.Xv_i$
smiles	IV:[nom,sg]	$\lambda x.Sx$
loves	(IV:[nom,sg]/(S/IV):[-nom, _ , _ , _]	$\lambda \mathbf{X} \lambda x.\mathbf{X}(\lambda y.Lxy)$
man	CN:[sg,m]	$\lambda x.Mx$
woman	CN:[sg,f]	$\lambda x.Wx$
a_i	((S/IV):[_ ,sg,Gender,i]/CN:[sg,Gender]	$\lambda X \lambda Y.(\eta v_i: Xv_i; Yv_i)$
if	(S/S)/S	$\lambda p \lambda q.(p \Rightarrow q)$

Our fragment enables us to construct meaning representations for the example sentences we started out with. The representation for *John smiles* becomes $\lambda X.(\eta v_i: v_i = j; Xv_i)(\lambda x.Sx)$, which reduces in two steps to $\eta v_i: v_i = j; Sv_i$. The representation for *John loves a woman* is a fairly complex expression which reduces in several steps to $\eta v_i: v_i = j; \eta v_k: Wv_k; Lv_i v_k$. We have assumed that the indices of subject and object are different; in fact, a procedure for checking co-indexings should be invoked to rule out all co-indexings with clashes in the gender or number feature. The representation for *If a woman smiles, John loves her,* in the reading where the pronoun is linked to *a woman,* will, after several reductions, boil down to $(\eta v_i: (Wv_i; Sv_i) \Rightarrow \eta v_k: (v_k = j; Lv_{kv_i}))$. Our final problem is to make sense of this representation.

Axioms for dynamic interpretation

The dynamic interpretation strategy treats meaning representations for natural language as imperative programs. This entails that the tools for analysis of imperative programming languages can be put to use. In particular, an axiom system for dynamic interpretation can be given in terms of Hoare style pre- and postconditions of programs. Axioms are phrased in terms of existential and universal conditions, with forms $\langle\phi\rangle\pi\langle\psi\rangle$ and $\{\phi\}\pi\{\psi\}$. The statement $\{\phi\}\pi\{\psi\}$ expresses that all states in which ϕ holds have the property that if π is processed in this state, ψ will hold of all output states. The statement $\langle\phi\rangle\pi\{\psi\}$ expresses that all states in which ϕ holds have the property that if π is processed in this state, ψ will hold in at least one output state. We can find the static meaning of a representation program by checking the conditions under which it will terminate successfully. Some examples of the Hoare axioms involved are given below; the full details can be found in ref. 1.

Using the axiom system, the static meaning of the representation $(\eta v_i: (Wv_i; Sv_i) \Rightarrow \eta v_k: (v_k = j; Lv_k v_i))$ can be derived by calculating the weakest condition ϕ which guarantees successful termination. This turns out to be $\forall v_i(Wv_i \rightarrow (Sv_i \rightarrow \exists v_k(v_k = j \wedge Lv_k v_i)))$, and this is indeed an appropriate meaning representation for example sentence (3).

Conclusion

Natural language understanding research at CWI concentrates on theoretical issues and

Axioms for Dynamic Interpretation

$$\{R(t_1 \cdots t_n) \rightarrow \phi\}\ R(t_1 \cdots t_n)\{\phi\} \qquad \langle R(t_1 \cdots t_n) \wedge \phi\rangle\ R(t_1 \cdots t_n)\langle\phi\rangle.$$

$$\frac{\{\phi\}\pi_1\{\psi\} \quad \{\psi\}\pi_2\{\chi\}}{\{\phi\}\ (\pi_1;\ \pi_2)\ \{\chi\}.} \qquad \frac{\langle\phi\rangle\pi_1\langle\psi\rangle \quad \langle\psi\rangle\pi_2\langle\chi\rangle}{\langle\phi\rangle\ (\pi_1;\ \pi_2)\ \langle\chi\rangle.}$$

$$\frac{\langle\phi\rangle\pi_1\langle\psi\rangle \quad \{\psi\}\pi_2\{\bot\}.}{\{\phi \vee \chi\}(\pi_1 \Rightarrow \pi_2)\{\chi\}.} \qquad \frac{\{\phi\}\pi_1\{\psi\} \quad \langle\psi\rangle\pi_2\langle\top\rangle.}{\langle\phi \wedge \chi\rangle(\pi_1 \Rightarrow \pi_2)\langle\chi\rangle.}$$

$$\frac{\{\phi\}\pi\{\psi\}}{\{\forall x\phi\}\eta x : \pi\{\psi\}.} \qquad \frac{\langle\phi\rangle\pi\langle\psi\rangle}{\langle\exists x\phi\rangle\eta x : \pi\langle\psi\rangle.}$$

emphasises the use of tools from programming language analysis for the analysis of natural language. It is expected, however, that the insights thus gained will greatly facilitate the task of building practically useful natural language interfaces in the not too distant future.

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4. R. Montague (1973). *Formal Philosophy, Selected Papers of Richard Montague,* R. Thomason (ed.), Yale University Press, New Haven & London.

PROJECTS

The following information is given for each project: a short description, the start-up year, research staff (project leader in italic) and cooperating institutions.

Semantics
Research into the semantic aspects of parallel computation according to various programming styles (imperative, applicative, logic, object-oriented); also foundational topics related to semantic modelling. (1984)

J.W. de Bakker, J.M. Jacquet, J.N. Kok, J.J.M.M. Rutten, J.H.A. Warmerdam.

ESPRIT BRA-partners, REX-partners, Free Univ. Amsterdam, Univ. Utrecht, Univ. Rotterdam.

Concurrency and real time systems
Research concerning process algebra, including real time and probabilistic extensions. Specification languages, system development methodology. 1990 (under a different title since 1982)

J.C.M. Baeten, J.A. Bergstra, J.F. Groote, A.S. Klusener, H.P. Korver, A. Ponse.

ESPRIT-partners, RACE-partners, Univ. Amsterdam, Univ. Utrecht, Philips Research Eindhoven, PTT Research Leidschendam, SERC Utrecht, SUNY at Stony Brook.

Extensible programming environments
Algebraic specification of programming environments, incremental development of language definitions, implementation of algebraic specifications. (1982)

P. Klint, A. van Deursen, J. Heering, E.A. van der Meulen, J. Rekers.

ESPRIT-partners, Univ. Amsterdam, Univ. Nijmegen, Univ. Utrecht, SERC Utrecht.

Algebraic and syntactic methods
Foundational research centering around term rewriting systems, with an emphasis on algebraic and syntactic methods; foundational research in process algebra. (1989)

J.W. Klop, M. Bezem, A. Middeldorp, Y. Toyama, F.-J. de Vries.

ESPRIT BRA-partners, Free Univ. Amsterdam, Univ. Amsterdam, Univ. Utrecht, Univ. Nijmegen, Univ. Leiden.

Logic and language
Research concerning logic programming, deductive and knowledge-based database systems, non-monotonic reasoning and natural language processing.

K.R. Apt, R.N. Bol, D.J.N. van Eijck, M. Moortgat, G. Morrill, C. Palamidessi.

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AMOEBA: A DISTRIBUTED SYSTEM

Introduction

A major trend in computer hardware is the use of networks to link different computers together. Current Local Area Networks (LANs, networks installed in a single building or in a small group of connected buildings) can transfer data at rates as high as 10 Megabits/second, and the next generation of (fiberglass-based) networks will improve upon this capacity by one or two orders of magnitude. Wide-area networks (those that span countries or the world) still use much lower transfer rates, but are likewise increasing their capacity in the near future.

The implications of networks for software and for users of computers are enormous. The possibilities are obvious: sharing of information, resources and peripheral devices, increasing the speed of a computation by distributing it over several cooperating computers, and improving accessibility by providing multiple instances of essential services.

The possibilities for cost reduction are also clear: essential but expensive or noisy devices like tape drives and printers can be made accessible over the network, so not every computer needs to be equipped with its own.

However, networks also come with new problems. Some important classes of problems articulated by the advent of networks are:

- heterogeneity: not all computers on the net need be of the same make and model, run the same software, or use the same set of naming conventions, data formats and protocols;
- failure modes: distributed applications can fail in new ways, e.g., parts may fail independently, or be temporarily be disconnected from each other by network failures *(partitions)*;
- reliability and accessibility: 'you know that you are using a distributed system when the failure of a computer down the hallway (which you have never heard of) prevents you from getting work done';
- security: a network is only as secure as the least well protected machine connected to it.

The field of distributed (operating) systems tries to exploit the possibilities of networks and solve its problems.

The Amoeba project

Research into distributed systems at CWI was concentrated for some six years in the Amoeba project. This project originated at the Free University of Amsterdam, and was a joint effort between CWI and the Free University from 1984 to 1990. The concrete result of this research is the construction of the Amoeba distributed operating system [ref.1].

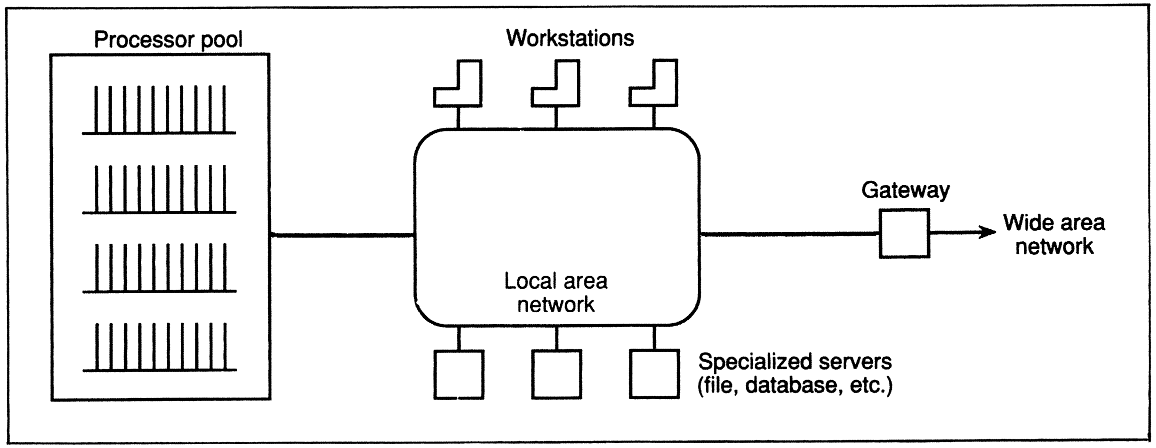
Amoeba is designed to exploit the power of LANs and microprocessor-based hardware - exactly the kind of hardware which is also used by the UNIX operating system. Amoeba runs on the *bare hardware,* and as such is a complete replacement for a vendor-supplied operating system. It therefore does not suffer from the inefficiencies of 'layered' systems (built on top of UNIX), and indeed Amoeba has been measured to be the fastest distributed operating system in the world [ref.2].
Amoeba uses various new techniques for providing a very high degree of *transparency* as a mechanism for coping with the problems of heterogeneity. Transparency is intended to hide differences as much as possible. There are several kinds of transparency, e.g., *location* transparency (hiding the difference in access methods between local and remote objects), *name* transparency (hiding the differences between names for objects on different systems), and *architecture* transparency (hiding the differences between processor architectures).

