CWI

Centrum voor Wiskunde en Informatica

ANNUAL REPORT

'92

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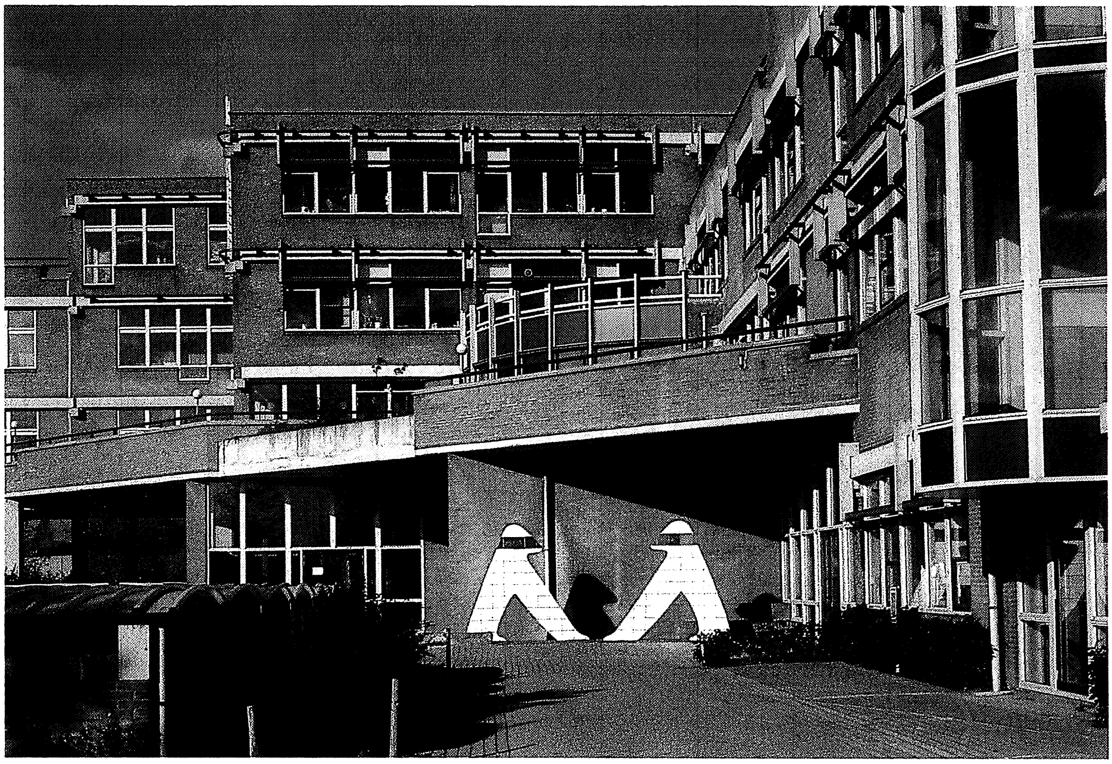

CWI is the National Research Institute for Mathematics and Computer Science. CWI is part of the Stichting Mathematisch Centrum (SMC), the Dutch foundation for promotion of mathematics and computer science and their applications. SMC is sponsored by the Netherlands Organization for Scientific Research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

ERCIM

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CONTENTS

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

INTRODUCTION

Policy

Following the reorganization carried out during 1991, CWI started the year 1992 with a programme to realize a new, practical equilibrium in the fast changing world of computer science and mathematics. This programme is set out in the *Mobile* memorandum (autumn 1992), itself a continuation of the previously published Interim Policy Document 1993-1997. A greater focus on applicability is central here, but with no diminution of the fundamental character of research. Transfer of knowledge to the scientific and business community at large also receives a top priority. This gives CWI a clearer profile in relation to new developments including inter-university research clusters. In fact, repositioning is a permanent activity for an institute like CWI, and sharp acceleration of the process is only occasional. Both aspects, applicability and knowledge transfer, have been basic principles since CWI was founded. At the same time, the importance of an institute like CWI was freshly underlined by the *Mathematics – Ordering a Complex World* (Wiskunde in Beweging) report commissioned by the Ministry of Science and Education from the Advisory Committee on Mathematics.

One important trend is that, much more than in the past, research is performed as part of larger, interconnected projects. These range from bilateral joint ventures to participation in major international programmes like the European Commission's ESPRIT and Human Capital & Mobility, and Japan's Real World Computing. This trend is reflected in CWI's present research programme and we are well equipped to carry it out, both in terms of research potential and supporting infrastructure. Active response to these wider frameworks dates back several years. Examples here include promoting synergetic effects between mathematics and computer science and definition of multi-disciplinary research programmes involving several participant groupings at and outside CWI. The *Mathematics and the Environment* programme started-up in early 1992, following on from *Multimedia* in 1991. The report year also saw preparation of the *Scientific Visualization* programme. Research in the area of *High Performance Computing and Communication* represents further penetration of major frameworks. Following on from the Rubbia report on this subject, which had been prompted by the European Commission, The Netherlands began the set up of a research infrastructure in 1992. CWI's active role here is evidenced by groundwork for cooperation with the University of Amsterdam in the field of computer-supported research of complex systems.