An important mechanism to provide transparency is the use of Remote Procedure Call, or RPC, as a common mechanism for accessing local and remote objects [ref.3]. RPC is modeled after 'local procedure call', with subtle modifications to accommodate the different failure and data sharing semantics. For the purposes of RPC, processes take on the roles of *client* and *server* respectively, where the client is the one that makes the call ('requests a service'), and the server executes it ('provides a service'). RPC is implemented highly efficiently by the Amoeba kernel, which hides the differences between local communication (to a process on the same machine) and remote communication (to a different machine), and is responsible for finding a server given its 'name' (actually a 48-bit number). Because of the possibility of a server crash during the execution of the call, every remote procedure call returns an error status code. This error code can also be used by the server to indicate refusal to service the request, either because the request contained an error, or because of inaccessibility of a resource needed by the server.

Amoeba offers mechanisms for efficiently replicating objects or services, to provide just the right level of reliability and/or accessibility; for instance, source files entered by a user are replicated to guard against failure of the disk where they are stored, while temporary files used by a compiler are not replicated, therefore gaining overall compilation speed.

Security is addressed by Amoeba using cryptographic techniques based on hard-to-invert, or 'one-way' functions, and a special kind of network connector called an *F-box* [see inset]. In the absence of physical *F*-boxes, data encryption can be used.

Amoeba's processing model
The conventional model for a Local Area Network, used by most workstation vendors and also by some distributed systems research groups, is that of a network connecting servers and workstations, where all or most computation is done in the latter. In contrast, Amoeba's model assumes a pool of shared



Four components of the Amoeba architecture.

processors doing most of the computation, and separate 'lightweight' display stations connected to a screen and keyboard. The latter are full-function computers but needn't be very fast or big, as they are only used to run the software needed by the graphical (or textual) user interface (see Figure). One of the advantages is that the processor pool can be placed on racks in an airconditioned room and may share power supplies, have noisy fans, etc., while the display stations, which must sit on user's desks, can be silent. Another advantage is that the yearly question, given a limited budget, of which users' workstations must be replaced by more powerful ones, is supplanted by the easier-to-answer question of how many processors can be bought to add to the processor pool. To make this model effective, Amoeba uses a load-balancing algorithm which spreads the aggregate load on the system caused by all

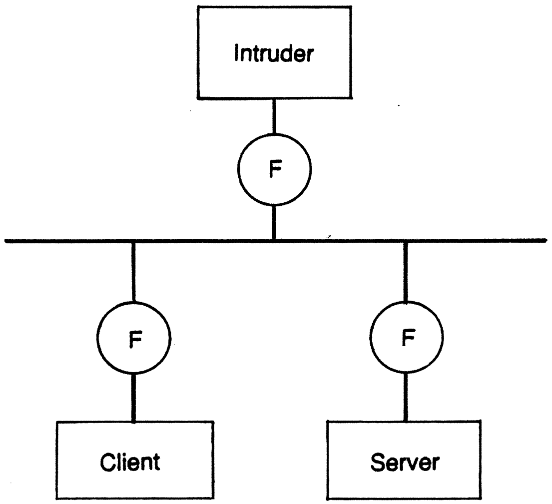
Security using one-way functions and F-boxes

All Amoeba services are identified by *ports*: 48-bit numbers chosen randomly from a large space. In order to tell the system that it is ready to implement a service, a server presents its port to the Amoeba kernel. Conversely, a client presents the service's port to the kernel if it wants to communicate with a server (using the RPC protocol).

As the number of services is much smaller than 2^{48} and ports are chosen at random, the port space is 'sparse': one is unlikely to guess a service's port, and exhaustive search (trying all possible combinations of ones and zeros) will take almost forever. Thus, a natural way of restricting access to a service is keeping its port secret except for those with the right to use it. Indeed, an Amoeba server accepts requests from any user knowing its port.

However, there is a flaw in the naive application of the scheme sketched above: every user of a service's port could impersonate the server, and thereby intercept service requests from other users, which might contain confidential data. This is especially a problem with public services like file servers, whose ports likely must be known to all users of a system. To prevent this type of fraud, a variation of the scheme is actually used.

This variation involves a *one-way function.* This is a function F from 48-bit numbers to 48-bit numbers, which scrambles the bits in such a fashion that it is hard to match the input with the output. Hence, given a port



Clients, servers, intruders, and F-boxes.

X, $F(X)$ is easy to compute, but given only $F(X)$, it is almost impossible to reconstruct the value of X, even though the function F itself is publicly known.

The server actually uses a private port or *get-port,* hereafter called G, which it really keeps secret; the users that are allowed to request its service are given a public port or *put-port,* called P. G and P are related by $P=F(G)$. With this scheme, users cannot impersonate the server: they only get to know P, from which it is not feasible to compute G, which is necessary to provide the service it identifies.

A different problem is posed by the possibility that an intruder places a direct 'tap' on the network, bypassing the Amoeba kernel. Such an intruder can impersonate a server without knowing its get-port G, by simply reading the client's request message from the network and injecting a correct-looking reply message into the net. (Knowledge of G is not required for the actual execution of a service, only to identify the service to the Amoeba kernel.)

This problem is solved by moving the computation of $F(G)$ into an intelligent network connector, the *F-box.* It is assumed that F-boxes cannot be tampered with and that the network cable itself is securely hidden in the walls of the building. As an alternative, a software implementation of F-boxes using data encryption is also possible.

The F-box will only let messages for a server through to a computer if that computer shows the value of G for that service to the F-box, so an intruder who can tamper with the computer or its operating system, but not with the network or with the F-box - a reasonable assumption - will have to know a service's get-port G before he can impersonate that service.

A similar scheme is used to prevent such intruders from reading replies destined for other users: clients must present a private port G' to the F-box before they can receive replies, and replies are tagged with with $P'=F(G')$. The port P' is transmitted to the server with the rest of the request. Again, the value G' is kept secret, and is only known to its user's workstation.

users together, evenly over the available pool processors.

Amoeba today and in the future

In 1990, CWI created or completed several major components of the system, such as the UNIX emulation, the RPC stub generator and a port of the *X* window system, as well as smaller components such as the load balancing server and a login server. Porting of the kernel software to new processor architectures was also done, in particular a port to the MIPS R2000 chip.

An interesting spin-off of the Amoeba project is an elegant interpreted programming language called Python. Originally created as a tool for system administration programming tasks, it became a complete object-oriented prototyping language of remarkable power. Python derives much of its power and elegance from experiences with the design and implementation of the language ABC in the project Computer Systems and Ergonomics in the same department.
Amoeba is being developed into a commercial product with the help of a Dutch software firm, ACE computing. Amoeba version 4.0 is to be released to the world in 1991.

The new Multimedia project starting at CWI in 1991 (see elsewhere in this Annual Report) will be using Amoeba as a basis for its research into distributed multimedia processing. To this end, Amoeba will be ported to the IRIS workstation of Silicon Graphics, Inc.

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1. SAPE J. MULLENDER, GUIDO VAN ROSSUM, ANDREW S. TANENBAUM, ROBBERT VAN RENESSE, HANS VAN STAVEREN (1990). *Amoeba: A Distributed Operating System for the 1990s.* IEEE Computer, Vol. 23, No. 5, May 1990, 44-53.
2. R. VAN RENESSE, H. VAN STAVEREN, A.S. TANENBAUM (1988). *Performance of the World's Fastest Distributed Operating System.* OSR, Vol. 22, No. 4, Oct. 1988, 25-34.
3. A.D. BIRRELL, B.J. NELSON (1984). *Implementing Remote Procedure Calls.* ACM Trans. Computer Systems, Vol. 2, No. 1, Feb. 1984, 39-59.

PROJECTS

The following information is given for each project: a short description, the start-up year, research staff (project leader in italic) and cooperating institutions.

Algorithms and complexity

The design and analysis of algorithms in distributed computing and VLSI. Fundamental studies and research in complexity theory. (1980)

P.M.B. Vitányi, E. Kranakis, J.T. Tromp.

Univ. Amsterdam, Univ. Utrecht, Univ. Rochester, MIT, Harvard, DEC-SRC, Univ. North Carolina at Chapell Hill, North-Eastern Univ., Boston Univ., Boston Coll., Technion, Patras Comp. Tech. Inst., Univ. Waterloo, Bell Labs, ENS, Univ. des Saarlandes, Moscow Univ., Yale Univ, Stanford Univ., Oxbridge Research, Dartmouth Coll.

Distributed systems

Research on performance, transparency, fault tolerance and scalability in distributed systems. (1984)

S.J. Mullender, H.G.P. Bosch, I.J.P. Elshoff, A.J. Jansen, A. Plomp, G. van Rossum, S. van der Zee.

Free Univ. Amsterdam, Univ. Twente, Univ. Amsterdam.

Computer systems and ergonomics
This project is concerned with the methodology of integration of functions and applications in computer systems in order to provide end-users with easily manageable tools. There are three subprojects:

- ABC. The aim of this project is the design, implementation and distribution of a simple, structured, interactive programming language, built in into an integrated environment and meeting the requirements of modern personal computing. (1975)
- Human-computer interfaces (Views). The design and pilot implementation of a direct-manipulation, open-architecture, WYSIWYG, computing environment, where consistency of user-interface is guaranteed across applications. (1988)

S. Pemberton, L.G. Barfield, E.D.G. Boeve, F. van Dijk, T.J.G. Krijnen, L.G.L.T. Meertens.

Minnesota Supercomputer Centre, TU München, Idaho Nat. Eng. Lab., Indiana Univ., Project GNU Univ. Utrecht, Univ. Groningen, Univ. Delft, Univ. Tilburg, Free Univ. Amsterdam, Univ. Twente.

Distributed adaptive information systems
Research on data models for adaptive information systems, programming languages for their applications, and their associated machine architectures; in particular the object-oriented approach for database modelling, the development and the evaluation of object-oriented database language concepts, and the development of software prototypes on (virtual) machines especially designed for an object-oriented programming environment. (1985)

M.L. Kersten, C.A. van den Berg, S. Shair-Ali, A.P.J.M. Siebes, C.J.E. Thieme, N.Th. Verbrugge, M.H. van der Voort.

Univ. Amsterdam, Univ. Twente, Philips Research Eindhoven, INRIA, Univ. Antwerp, ICL.

Constructive algorithmics
The development of concepts, notations, formalisms and methods, on a high level of abstraction, for deriving algorithms from a specification. The aims 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. (1977)

L.G.L.T. Meertens, M.M. Fokkinga, J.T. Jeuring, S. Pemberton, J.C.S.P. van der Woude.

Univ. Groningen, Univ. Nijmegen, Univ. Utrecht, Univ. Oxford.

Cryptology
All aspects of cryptology and information security are covered. Particular emphasis is given to the construction and analysis of cryptographic algorithms and protocols, practical implementations, and related complexity-theoretic investigations.

D. Chaum, C.J. van Antwerpen, J.N.E. Bos, M.J. Coster, M.W. van der Ham, E.J.L.J. van Heyst, A.G. Steenbeek (CWI-STO).

PTT Research Leidschendam, Univ. Eindhoven, Philips Crypto BV, Univ. Leiden, Aarhus Univ., Siemens AG, Cath. Univ. Leuven, Univ. Tel-Aviv, Univ. Karlsruhe.

Department of 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	*programmers*:
V.C.J. Disselkoen	H.J. Schouten	M.A. Guravage
W. Eshuis	D. Soede	R. van Liere
I. Herman	P. Spilling	
H.E. Klarenbosch	P.J. Veerkamp	*trainee*:
A.A.M. Kuijk	J. van der Vegt	I.Chr. Maurice

IIICAD

Introduction

Computer Aided Design (CAD) systems support a designer in performing a certain task, i.e. they help the designer to design. Ideally a CAD system is a designer's electronic workbench on which an artifact can be modeled. The designer communicates with the system using his own terminology. The designer's commands are interpreted by the user interface and translated into system commands. It shows the designer the current state of the design object and the results of the given commands. Moreover, the system allows the designer to test the artifact for strength, production costs, feasibility and so forth.

In order to achieve such a performance, knowledge about the design process and the design object must be embedded in the system. For example, when the design concerns a linear motion mechanism, the system needs some idea of what motion is and how such a mechanism can be established. During a design session the system interrogates the designer and tries to find a proper solution to the design problem. Throughout questioning and answering the design object description grows and becomes more precise.

The system described above can by far not be realized using the present technology. The current generation CAD tools are merely drawing systems allowing the designer to build a geometric representation of the design object. Improving the performance can only be achieved by thorough research on the design process, on the description of the design object and on the representation of knowledge in general. Applying techniques from artificial intelligence seems an obvious approach. However, these techniques must be adapted to the different nature of design, since problem solving in design is not simply a matter of applying a number of rules. At several stages of the design process the designer cannot justify why he takes a certain decision. He intuitively knows that it is the right one. For that reason, a successful completely automated design system can never be realized. The system must always let the designer direct the design process and assist him in doing so.

The IIICAD (Intelligent Integrated Interactive CAD) project partly funded by NFI (Nationale Faciliteit Informatica) has been conducted at CWI for more than four years now. The research was initiated by Paul ten Hagen and Tetsuo Tomiyama. Tomiyama served as a project leader for two years, after which he became associate professor at the University of Tokyo (UoT). From that time on, both CWI and UoT developed their own system, although in close cooperation. Researchers from CWI have visited the UoT and vice versa.

History of CAD

As computer graphics software and hardware grew increasingly sophisticated, it became apparent that one of its major applications would be computer aided design. Drawing has always been a labour intensive part of the design process, and the use of a computer for

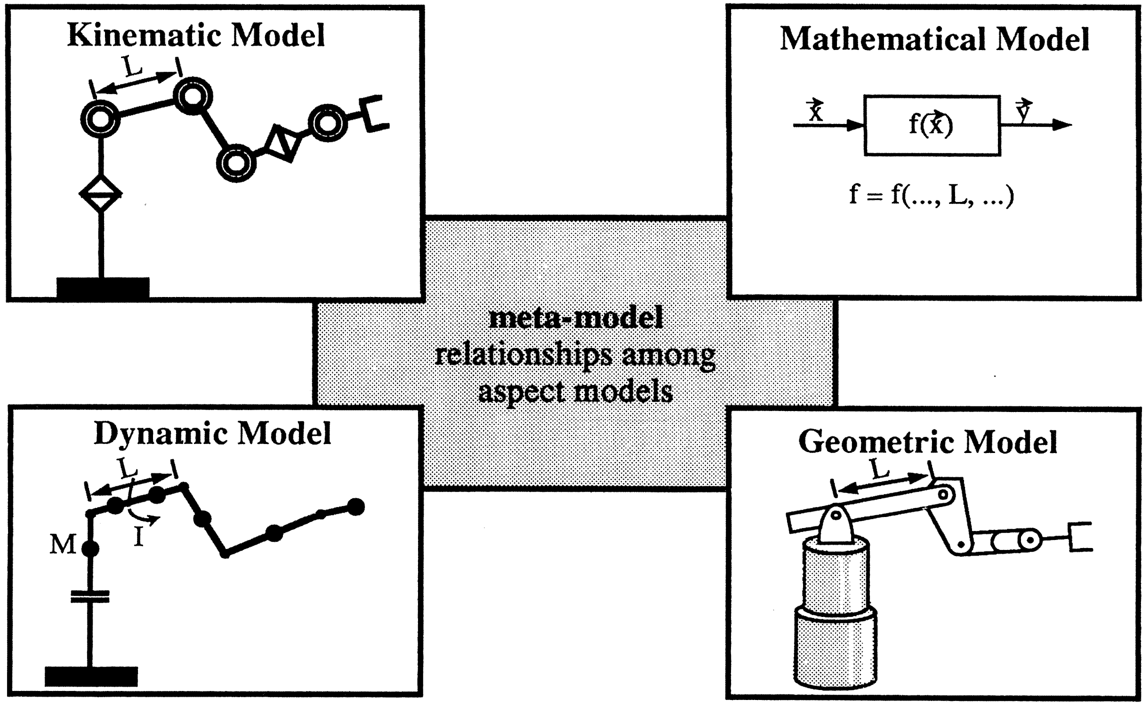


Figure 1: example of a future integrated CAD system which should contain a meta-model and several aspect models derived from it.

drawing would greatly contribute to the designer's accuracy and productivity. Research was focused on the production of high quality graphics, and a designer was given a tool to generate a drawing of the artifact. A next generation was equipped with a database where product data could be stored and retrieved.

Although CAD systems have become an essential tool for designers in various disciplines, it is also recognized that they still are inflexible and task dependent. Supporting a designer in performing the design task is the purpose of a CAD system. Certain routine tasks are delegated to the system. However, the majority of existing CAD systems are merely sophisticated workbenches for engineering drawing. As the application domain becomes more complex, designing becomes unmanageable with this type of support alone. Therefore, we need a more sophisticated system which can assist a designer in an *intelligent* way.

An important aspect of such a system is that the design object description is *not* based upon geometric information. The design object must be represented in terms of function and behaviour (in the sequel we call such a representation a *meta-model*). A geometric model can then be derived from this representation. Having only a geometric representation makes it difficult to derive dynamic properties such as the strength of a connection or kinematic properties like the range of a robot arm. The meta-model representation allows the system to reason about several aspects of the design object.

A product's specification needs to be verified during several stages of the design process. The design object representation must be tested for whether it meets the requirements. Tools were developed to determine its strength, its dynamic behaviour, its costs, and so forth. This can be achieved by a FEM (Finite Element Method) modeler, a dynamic modeler, a cost analysis module, etc. These were separate tools, forcing the CAD data to be transferred from one system to another, and back. This is an undesirable situation, and a future CAD system must therefore be an *integrated* system. It contains a central design object model (the meta-model), and it has several modelers incorporated in it, allowing the designer to analyze his product in several ways. We call a model derived from the meta-model an aspect model (Fig. 1 gives an example of some aspect models).

Furthermore, to obtain a good system it must be highly *interactive,* using the best human computer interaction techniques. Since the early CAD systems were mainly concerned with geometric information, the user interface was consequently focused on the manipulation of geometric properties. Particularly during conceptual design the user interface is of crucial importance. At this stage the most important decisions are made and the user interface must allow the designer to fully express his thoughts and intentions. The meta-model is then constructed on the basis of the dialogue between the designer and the system. After conceptual design, the meta-model is further extended during fundamental and detailed design, obtaining a more precise description of the design object.

Nowadays CAD systems hardly deserve the name computer aided design since they are merely computer aided draughting systems. In recent years, many people have started to use the name ICAD (Intelligent Computer Aided Design) rather than CAD. We have two good reasons for not doing so. First of all, ICAD is a registered trademark from ICAD Inc. which developed the ICAD system on a LISP/SYMBOLICS machine. It is a knowledge-based modeling environment that allows for symbolic representation of a product. Drawbacks of the system are that it is more a programming environment than a design system. Furthermore, the system lacks an underlying design process model. Last but not least the system is designed for very large companies which have several programmers to maintain the system. Secondly, the name IIICAD (Intelligent Integrated Interactive CAD) suits better than ICAD, because the system must not only be intelligent, but integrated and interactive as well.