As every year, CWI defined the general guidelines set down in its policy documents in an action plan. In 1992 this was presented in a new format.

National and international programmes

CWI's basic funding from NWO (Netherlands Organization for Scientific Research) is complemented by income from contract research. An important part of these activities comes under national programmes like SION, NFI and STW, and European Community programmes like ESPRIT and RACE.

A substantial budget injection some years ago positioned SION to accept project proposals from CWI. This reinforcement at the research level paralleled the previously strengthened board-level relationship between SMC and SION (three SMC trustees including the vice-chairman to be SION nominees); this had resulted in regular management consultations and enhanced policy alignment. The overall outcome has been a rise in the number of SION projects allocated to CWI from one in 1990 and two in 1991, to four in 1992 and five in 1993. The projects started in the report year are: *Computational learning theory; Declarative and procedural aspects of non-standard logics; MathViews – Functional and architectural aspects of mathematical objects*; and *Extensions of orthogonal rewrite systems – syntactic properties*.

The National Informatics Facility (NFI) promotional programme came to an end in 1992.

Smog above Rotterdam Harbour (photo: Geosens). CWI's ongoing Mathematics & the Environment programme develops algorithms for the air pollution models used to predict smog.

The last NFI programme allocated to CWI was *ALADDIN - algorithmic aspects of parallel and distributed computing*. There is a strong emphasis here on knowledge transfer by means of expert training, development of lecture course notes, and the organization of seminars and colloquia.

CWI has successfully participated in various Technical Science Foundation (STW) projects since this body was founded. Under the STW formula, knowledge transfer to industry is inbuilt in every project; this matches excellently with CWI's approach. As a matter of principle, STW seeks to accept a given minimum percentage of applications. Regrettably, in 1991, this policy led to a temporary halt to all grants, due to insufficient funding. Following resumption during 1992, CWI was awarded two further projects: *Parallel codes for circuit analysis and control engineering*, and *Parameter identification and model analysis for non-linear dynamic systems*.

CWI has always competed successfully in the widespread European Community programmes (ESPRIT, RACE, BRITE, SCIENCE, COMETT), ever since the start some ten years ago. Up to the present most ESPRIT projects in which CWI participated had been in the area of software technology. In 1992 the emphasis shifted drastically following the award of three major projects in quite different fields: *PYTHAGORAS* (research into the quality of new database management systems), *CAFE* (Conditional Access For Europe: security and privacy of payment traffic via computer networks) and *MADE* (Multimedia Application Development Environment: the construction of an object-oriented software base with related programming tools). CWI has been allocated a leading position in the first two of these projects. Once again, this unique position underlines the confidence of the international research community in CWI as a pioneering resource for research and knowledge transfer. It also underlines CWI's excellent ongoing ability to link with ESPRIT despite this programme's increasingly stronger focus on application in the 1990s.

CWI had already participated in *COMPULOG*, an ESPRIT network of excellence, and has been appointed coordinator for the second phase of this project (coordinator K.R. Apt).

Two RACE projects, *RIPE* and *SPECS*, were ended in 1992. RIPE (RACE Integrity Primitives Evaluation) resulted in a number of recommendations to the European Commission in the area of Integrity Protection. The SPECS project concerned the specification and programming environment for communication software.