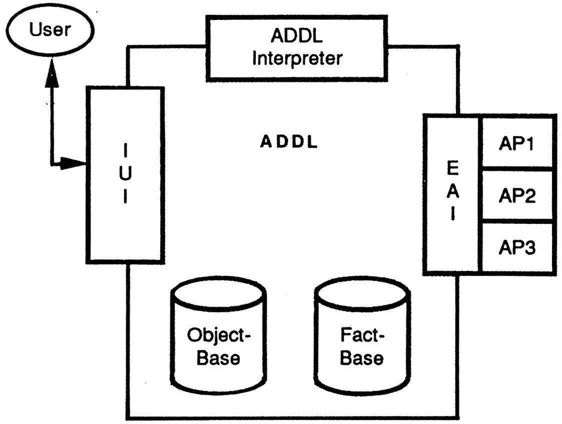
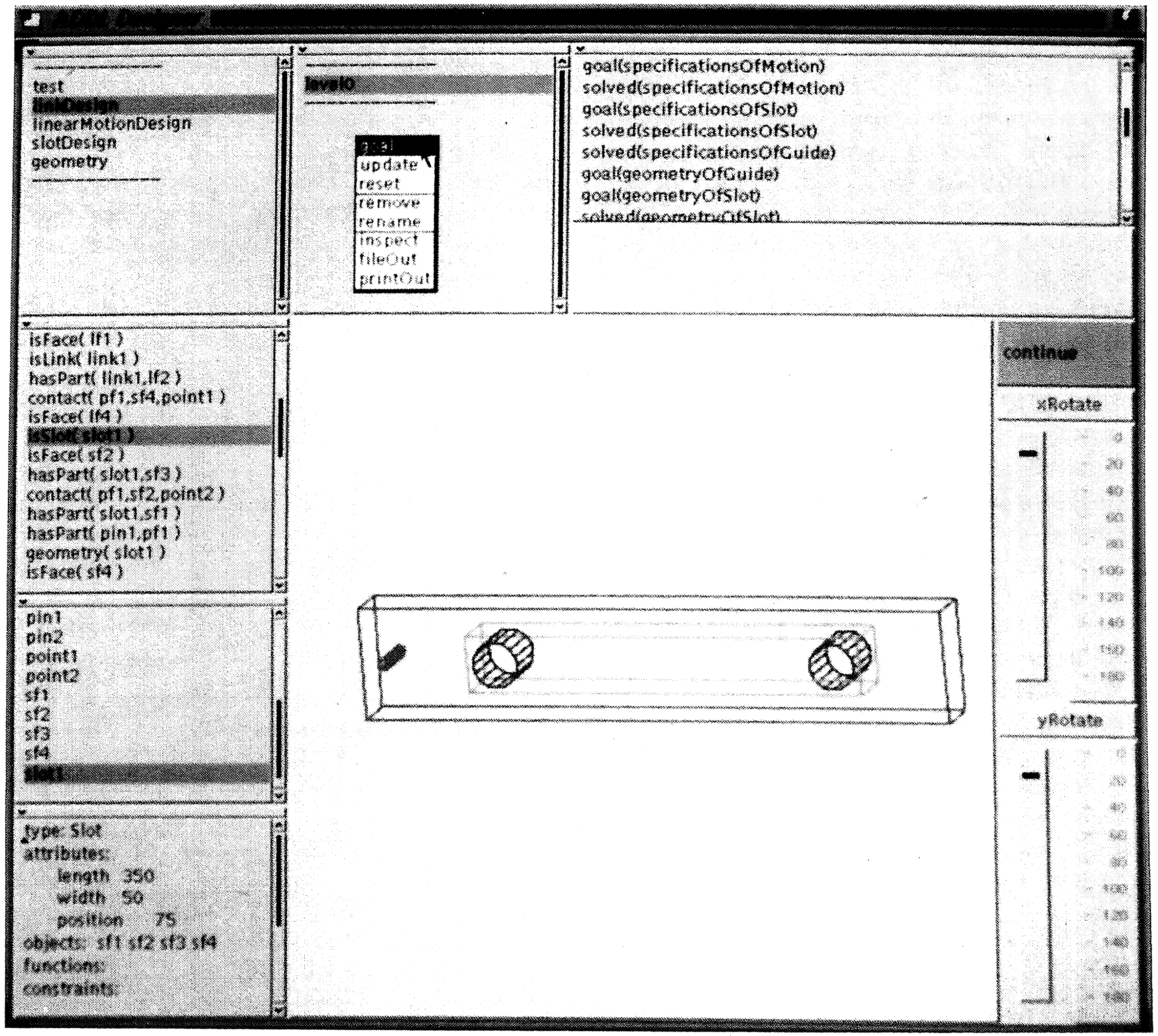


Figure 2: block diagram of the IIICAD architecture.

The IIICAD system

We want IIICAD to be a system based on expandable ideas and a framework where designers can exercise their faculties at large. We believe that the essential thing in designing is that the designer creates his own design environment and the IIICAD system must give him the freedom to do so. The system must understand the designer's commands and translate them to system tasks. Routine tasks must be automatically performed, but irregularities must be detected and reported so that the designer can react adequately upon them. The intended behaviour of the system requires the system to know about many different aspects of design. A lot of different kinds of knowledge must be embedded in the system in order to achieve the above functionality. The IIICAD architecture is composed of several components. Each of these has knowledge about and the responsibility of one or more of the charged tasks. The architecture is shown in a block diagram in Fig. 2.

The IIICAD system consists of i) an *ADDL interpreter,* ii) a *fact-base,* iii) an *object-base,* iv) an *'intelligent user interface'* and v) an *'external application interface'.* The kernel language of the system is ADDL (Artifact and Design Description Language), i.e. the several system components are either an integral part of the language (the object-base and the fact-base) or they have an interface to ADDL (the ADDL interpreter, the intelligent user interface, and the external application interface). More about ADDL will be presented in the next section.



An experimental version of the IIICAD system is currently operational at CWI. The design problems solved by the system are those concerned with a linear motion mechanism. At present, the focus of attention is on the representation of design knowledge (both object and process). The user interface and the geometric modelers are under construction. Currently, the interaction with the designer takes place through a question and answer dialogue. The state of the design object model is shown by a wire-frame modeler and by a 'view' on the fact-base and the object-base.

The fact-base contains all the facts currently known about the object to be designed. It is gradually extended as the design proceeds containing more and more detailed information about the design object. The fact-base constitutes the *meta-model.* The object-base has a dual function: i) it is used as a database for storing object descriptions to be applied as *prototypes* for components of the design object, and ii) it is used to keep the *instantiations* of these components. An instantiation is a copy of a prototype being manipulated during the design process. The object-base contains the data currently known about the design object.

The Intelligent User Interface (IUI) interacts with the designer. It translates tasks given by the designer to system commands. Furthermore it shows the designer the design tasks the system is currently involved in, and it reports the most recent state of the design object.

External applications are programs which provide the IIICAD system with information unavailable from one of the system components. An example of an external application is a cost analysis program which computes the manufacturing costs of the designed product. The information can be provided in the form of extra information about the design object description or it can be the evaluation of the design object in a certain context, e.g. FEM analysis. The External Application Interface (EAI) takes care of the contents of the flow of information between the IIICAD system and an external application. External applications can be written either in ADDL or in another programming language. In the former case, the EAI has an almost trivial job.

ADDL

The IIICAD system is a computer system under development at CWI which assists the designer in such a way that he can fully employ his creative skills. For the implementation of the system a new programming language has been developed: ADDL (Artifact and Design Description Language). It is based on object-oriented and logic programming concepts and one of its main features is a *scenario.* A scenario is a collection of rules representing the design knowledge that can be applied at a certain state of the design object. There are two types of scenarios in ADDL: i) *Action level* scenarios direct the design process. They reason about the design process, and determine (in dialogue with the designer) what design step to take next. *Action level* scenarios state design goals. ii) *Object level* scenarios extend the design object description. They reason about the design object, and add (in dialogue with the designer) new information.

The ADDL meta-model represents a qualitative description of the design object, i.e. it describes the design object in terms of function and behaviour. The fact-base, which consists of first order propositions, stores the meta-model. The propositions describe relationships among objects. The objects are stored in the object-base. An ADDL object is a uniform data-structure describing all possible components of the design object. An object is created by making a copy of a prototype object used as a template. It consists of a number of attributes, such as length, height and width, and a number of operations, such as volume, intersection and surface-area.

PROJECTS

The following information is given for each project: a short description, the start-up year, research staff (project leader in italic) and cooperating institutions.

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. (1980)

A.A.M. Kuijk, I. Herman, M. Bakker (CWI-STO), E.H. Blake (STW), F.J. Burger (CWI-STO), V.C.J. Disselkoen (STW), M.A. Guravage (STW), B.P. Rouwhorst (CWI-STO).

PTL Groningen, Philips, Univ. Twente, ISO-working group TC97/SC24, Dataflow Technology Nederland BV, Parallel Computing, GMD, INRIA Paris, Univ. Tübingen, Univ. East Anglia.

User interfaces

This project focusses on systems using graphical information. The user interface for these systems must support the construction, manipulation and interpretation of pictures. For the construction and manipulation of pictures by users a picture editor will be developed, while for the interpretation of pictures by the computer the construction process and associated semantic information will be used.

M.M. de Ruiter, *C.L. Blom*, P.J.W. ten Hagen, J. van der Vegt.

Univ. Nijmegen, Univ. Amsterdam, GMD St. Augustin.

Dialogue environments

• Dialogue programming. (1983)
The project is aimed at the development of a complete programming method for interactive dialogues. Currently a prototype system (DICE) exists which is being applied to a number of test applications. The experimental system has revealed a further set of fundamental problems which will be addressed in the next version. This will allow us to widen the scope of application to machine-machine dialogues and simplify the embedding in a variety of general purpose programming languages. Previous results concerning methodology of graphical interaction and window management will in the next few years form the basis of a new generation of international graphics standards.

P.J.W. ten Hagen, H.J. Schouten, R. van Liere, D. Soede (CWI-STO).

PTL Groningen, Univ. Twente, Philips CAD Centre, TNO, Océ, Philips, Univ. Amsterdam, Techn. Hochschule Darmstadt, Univ. Tokyo, GMD, Rutherford Labs, Univ. Southern California.

• User controlled systems. (1987)
User controlled systems are information systems for which all tasks are command driven. Meta-level commands allow the definition of new tasks. The task oriented architecture requires a high degree of integration among program libraries and databases. In addition this task oriented approach must bring about comprehensible user interfaces for very complex systems, such as CIM systems (Computer Integrated Manufacturing).

W. Eshuis, D. Soede (CWI-STO), P. Spilling.

PTL Groningen, Univ. Twente, Delft Hydraulics.

Intelligent CAD systems

The project 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 (IDDL, Integrated Data 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.

F. Arbab, P.J.W. ten Hagen, J.L.H. Rogier, P.J. Veerkamp (NFI), H.E. Klarenbosch, D.B.M. Otten, R.C. Veltkamp.

Univ. Tokyo, Computer and Automations Institute Budapest, Univ. Southern California, Univ. Delft, Univ. Amsterdam, Univ. Twente, Bilkent Univ. Ankara, Univ. Strathclyde, Univ. Edinburgh.

MULTIMEDIA

Introduction

Multimedia is a broadly-defined research area that addresses problems related to the capture, encoding, manipulation and presentation of information via a computing system. At CWI, as at many other research institutions, multimedia research is seen as an important new area of theoretical and practical study that impacts many of the traditional fields of computer science. The multi-disciplinary aspects of multimedia research are reflected in our choice of making it one of CWI's initial *research themes;* these are areas that are jointly studied by researchers from a number of CWI's departments. The initial participants in the multimedia research theme come from the departments of Algorithmics and Architecture (databases and user interfaces), Operations Research, Stochastics and System Theory (performance modelling), Computer Systems and Telematics (operating systems and network protocols), and Interactive Systems (complex data modelling and user interfaces).

The common focus of the research theme is to study the problems associated with providing multimedia support in a heterogeneous, distributed computing environment; the particular problems of interest include the development of user interaction models for multimedia data, the development of multimedia databases, the development of operating systems extensions to support multimedia information processing and the development of communications protocols to support the transfer of multimedia data.

Overview

In order to understand the problems associated with multimedia research, it is useful to make a distinction between *multimedia applications* and *multimedia systems.* Multimedia applications make use of mixed-forms of text, images and sound data when presenting or accepting information to/from a user. Multimedia systems provide a set of facilities that allow multimedia applications to manipulate multimedia data in an integrated manner. The presence of multimedia applications does not imply the presence of a well-defined multimedia system: many current applications provide a multimedia environment on an ad-hoc basis. The purpose of research into multimedia systems is to reduce the ad-hoc nature of this support, and to thereby make applications more regular and uniform. The purpose of research into multimedia systems is also to extend the facilities available to all applications, so that multimedia data can be integrated throughout a computing environment.

We can put the research aspects of multimedia systems into perspective by examining the input/output (I/O) facilities that have evolved through the years on digital computers. Consider that all user/computer and computer/computer communication has been modelled as a sequential stream of (possibly block-oriented) data transfers between the two end-points of a communication dialogue. This model has impacted the design of languages, operating systems, architectures and I/O devices since the late 1940's. Multimedia applications, on the other hand, have as a general property the integrated access and manipulation of multiple streams of information. In these systems, it is the synchronized processing of information from several sources (each with its own characteristics) that is important, with the emphasis being placed on integration and synchronization as the new aspects of multimedia support. While it is possible to simulate synchronized access across multiple streams by sequencing through a set of disjoint single streams, doing so severely limits the expressive capabilities of the user as well as the support capabilities of the underlying system. The research into multimedia software (and hardware) facilities is increasingly concerned with providing better synchronization and integration tools at all levels of information processing. In this respect, multimedia research can have an impact on the restructuring of languages, operating systems, architectures and I/O subsystems.

In addition to the manipulation of data streams, research into multimedia systems is also concerned with the processing of the individual data streams. Progress in supporting this processing can be considered in terms of multimedia system *generations.* Early multimedia implementations can be described as first-generation systems: information streams in these systems are stored as unstructured data, with the result that only limited manipulation of the data is possible. An example of a first-generation system might be one that uses FAX-like data images to augment a text-based information stream. The major drawback of these systems is their inflexibility; information can usually be manipulated only via .q 'cut-and-paste' type operations, with only limited content-based filtering and processing available. In contrast, second-generation multimedia systems offer the potential for manipulating the contents of an information stream - rather than simply controlling the stream itself - by including structure information with the data. The benefits of using structured data can include: higher reliability by having error detection/correction information carried with the data, increased flexibility by having the structure information provide the basis for searching and synchronizing of data, and better performance by providing special-purpose encoding mechanisms for each of the types of data used. By extension, one can consider third-generation multimedia systems ones in which the contents of the information stream can be further utilized. In third-generation systems, it might be possible to create links between and among streams that are based on information content instead of (or in addition to) information structure, such as analyzing the speech content of a stream to find a cue to an accompanying diagram. At present, commercial implementations of first generation systems are widely available, where second and third generation systems are still in the development and research stages.

CWI's research interests

CWI's research into support for multimedia systems began in mid-1990. The general area of interest to us is the study of distributed, heterogeneous multimedia systems. Distributed systems are those in which both the multimedia data and the processing routines that manipulate that data are located across a network of computers in a user-transparent manner. Heterogeneous systems are those in which each of the workstations in the network have mixed capabilities - that is, not all systems will be able to reproduce documents to the same degree of detail or accuracy, but we assume that all workstations in the network will want to access some portion of the multimedia data. We assume that the amount of data that can be transferred between and among workstations is technology dependent, but that the fundamental facilities that allow for information location, synchronized information access and system-constrained presentation are a central requirement of all systems.

There are four areas of study that are of interest to us during the initial period of our work: the development of user interfaces that allow for the expression and manipulation of multimedia information, database models that allow for storage and access models for synchronized data streams, distributed operating systems support for partitioning work and gathering/scattering data in the network, and protocol support for allowing synchronized multi-stream data communication. Each of these areas contribute a portion of the support for multimedia applications.

The relationships between the four study areas above and the multimedia project can be described in terms of a pipeline process of constructing, sharing and viewing *multimedia documents* (see the insert box). We assume that each such document is composed and processed in a series of five steps: information capture, document construction, presentation layout, local constraint filtering, and user access and viewing. Although we initially consider these steps as being discrete, they are actually high-connected, with feedback loops present among all of the components. Each step is briefly considered in the following paragraphs:

Information capture. This phase provides the means of collecting and saving information for later presentation. 'Later' in this sense may mean hours later or seconds later, depending on the dynamics of the document. As part of the capture process, information is tagged with attribute information that can be used during recall, and it is placed (complete with any structural information available) as an object in an appropriate database. Note that the concept of captured information is quite broad: it may extend from scanned images or recorded sound to synthesized image data or reproduced voice. In the latter cases, the information may consist of programs that produce the desired data rather than the data itself.

Document construction. This phase provides an author with the ability to bundle together captured (pseudo-) data into a single document. The document does not hold the information itself, but instead contains structured references to data blocks as well as synchronization information that describes the relationships between the blocks. Each instance of a data block is treated as a separate event. The relationships among the events is defined independently of any particular system that will be used to 'playback' the document. It is the task of the target system to implement the synchronization information (if possible) or to provide the user with an acceptable alternative, as is described by author-supplied presentation attributes.

Presentation layout. This phase is similar to the document construction phase, except that it concentrates on the mapping of a document to a virtual presentation environment. For example, the author may layout the location of information on a display screen or she may assign a sound channel to one of the two speakers on the display. As in the previous phase, there is no association with a particular output system during this phase: the virtual system defines all of the facilities that the author finds necessary to implement a document.

Local constraint filtering. This phase consists of a number of programmable elements that can be used to implement aspects of a virtual presentation environment on a particular workstation. This may include data conversions from one format to another or it may include data reductions from, say, stereo to mono sound. The filters necessary may be obtained from standard libraries or they may be delivered along with a document.

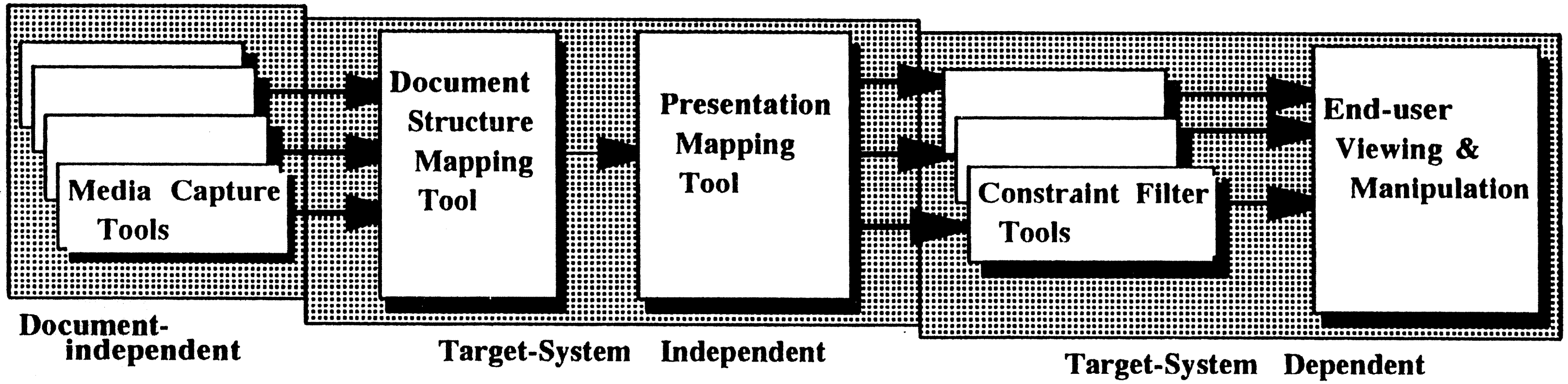
User viewing and access. This final phase allows a user to access a document. In so doing, the user may override the preferences of the author regarding placement or ordering of data, or the user may choose to increase or decrease the pace of the presentation. Depending on the dynamics of the document, the presentation to the user may occur in real-time or the user may receive the document as archived data.

Each of the phases impact (to differing degrees) the four areas of user interface design, database support, operating system support and protocol implementation.

Present status

The multimedia research theme is in its beginning stages at CWI. Time is being spent on understanding the general problem and in understanding those components which can be fruitfully be addressed locally. Time is also being spent on building a local research infrastructure that will enable separate groups (with separate responsibilities) to attack the multimedia problem in a federated manner. In addition, links are being established with other research groups that are considering complementary aspects of the multimedia problem so that our resources can be used as effectively as possible.

In concrete terms, we have defined a demonstration project that will serve as a small-scale proof-of-concept experiment for the CWI/Multimedia Pipeline. This effort, called the VANGOGH project, will study two aspects of multimedia manipulation in a distributed environment: a multimedia mail and messaging system and a system for comparing documents that have been annotated by several reviewers in a network. These projects are scheduled for completion by the end of 1991.