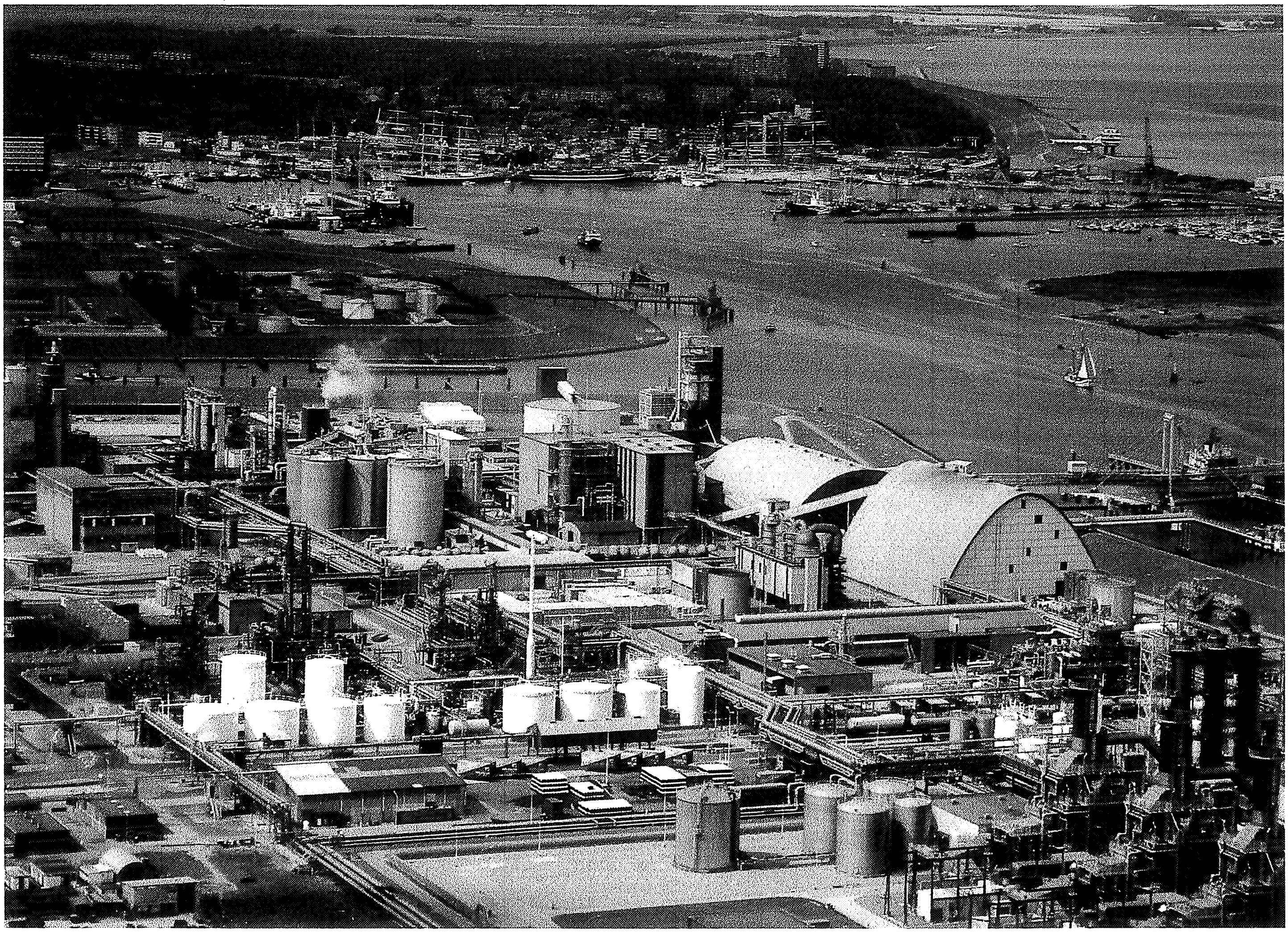
The BRITE EURAM project around solution of the Navier-Stokes equations which are so vital for the aero-space industry, ended in 1992. As a follow-up to this, BRITE supports a new CWI project, *Multi-grid methods in CFD*, in which multi-grid methods are applied to 3-D flows, an important part of the project being visualization of the results.

Lastly, the SMC Library participates in the European Commission's *RIDDLE* project (Rapid Information Display and Dissemination in a Library Environment). Researchers are looking into how far automatic storage of contents listings for periodicals can be used to position information on separate contributions in an on-line catalogue.

Knowledge transfer, central role

Knowledge transfer in regard to applications is also a recognized priority at European Community level. CWI has always taken account of wider, public issues when selecting research subjects. An important aim, alongside participation in national and international programmes, is to increase the number of commissions from third parties, i.e. industry, government and the major technological institutes (Dutch acronym GTI). These prospects were energetically pursued in 1992. These contracts spur us toward high-grade fundamental research with the important angle of

PYTHAGORAS, an ESPRIT project coordinated by CWI, develops a software test pilot to assess quality of new database management systems. The coin depicting Pythagoras dates from the reign of the Emperor Trajan (AD 98 - 117).



benefiting the community at large and are, of course, a source of additional income. Given the length of the road from fundamental research to practical applications, CWI strives for strategic alliances with GTIs and TNO (Netherlands Organization for Applied Scientific Research) and similar. These bodies make ideal agents and intermediaries.

By the end of 1992 there were over 60 third party contacts at various stages of development. Among important ongoing commissions are:

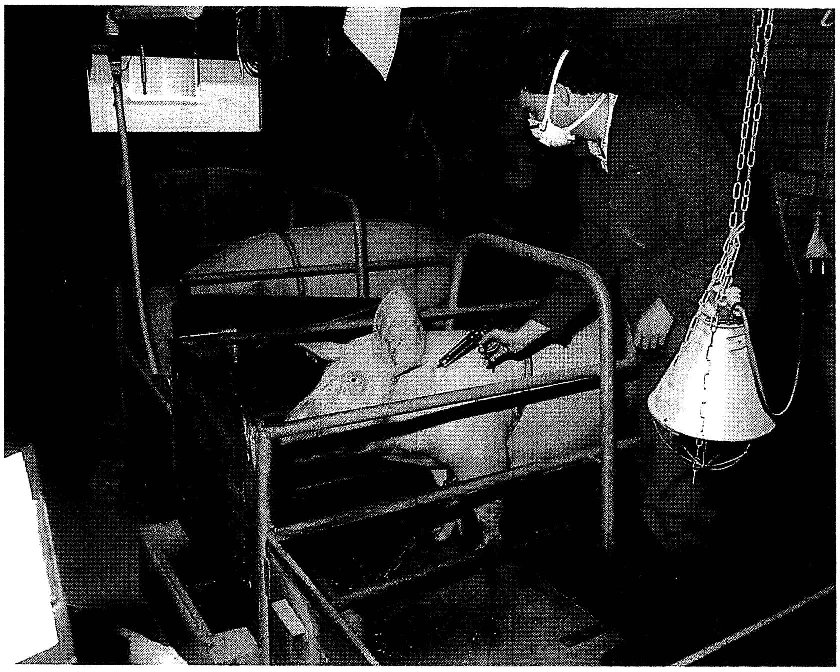
- modelling the spread of pollution in ground water and the air (National Institute of Public Health & Environmental Protection);
- development of a strategy to combat epidemics in pig breeding units (Central Veterinary Institute);
- research into large-scale computation (CRAY research grants);
- development of FERSA, an interactive apparatus for lip- synchronized talking-face animations (in cooperation with consultant P.A. Griffin and TV post-production company Valkieser Group);
- integration of multi-media technology in management games (LaserMedia);
- parameter identification in reaction kinetics (AKZO).

The long-term consultation project 'Basis Levels in Coastal Areas' (with the Public Works department), and its final report, were also completed in 1992.

The *CWI in the Market-place* presentation day, organized in 1992, was further evidence of our systematic programme to generate research commissions. Some sixty interested prospects

CWI researches parameter identification in large systems of non-linear differential-algebraic equations describing complex chemical, biochemical or pharmaceutical processes. This follows up a consultancy project for the chemicals multinational, AKZO. (Photo: AKZO plant at Delfzijl).

CWI researches the mathematical modelling of epidemics in structured populations. In cooperation with the Netherlands Central Veterinary Institute, this is being used to determine vaccination strategy to control the spread of Aujeszky's disease in pig breeding units.
(Photo courtesy Zuid-Nederland Veterinary Service Foundation).



from industry and government were given an overview of the CWI research potential in a series of lectures and demonstrations. Based on its success, it has been decided to make this an annual event.

An important part of knowledge transfer occurs via conferences, workshops and courses, a selection of which we mention here.

- H.J.J. te Riele and P.J.W. ten Hagen each led a successful ERCIM course, respectively *Large Scale Parallel Scientific Computing* (once, in the UK) and *User Interfaces for Picture Systems* (twice, in the UK and France).
- Fifty participants were drawn to the *Semantics: Foundations and Applications* workshop, which formed part of the REX programme (Research and Education in Concurrent Systems). This programme will be ended in 1993, by when it will have run for ten years. A major symposium will mark the event.
- CWI was responsible for programming the major *Joint International Conference and Symposium on Logic Programming*, held in Washington D.C. The programme committee was chaired by K.R. Apt.
- Some fifty participants came to the *Summer School in Group Theory* organized by CWI at Twente University.
- Around 200 researchers participated in the *11th Benelux Meeting in Systems & Control*, which was held in The Netherlands in 1992.
- Lastly, our traditional summer school for high-school maths teachers centred on *System Theory*.

There were many publications in journals, congress reports, etc., in addition to several books written by and with input from CWI researchers. Among the titles are:

- *Handbooks in Operations Research and Management Science*, Volume 3 (E.G. Coffman Jr., J.K. Lenstra, A.H.G. Rinnooy Kan, editors);
- *Analysis of Random Walks* (J.W. Cohen);
- *Proceedings of the REX Workshop Real-Time: Theory in Practice* (J.W. de Bakker, W.P. de Roever, G. Rozenberg, editors);
- *Ten Years of Concurrency Semantics - selected papers of the Amsterdam Concurrency Group* (J.W. de Bakker, J.J.M.M. Rutten, editors);
- *Computer Graphics and Mathematics* (B. Falcidieno, I. Herman, editors).

Alongside publication of research results, one of the most important means of knowledge transfer is the nurturing of a scientific cadre for the research community. CWI has well-established and close links with the academic community, over a broad front. Evidence of this are the many CWI staffers with part-time professorships and the degrees regularly awarded to many younger members of the CWI team. For the latter it was a record year with no less than 16 new Ph.D.s (five for Numerical Mathematics, three for Algorithmics & Architecture, and two each for the other departments).

On the international scene, CWI's centre role was further reinforced with the decision to set up *RIACA* (Research Institute for Applications of Computer Algebra) by the Dutch Computer Algebra Foundation (CAN), the Research Institute for Symbolic Computation (RISC) at Kepler University in Linz (Austria), and SMC. Like CAN's offices, this institute will be accommodated at CWI, with SMC acting as secretary.

Other research

The specific projects mentioned above are only part of the research activities covered at CWI during the report year. Further selected activities are summarized below.

Dynamical systems
An application was accepted under NWO's Non-Linear Systems priority programme for CWI's planned Dynamic Systems Laboratory. CWI will receive Dfl. 600,000 for this in 1993.

Epidemiology
Research was completed into definition and applications of an epidemiological threshold number R_0 for structured populations (thesis J.A.P. Heesterbeek).

Operations research
Considerable time was devoted to preparation of several books on Scheduling and Combinatorial Optimization (including Polyhedral Combinatorics), to be published during the next few years, with CWI staffers as author or joint author (J.K.Lenstra, A.Schrijver).

Performance analysis & control
In addition to ongoing national financing, the Performance Analysis and Control of Computer and Communication Networks project received an extra boost from participation in the ESPRIT BRA project QMIPS (Quantitative Modelling in Parallel Systems).

System identification
Alongside the System Identification SCIENCE project coordinated by CWI, which is now receiving support from the EC's Human Capital & Mobility programme, CWI also started research into System Identification for Compartmental Systems as part of its multi-disciplinary Mathematics & the Environment programme.

Discretization of evolution problems, semi-conductor equations
The Numerical Mathematics department produced no less than five Ph.D. theses: three in the area of discretization of evolution problems (P.A. Zegeling: Moving-Grid Methods for Time-Dependent Partial Differential Equations, E.D. de Goede: Numerical Methods for the 3D Shallow-Water Equations on Supercomputers, B.P. Sommeijer: Parallelism in the Numerical Integration of Initial Value Problems) and two theses completing research into semi-conductor equations (J. Molenaar: Multigrid Methods for Semiconductor Simulation, R.R.P. van Nooyen: Some Aspects of Mixed Finite Element Methods for Semi-conductor Simulation).

Singular perturbations
Research started into singular perturbation problems in cooperation with the Ekaterinburg (formerly Sverdlovsk) Institute for Mathematics and Mechanics (Russia).

Computational number theory
A project group of the same name has been formed to exploit CWI's very considerable expertise in the area of computational number theory.

Concurrency, communication
For many years now, European Commission projects have accounted for much of the Software Technology Department's research, and this volume further increased in 1992. Alongside the initial activities in Mathematical Structures in Semantics for Concurrency (MASK, a SCIENCE programme coordinated by CWI), 1992 saw the start of participation in Broadband Object-Oriented Service Technology (BOOST, a RACE project), and two ESPRIT BRA projects: CONCUR II (Calculi and Algebras of Concurrency: Extensions, Tools and Applications) and CONFER (Concurrency and Functions: Evaluation and Reduction). The RACE project SPECS (Specification and Programming Environment for Communications Software) ended in 1992.

Logic programming
Two new projects were started in CWI's Logic & Language programme: Logic Programming and Non-monotonic Reasoning, and Formal Aspects of Prolog and Logic Programming (part-

funded by the ESPRIT BRA Network of Excellence Compulog II).