Elements of CWI's multimedia research

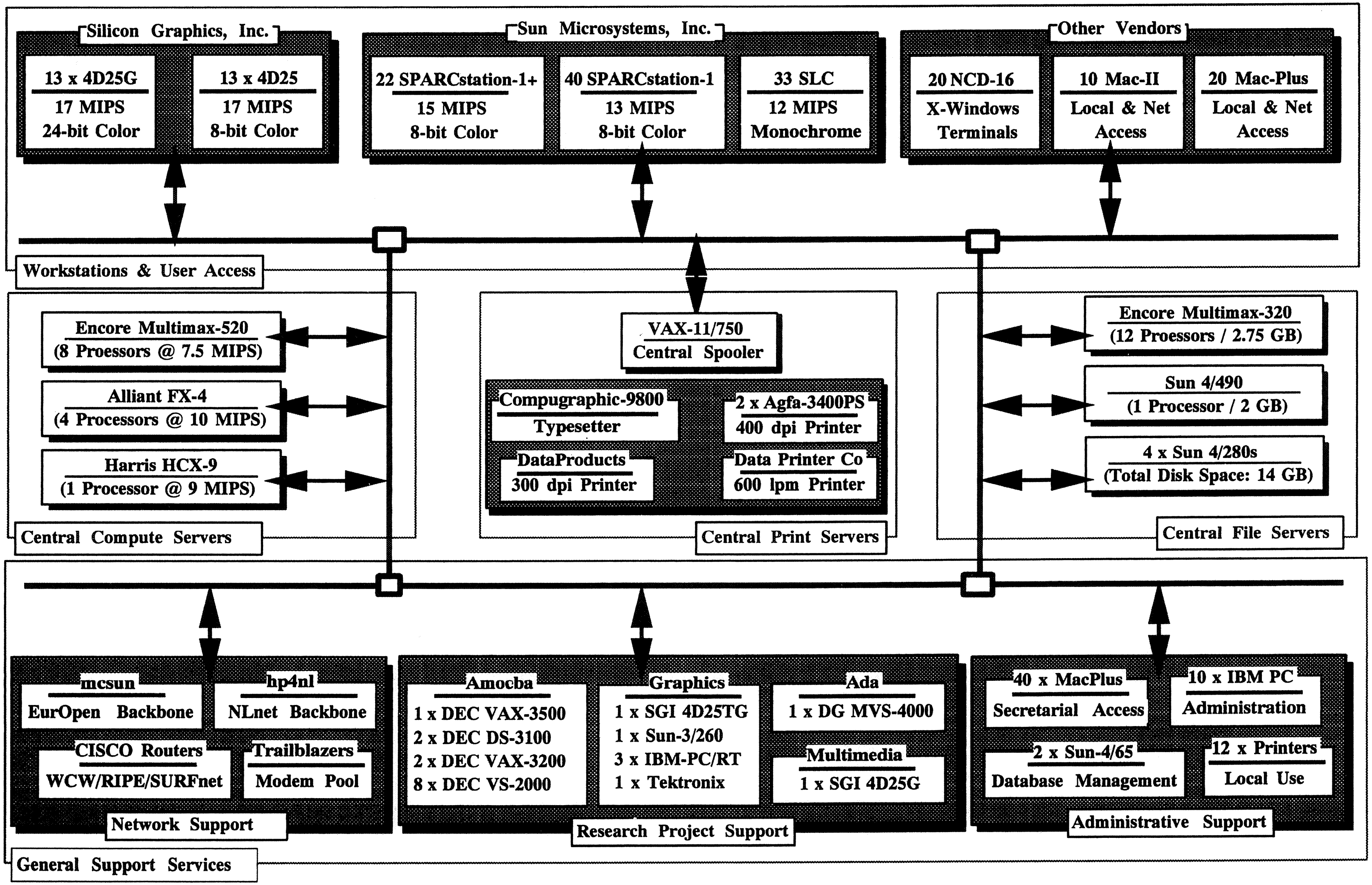
The general elements of the multimedia problem can be connected into a *pipeline* in which information flows from one stage to the next on its way from document definition to final document viewing. At CWI, different groups will combine their expertise in systems architecture, operating systems, distributed databases, user interface design and interactive systems to address different parts of the pipeline process.

The elements of the pipeline are:

- *Media block capture tools:* tools that allow the user to iteratively capture (and edit) the information that is placed in a *multimedia document.* Research issues include: storage models for multimedia data, database models and data attribute specification, content-based labeling of information.
- *Document structure mapping tool:* tools that allow the user to build and edit the multimedia documents. Research topics include: access interfaces, relationship models for expressing synchronization information, data attribute models for expressing requirements, hypermedia models for navigational support.
- *Presentation mapping tool:* tools that allow an author to layout documents in a *virtual presentation environment.* Research areas include: user interface models for designing documents and system models for estimating resource use.
- *Constraint filtering tools:* tools that allow documents to be processed correctly in a heterogeneous environment; constraints can either be *resource driven* (such as the mapping of colour documents to a black&white environment) or *preference driven* (such as replacing or modifying parts of a received document). Research areas include: interaction models, filtering algorithms, data reduction and processing algorithms and system architectural support.
- *Document viewing and reading tools:* tools that allow a user to access and playback documents. Research areas include: systems architectures for supporting data transfers and implementing synchronizations, user interface design for controlling multimedia data and database designs for continuous-data retrieval.

The CWI/Multimedia Pipeline provides a common framework upon which separate research projects can contribute to solve complementary aspects of the multimedia problem.

CWI Computing Equipment Resources (as of December 31, 1990)



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

TROPICS (2427): Transparent Object-oriented Parallel Information Computing System
December 1988 - March 1990
Nixdorf, Olivetti, Thomson, Philips, CAP Sogeti
Associated contractor of Philips
M.L. Kersten

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 - September 1991
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 - January 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 - January 1992
Univ. East Anglia (coordinator), CNRS, Imperial College, Univ. Nijmegen, ICL
J.W. Klop

RACE

RIPE (1040): RACE Integrity Primitives Evaluation
November 1988 - January 1991
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
F.W. Vaandrager

SCIENCE

Evolutionary Systems: deterministic and stochastic evolution equations, control theory and mathematical biology
March 1990 - March 1993
Universities of Tübingen, Besançon, Graz, Mons and Zürich, Scuola Normale Superiore Pisa, Techn. Univ. Delft
O. Diekmann

Combinatorial Optimization: algorithmic approaches to large and complex combinatorial optimization problems
October 1990 - October 1993
Universities of Louvain, Augsburg, Grenoble

(Université Joseph Fourier) and Valencia, CNR Rome
A. Schrijver

Other programmes

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

ESA project HERMES: Convergence acceleration and accuracy improvement of a geometric adaptive multigrid method for finite volume Euler and Navier-Stokes flow computations
La Société Avions Marcel Dassault, Breguet Aviation
July 1987 - January 1991
P.W. Hemker

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

OSF (Open Software Foundation)

S.J. Mullender

National Programmes

SPIN (Stimulation Project Team Computer Science)

PRISMA: Parallel Inference and Storage Machine
October 1986 - October 1990
Philips (main contractor), Universities of Twente, Utrecht and Amsterdam
M.L. Kersten/P.J.F. Lucas

FLAIR: Flexible automation
January 1987 - January 1991
Univ. Twente
P.J.W. ten Hagen

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

SION (Netherlands Foundation for Computer Science)

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

NFI (National Facility Computer Science)

Cryptography and computer security
September 1984 - September 1990
D. Chaum

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

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

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

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

STW (Foundation for the Technical Sciences)

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

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

Overload control for communication systems
February 1986 - August 1990
Philips Telecommunication, Univ. Twente
J.H. van Schuppen

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 1991
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

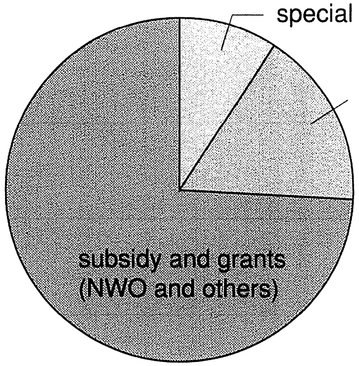
SPI (Special Programme Computer Science)

Algorithms and Complexity
January 1989 - January 1991
P.M.B. Vitányi

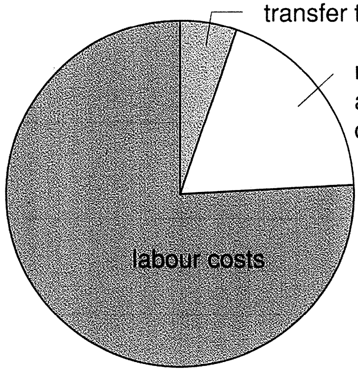
FINANCES 1990

In 1990, SMC spent Dfl. 20.24 million, of which about Dfl. 1.71 million was allocated to research by the national working parties and Dfl. 18.53 million to CWI.
The expenses were covered by a subsidy from NWO (Dfl. 15.46 million), other subsidies and grants (Dfl. 0.84 million), from the European Community for its ESPRIT, BRITE, BCR and RACE projects (Dfl. 1.47 million), and from national programmes (Dfl. 0.32 million).
Finally, an amount of about Dfl. 3.25 million was obtained as revenues out of third-party-services, sponsorships and other sources.
During 1990 CWI also employed 24 researchers in externally financed positions, for example by STW and industry. These are not included in the adjacent financial summary.

income CWI



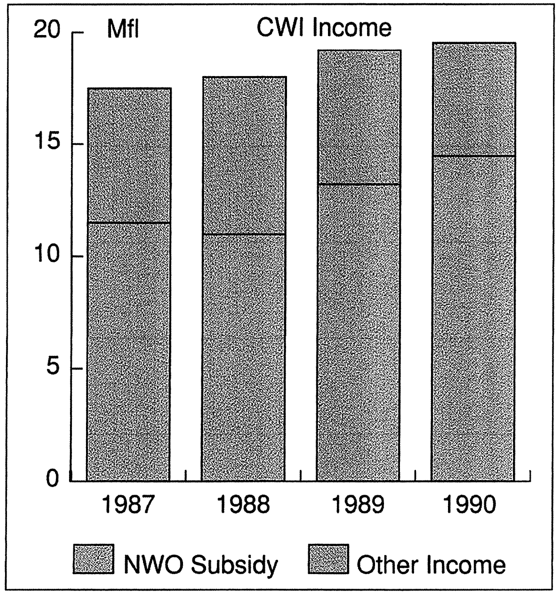
expenses CWI



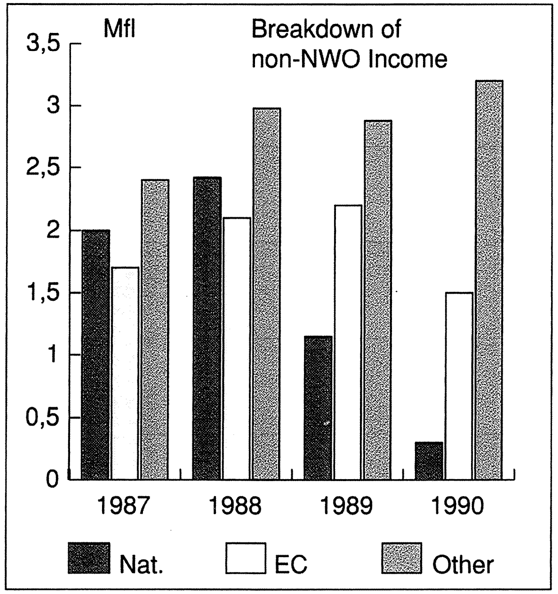
	national working parties	*CWI*	*SMC*
	× *Dfl.* 1000		
INCOME			
subsidy and grants			
- NWO	1828	13635	15463
- other	-	835	835
national programmes			
- SPIN	-	280	280
- IOP	-	41	41
international programmes			
- ESPRIT	-	806	806
- RACE	-	478	478
- BRITE	-	123	123
- BCR	-	61	61
liaison programme	-	42	42
other			
- proceeds from services and courses	-	1010	1010
- sales of publications	-	161	161
- network services	-	472	472
- miscellaneous income	-	1045	1045
- subsidies previous years	-	565	565
total income	1828	19554	21382
EXPENSES			
labour costs	1668	14034	15702
materials and overhead	38	3495	3533
transfer to SARA	-	1007	1007
total expenses	1706	18536	20242