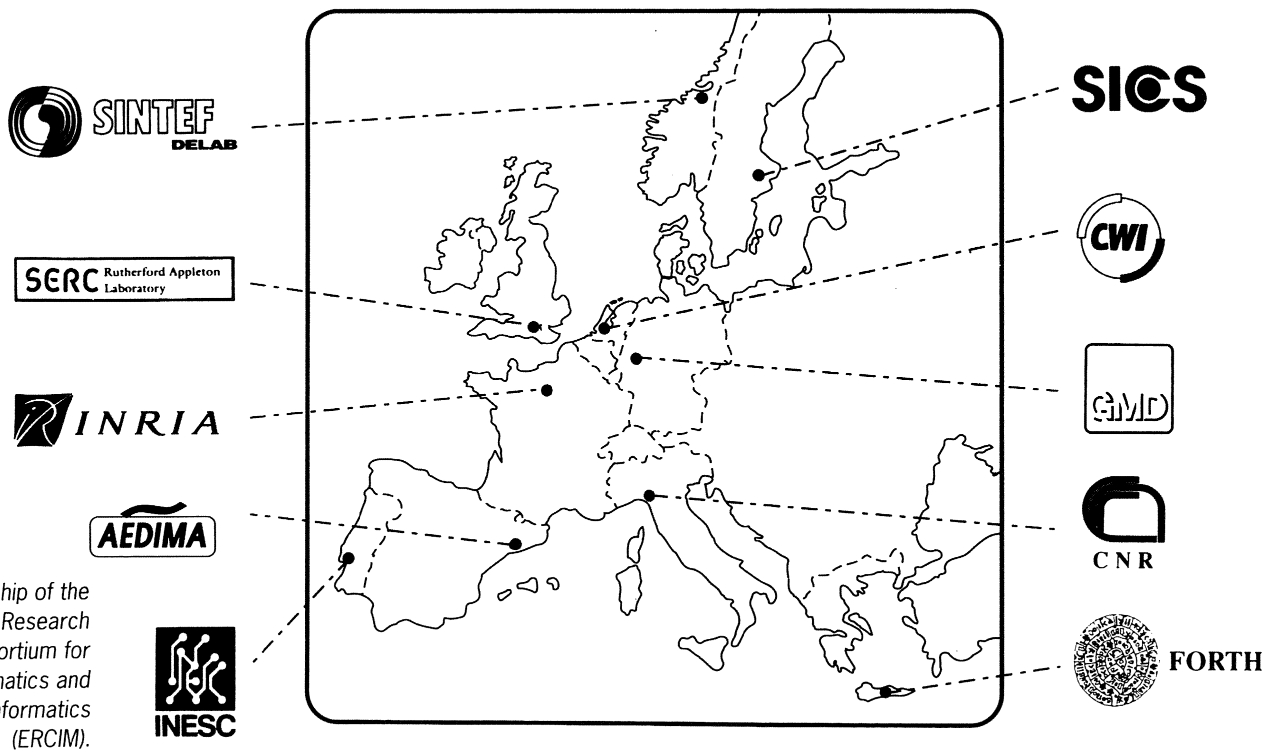
Privacy, digital signatures
Results of cryptology research included two Ph.D.'s: J.N.E. Bos (Practical Privacy) and E.J.L.J. van Heyst (Special Signature Schemes).

Parallel communication model
Completion of the initial version of the MANIFOLD language (a communication model for parallel systems) was followed by development of a mark II. This is simpler and more flexible. Benefits include enhanced portability, e.g. to a massively parallel system like Parsytec.

ERCIM

Development of the Research Consortium for Informatics and Mathematics (ERCIM) progressed apace. Norway (SINTEF-DELAB), Greece (FORTH-ICS), and Sweden (SICS) became members in 1992. The consortium now has nine members from northern, western and southern Europe. All are national research institutes in the area of informatics and applied mathematics. With its total of almost 4,000 researchers ERCIM has the ability and determination to be a leading player in the guidance and realization of European research policy on information technology.

In 1992, ERCIM was registered under French law as a European Economic Interest Group (EEIG). This allows ERCIM to act officially within the European Community, on behalf of its members, to acquire research funding, or to act as partner in joint projects with third parties. The initial result of this was the allocation of an ECU 600,000 grant under the EC's Human Capital & Mobility programme, as support for ERCIM's fellowship programme. This allowed the 1992/93 round to be increased from six to nine fellowships. These 18-month fellowships are spent at two or, preferably three ERCIM member institutes. ERCIM's courses for advanced researchers were already supported under the EC's COMETT II programme.



Membership of the European Research Consortium for Mathematics and Informatics (ERCIM).

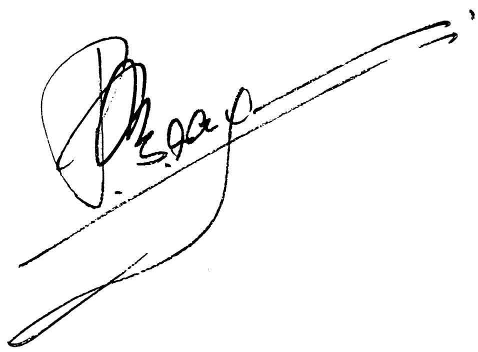
An important step, and one necessitated by the fast growth of ERCIM, was the formation of a strong Executive Committee to implement policy as established by ERCIM's Board of Directors (President: Prof. Cor Baayen, CWI). Chaired by Prof. Bob Hopgood (RAL), the Executive Committee drew up a business plan which has prompted activity on several fronts. The EC's support for the ERCIM Fellowship Programme was the first tangible fruit of this. An official response was also formulated to the European Commission's Fourth Framework Programme. In this, ERCIM urges concentration on strategic research - in direct contrast to the present, direct-to-market tendency. Further, it was decided in principle that ERCIM would participate as European partner in the Japanese Real World Computing project. ERCIM also made an appearance at the annual ESPRIT week in Brussels.

The quarterly journal, ERCIM News, was just one of many publications by the consortium. The full list includes:

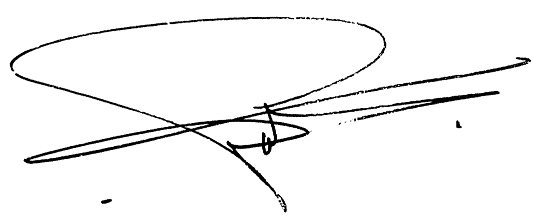
- proceedings of the half-yearly workshops in Pisa (Numerical Linear Algebra, Software Quality, Knowledge Representation) and Heraklion (Network Management, Software Reuse, Parallel Architectures for Computer Vision, Numerical Methods in Wave Propagation);
- Strategic Research: a Major Focus for the Fourth Framework Programme;
- several reports by ERCIM fellows.

However much care and preparation there may be, a change of course plus a reorganization demands commitment and creativity by all employees. We count ourselves lucky that research and support staff have both displayed these qualities in abundance during the first year of adjustment. This justifies our confidence that we can progress along the route we have started.

P.C. Baayen, Scientific Director



G. van Oortmerssen, Managing Director



ORGANIZATION

CWI (Centre for Mathematics and Computer Science) is the research institute of the Foundation Mathematical Centre (SMC), which was founded on 11th February 1946. SMC falls under The Netherlands Organization for Scientific Research (NWO), the main source of funding.

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

SMC also finances National Research Activities in Mathematics at Dutch Universities. This consists of some 55 research projects, organized in eight national working parties in the following fields:

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

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

In 1992, two additional types of activities: *Special Attention Areas* and *Special Years* were started, on the subjects 'Mathematical aspects of non-linear dynamical systems' and 'Logic', respectively.

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

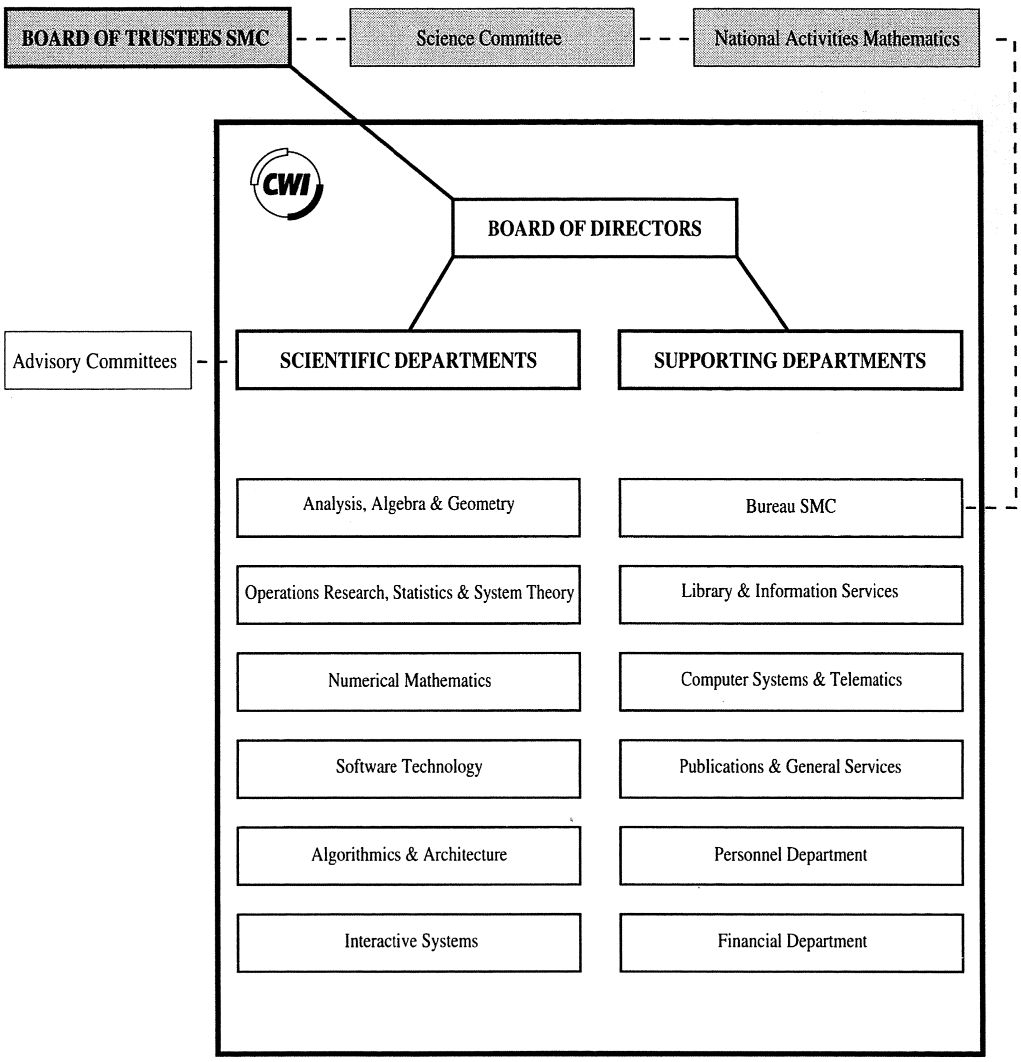
In recent years CWI was evaluated by international visiting committees: the subjects statistics, stochastics and system theory in 1987; algebra, analysis, geometry, optimization and numerical mathematics in 1989; and computer science in 1991.