CWI Budget Computer Equipment		
× *Dfl.* 1000		
NWO	600	
IAS	2000	
total income (= expenses)	2600	

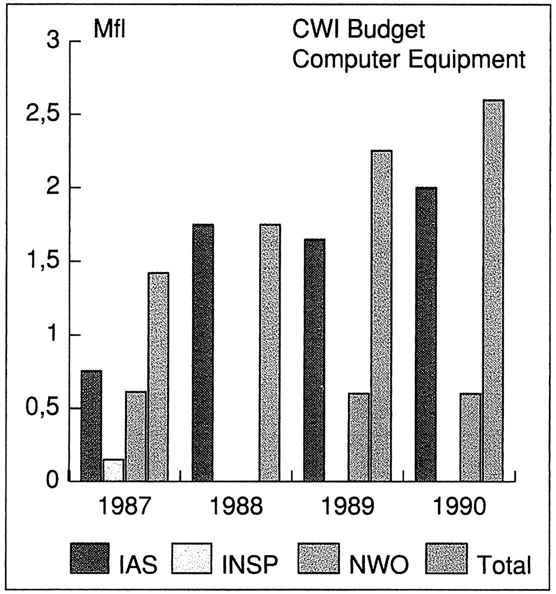
FINANCES 1987-1990



NWO grant as propotion of total operating costs for 1987-1990. The increase of NWO income after 1988 occurred in the salary domain.

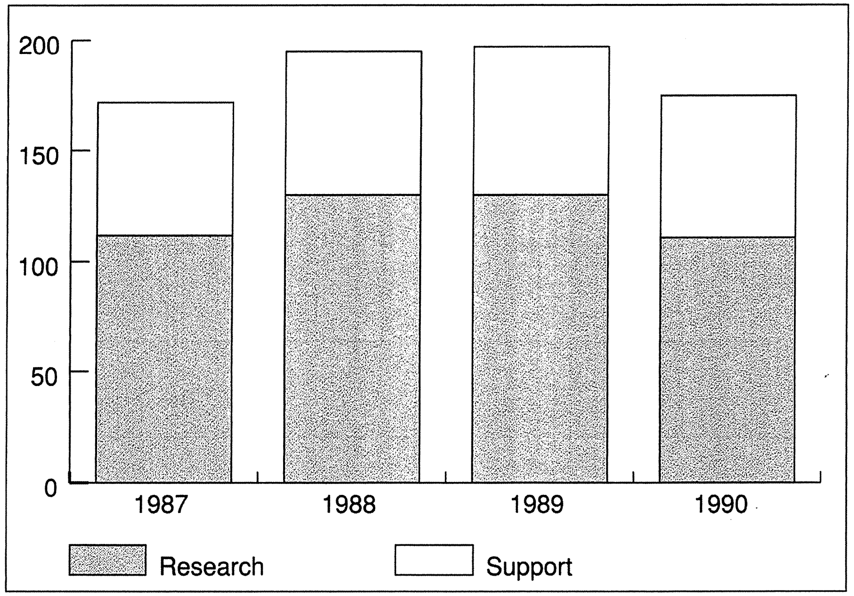


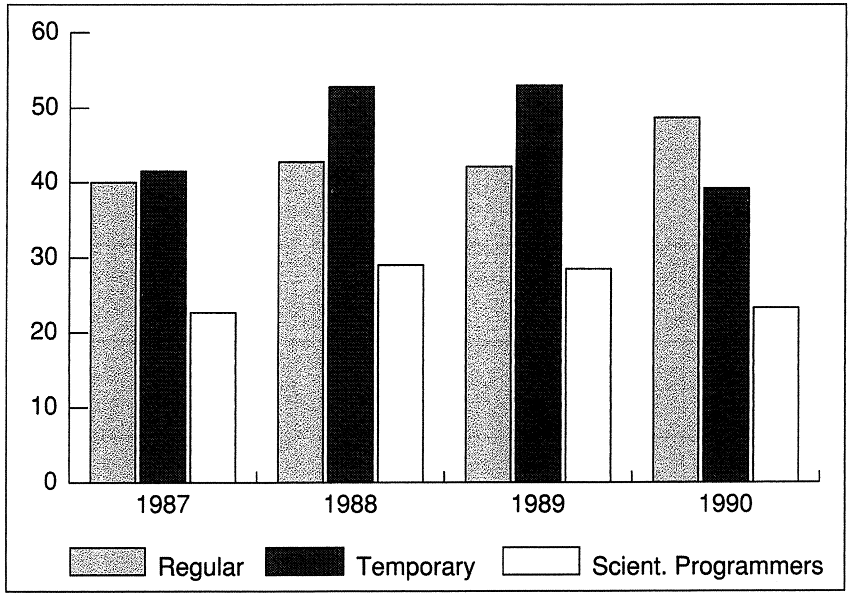
CWI participation in EC programmes in 1990 showed some decrease, due to the fact that ESPRIT II puts a stronger emphasis on applications than its predecessor ESPRIT I. Furthermore, in 1990 the national stimulation programmes in computer science had almost come to their end.



Mainly due to the grant from the IAS government support scheme for scientific equipment, CWI's computer equipment situation further improved.

PERSONNEL 1987-1990





The size of the personnel force is expressed in full-time equivalents, averaged over the year in question. Not included are externally financed positions (e.g. from STW and industry). For the years 1987-1990 these amounted to 17, 21, 23 and 24 respectively. To the right the breakdown of the research personnel is shown.

Foreign Visitors

Analysis, Algebra and Geometry

D.G. Aronson (USA)
L. Berg (FRG)
Y. Censor (Israel)
I.B. Cohen (USA)
A. van Daele (Belgium)
M. Duflo (France)
P. Feinsilver (USA)
H. Fujii (Japan)
M. Gaetano (France)
F.G. Greiner (FRG)
E. Gutkin (USA)
I. Havel (Czechoslovakia)
M.E.H. Ismael (USA)
R.A. Liebler (USA)
P. Littelmann (France)
S. Majid (UK)
O. Mathieu (France)
Y. Morita (Japan)
G. Olshankiĭ (USSR)
P. Pandžić (Yugoslavia)
W. Pusz (Poland)
W.B.G. Ruitenburg (USA)
K.E. Schuler (USA)
A.L. Schwartz (USA)
A.M. Semenov Tián-Shansky (USSR)
S. Sigurdsson (USA)
P.E. Sobolevski (USSR)
S. Tsaranov (USSR)
J. Turi (USA)
H. Yamada (Japan)
S. Zakrzewski (Poland)
D. Zvirenaite (USSR)

Operations Research, Statistics, and System Theory

F. Baccelli (France)
R.K. Boel (Belgium)
M.A. Cameron (Australia)
D.M. Chibisov (USSR)
E.G. Coffman, Jr. (USA)
K. Doksum (USA)
F. Fagnani (Italy)
S. Gaidov (USSR)
A. Gandolfi (USA)
Ph. Heidelberger (USA)
M. Husková (Czechoslovakia)
J. Jacod (France)
P. Janssen (Belgium)
Y. Kogan (Israel)
V. Korolyuk (USSR)
F. LeGland (France)
L. Lerer (Israel)
H. Levy (Israel)
A. van de Liefvoort (USA)
F. Maffioli (Italy)
D.M. Mason (USA)
H.J. van der Meer (FRG)
J. Memin (France)
R. Middleton (UK)
R.R. Muntz (USA)
I. Norros (Finland)
M. Pavon (Italy)
S. Pinzoni (Italy)
B.A. Reed (Canada)
K. Richter (FRG)
Ph. Robert (France)
N. Robertson (USA)
M. Sebek (Czechoslovakia)
K.C. Sevcik (Canada)
A.N. Shiryaev (USSR)
H. Takagi (Japan)
E. Valkeila (Finland)
L. Vincent (France)
L. Vostrikova (France)
U. Yechiali (Israel)
J. Zidek (Canada)

Numerical Mathematics

C. de Andrade (Brazil)
Y. Censor (Israel)
H. Embrechts (Belgium)
T.L. Freeman (UK)
D. Goovaerts (Belgium)
P.P.N. de Groen (Belgium)
W. Ichinose (Japan)
J. Michelsen (Denmark)
S.G. Petiton (USA)
B. Philippe (France)
Phuong Vu (USA)
J.H.D. Roose (Belgium)
Shun Doi (Japan)
G.S. Singh (India)
Subhankar Ray (USA)
S. Vandewalle (Belgium)

Software Technology

N. Ascher (USA)
E. Badouel (France)
M. Baudinet (Belgium)
M.Y. Bekkers (France)
E. Best (FRG)
H. Blair (USA)
W. Brauer (FRG)
P.-H. Cheng (France)
K. Clark (UK)
M. Dauphin (France)
G. David (Portugal)
I. Deville (Belgium)
M. Dunn (USA)
M. Falaschi (Italy)
P. Flener (Belgium)
L. Fribourg (France)
P. Fritzson (Sweden)
M. Gabbrielli (Italy)
P. Gärdenfors (Sweden)
J. Gustavson (Switzerland)
M. Hennessy (UK)
P. van Hentenrijck (Belgium)
Y. Inagaki (Japan)
R. Kennaway (UK)
Z. Khasidashvili (USSR)
J. Komorowsli (Norway)
V. Kutepov (USSR)
T. Langholm (Norway)
S. Lavington (UK)
G. Levi (Italy)
M. Majster-Cederbaum (FRG)
J. Maluszynski (Sweden)
M. Martelli (Italy)
R. Milner (UK)
T. Mizutani (Japan)
J.F. Monin (France)

U. Montanari (Italy)
L. Monteiro (Portugal)
M. Morreau (USA)
U. Nilsson (Sweden)
P. Panangaden (Canada)
F. Pereira (USA)
L. Plümer (FRG)
A. Porto (Portugal)
V. Pratt (USA)
W.P. de Roever (FRG)
Ko Sakai (Japan)
D. de Schreye (Belgium)
R. Sleep (UK)
S. Sokolowski (Poland)
Y. Toyama (Japan)
G. Winskel (Denmark)
P. Wolper (Belgium)
S. Yoccoz (France)
J.I. Zucker (Canada)

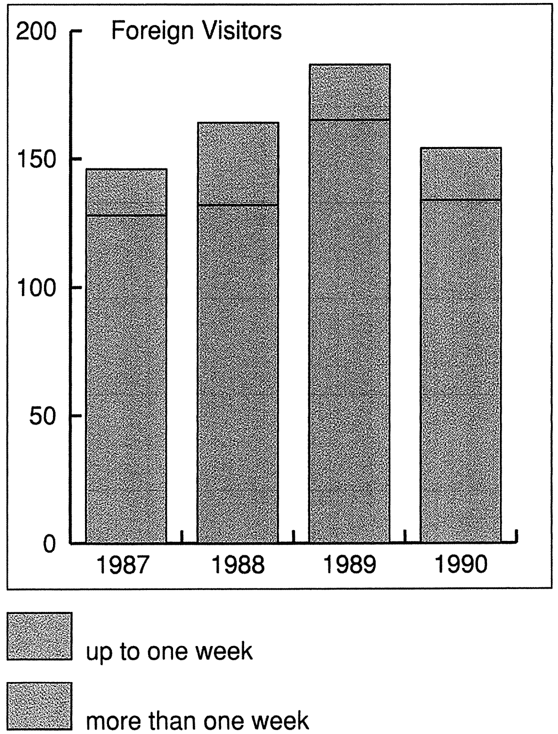
Algorithmics and Architecture

M. Büttger (FRG)
A. Goldberg (USA)
S.J. Hegner (USA)
G.S. Kissin (Canada)
D.D.M. Krizanc (USA)
C.C. Morgan (UK)
Ch. Münthe (FRG)
K. Ohta (Japan)
T. Okamoto (Japan)
B. Pfitzman (FRG)
M. Satyanarayanan (USA)
A. Stepanov (USA)
J. Wilkes (USA)

Interactive Systems

S. Finger (USA)
A. Gagalowicz (France)
R. Hubbold (UK)

FOREIGN VISITORS 1987-1990



List of Publications

Department of Analysis, Algebra and Geometry

Report series

AM-R9001 N.M. Temme, A.B. Olde Daalhuis. *Uniform asymptotic approximation of Fermi-Dirac integrals.*

AM-R9002 M. Zwaan. *Dynamic MRI reconstruction as a moment problem, Part III. An error analysis of reconstruction by sinc and spline interpolation in a Hilbert space setting.*

AM-R9003 H.J.A.M. Heijmans. *Grey-level morphology.*

AM-R9004 O. Diekmann, M. Kretzschmar. *Patterns in the effects of infectious diseases on population growth.*

AM-R9005 S.N.M. Ruijsenaars. *Finite-dimensional soliton systems.*

AM-R9006 J.B.T.M. Roerdink. *Mathematical morphology on homogeneous spaces, Part II. The transitive case.*

AM-R9007 O. Diekmann, S.A. van Gils. *The center manifold for delay equations in the light of suns and stars.*

AM-R9008 J. van de Lune, E. Wattel. *Systematic computations on Gauss' lattice point problem (In commemoration of Johannes Gualtherus van der Corput 1890-1975).*

AM-R9009 H.J.A.M. Heijmans. *From binary to grey-level morphology.*

AM-R9010 J.M.A.M. van Neerven. *On the topology induced by the adjoint of a semigroup of operators.*

AM-R9011 A.B. Olde Daalhuis, N.M. Temme. *Uniform Airy type expansions of integrals.*

AM-R9012 J.B.T.M. Roerdink. *Mathematical morphology on the sphere.*

AM-R9013 T.H. Koornwinder. *Askey-Wilson polynomials as zonal spherical functions on the SU(2) quantum group.*

AM-R9014 T.H. Koornwinder. *Handling hypergeometric series in Maple.*

AM-R9015 E. Badertscher, T.H. Koornwinder. *Continuous Hahn polynomials of differential operator argument and analysis on Riemannian symmetric spaces of constant curvature.*

AM-R9016 H.J.A.M. Heijmans. *Morphological filtering and iteration.*

AM-R9017 O. Diekmann. *Modelling infectious diseases in structured populations.*

AM-R9018 G. Greiner, J.M.A.M. van Neerven. *Adjoints of semigroups acting on vector-valued function spaces.*

AM-R9019 H.J.A.M. Heijmans, P. Nacken, A. Toet, L. Vincent. *Graph morphology.*

AM-R9020 G.I. Olshanskiĭ. *Complex Lie semigroups, Hardy spaces and the Gelfand-Gindikin program.*

AM-R9021 G.I. Olshanskiĭ. *Twisted Yangians and infinite-dimensional classical Lie algebras.*

AM-R9022 J. de Vries. *A proof of the relativized non-metric form of Furstenberg's structure theorem.*

AM-R9023 O. Diekmann, K. Dietz, J.A.P. Heesterbeek. *The basic reproduction ratio for sexually transmitted diseases, part I: Theoretical considerations.*

AM-R9024 J.B.T.M. Roerdink, M. Zwaan. *Cardiac magnetic resonance imaging by retrospective gating: Mathematical modelling and reconstruction algorithms.*

AM-R9025 J.B.T.M. Roerdink. *On the construction of translation and rotation invariant morphological operators.*

AM-R9026 V.V. Koroliuk. *Central limit theorem for non-homogeneous processes with independent increments and semimarkov switchings.*

Publications in Journals, proceedings, etc.

AM1 W. van Assche, T.H. Koornwinder (1990). Asymptotic behaviour for Wall polynomials and the addition formula for little q-Legendre polynomials, to appear in *SIAM J. Math. Anal.*

AM2 F. van den Bosch, J.A.J. Metz, O. Diekmann (1990). The velocity of spatial population expansion. *J. Math. Biol. 28,* 529-565.

AM3 A.M. Cohen (1990). Local recognition of graphs, buildings and related geometries, W.M. Kantor et al. (eds.). *Pingree Park Proc.,* Oxford, UK, 85-94.

AM4 A.M. Cohen (1990). Coxeter groups and three related topics. Lecture notes of ASI *Generators and Relations in Groups and Geometries* Castelvecchio Pascoli, Italy, April 1990.

AM5 A.M. Cohen (1990). Presentations of some finite quaternionic reflection groups, to appear in *Proceedings of the 3rd Isle of Thorus Conference.*

AM6 A.M. Cohen, F. Buekenhout (1990). *Diagram Geometry* (in preparation).

AM7 A.M. Cohen, R.L. Griess (1990). *Non-Local Lie Primitive Subgroups of Lie Groups,* preprint.

AM8 A.M. Cohen, M.W. Liebeck, J. Saxl, G.M. Seitz (1990). *The Local Maximal Subgroups of Finite Groups of Lie Type,* preprint.

AM9 A.M. COHEN, G.C.M. RUITENBURG (1990). Rational generating functions, to appear in *Seminar proceedings.*

AM10 A.M. COHEN, G.C.M. RUITENBURG (1990). *Algebra and Algorithms* (in preparation).

AM11 A.M. COHEN, E.E. SHULT (1990). Affine polar spaces. *Geom. Didicata, 35,* 43-76.

AM12 O. DIEKMANN, J.A.P. HEESTERBEEK, J.A.J. METZ (1990). On the definition and the computation of the basic reproduction ratio R_0 in models for infectious diseases in heterogeneous populations. *J. Math. Biol. 28,* 365-382.

AM13 O. DIEKMANN, M. KRETZSCHMAR (1990). Patterns in the effects of infectious diseases on population growth, to appear in *J. Math. Biol.*

AM14 O. DIEKMANN, S.M. VERDUYN LUNEL (1990). A new short proof of an old folk theorem in functional differential equations. *Semesterberichte Functional Analysis 17,* 11-16.

AM15 O. DIEKMANN, S.A. VAN GILS (1990). The center manifold for delay equations in the light of suns and stars. R.M. ROBERTS, I.N. STEWART (eds.). *Singularity Theory and Its Applications,* Warwick, 1989, Vol. 2.

AM16 O. DIEKMANN, K. DIETZ, J.A.P. HEESTERBEEK (1990). *The Basic Reproduction Ratio R_0 for Sexually Transmitted Diseases, Part I: Theoretical Considerations,* preprint.

AM17 O. DIEKMANN, M.W. SABELIS, JIN CHENG-FU, J.A.J. METZ (1990). *Variable Prey Vulnerability Stabilizes a Predator-Prey Interaction of the Volterra-Lotka Type,* preprint.

AM18 A. GRABOSCH, H.J.A.M. HEIJMANS (1990). Cauchy problems with state-dependent time evolution. *Japan J. Appl. Math.*

AM19 M. HAZEWINKEL (ed.) (1989, 1990). *Encyclopaedia of Mathematics, Vols. 3,4,5,6,* Kluwer, Dordrecht.

AM20 M. HAZEWINKEL (1990). Introductory recommendations for the study of Hopf algebras in mathematics and physics. *CWI Quarterly* (to appear).

AM21 M. HAZEWINKEL (1990). *Solitons, Lie Algebras and Worse* (in preparation)

AM22 M. HAZEWINKEL (1990). Nongaussian linear filtering, identification of linear systems, and the symplectic group. F.A. GRUNBAUM, J.W. HELTON, P. KHARGONEKAR (eds.). *Signal Processing, Part II: Control Theory and Applications,* Springer-Verlag, 99-114.

AM23 M. HAZEWINKEL (1990). 46 (small) supplementary articles on developments in mathematics in the eighties for the third supplement volume of the Dutch Oosthoek encyclopaedia and the Dutch version of the Larousse encyclopaedia, Kluwer.

AM4 M. HAZEWINKEL, H. NIELAND (1990). Algebra, knopen en DNA, article in *NRC Handelsblad,* December.

AM25 J.A.P. HEESTERBEEK, J.M.A.M. VAN NEERVEN, H. SCHELLINX, M. ZWAAN (1990). The nature of fractal geometry. *CWI Quarterly 3,* 137-149.

AM26 J.A.P. HEESTERBEEK, J.M.A.M. VAN NEERVEN, H. SCHELLINX (1990). Several elementary proof that $0=1$, to appear in *Nieuw Archief voor Wiskunde.*

AM27 H.J.A.M. HEIJMANS (1990). From binary to grey-level morphology. R.M. HAVALICK (ed.). *Mathematical morphology: Theory and Applications,* Springer-Verlag (to appear).

AM28 H.J.A.M. HEIJMANS, C. RONSE (1990). The algebraic basis of mathematical morphology. Part I: Erosions and dilations. *Comp. Vis. Graph. Im. Proc. 50,* 245-295.

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