The year 1992 saw the publication of the Government's Advisory Committee on Mathematics report (see also the Introduction), in which some recommendations are made with regard to CWI's future organization.

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

The organization structure of SMC and CWI is shown on the opposite page. The structure of the scientific departments is less rigid than it appears, given considerable inter-departmental collaboration. This has led to the definition of Multidisciplinary Research Programmes cutting right across the departmental research groups - and staffed by members of these groups. In 1992 two such programmes, *Mathematics & Environment* and *Multimedia*, had reached the stage of actual implementation supported by state-of-the-art computer facilities and a well stocked library. Researchers at CWI are ideally equipped to handle the dynamic and interdisciplinary demands of present day research.

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



RESEARCH HIGHLIGHTS

Algorithmic Algebra

Research Programme	:	Algebra, discrete mathematical structures and computer algebra
Researcher	:	M.A.A. van Leeuwen

Introduction

Over the last century algebra has developed into a widely ramified collection of abstract theories, but in recent years new emphasis has been put on effective (i.e., algorithmic) techniques. This was triggered by the advent of computers and the wish to apply their increasing capabilities to the kind of computations that had traditionally been done using pencil and paper. New perspectives arise because on the one hand the range of feasible computations is greatly increased, and on the other hand it becomes increasingly desirable to replace heuristic methods by truly algorithmic ones. At CWI efficient algorithms are being developed and implemented in several algebraic areas. Also convenient ways to make algorithms from various sources available to users are investigated.

Some ancient and recent history

The algorithmic aspects of algebra date back to its very origin, in that algebra developed from arithmetic by the introduction of formal symbols for unknown quantities. Originally, algebra was the art of manipulating expressions and equations containing these formal symbols so as to eventually obtain a solution for some given problem. The term is derived from the Arabic 'al-Jabr', literally meaning 'restoration', and was introduced by the great 9th century mathematician al-Khowarizmi, whose name also lives on in the term 'algorithm'. It transpired that the algebraic method was quite generally applicable, and not restricted to problems stated in terms of arithmetic; as various mathematical fields were developed many of them employed algebraic techniques to find explicit solutions to problems, and there also are numerous applications in other sciences and engineering as well. Meanwhile, algebra itself has evolved from studying the formal expressions and the rules by which they may be manipulated, to the investigation of the mathematical structures, among them those consisting of the set of *all possible* formal expressions of a certain kind; for instance the theory of polynomial rings is derived in this way from the study of arithmetic expressions (not involving division). While this has contributed to an increased insight into the mathematical foundation of formal computations, a further consequence is that in large parts of algebra the primary focus is not on explicit calculations.

As their name suggests, computers have been used for computing, ever since they first appeared, but remarkably rather than first taking over the algebraic pencil-and-paper type of computation they went for the slide-rule type: calculation with approximated numbers (but on an unprecedented scale), also termed *numeric* computation. While their digital nature would seem to make computers pre-eminently suited to perform exact algebraic manipulations, there were technical difficulties which caused this *symbolic* mode of computation to start up much slower than its numeric counterpart; one such problem is the unpredictability of memory requirements in many symbolic computations. Nevertheless programs performing symbolic manipulations have been developed over the years, and have culminated in several extensive packages such as Macsyma, Reduce, Maple and Derive. These programs are only just starting to reach the full range of scientific and industrial researchers for whom they are potentially useful, due to the combination of fast processing, ample memory and interactive use required for many of the computations, now becoming available on a large scale in the form of powerful workstations and personal computers.

This mode of computation is commonly referred to as 'Computer Algebra' in accordance with the traditional association of formal manipulations with algebra. However, the problems that can be tackled are by no means restricted to algebraic ones, and include such analytic problems as symbolic integration and (formal) solution of differential equations; indeed computer algebra is probably being used more heavily in the natural sciences than in mathematics. In fact, until recently relatively little attention has been given in computer algebra to computations in algebraic structures which are not modelled after formal expressions representing numbers; examples are groups and Lie algebras. And yet there is also much to be gained in these areas from being able to perform explicit computations ('experimental' mathematics); and since there is generally no possibility for numeric approximation in these fields, calculations will always have many of the characteristics of symbolic computation, even if they do not involve handling symbols representing unknown objects. In other words, in this area the distinction between representing mathematical objects by explicit coordinates (often using numbers, not in an approximate way, but as *exact* entities) or by formal expressions (which we shall call 'truly symbolic') is not a very fundamental one, and one often seeks to switch between them. Hence, apart from the 'general' computer algebra packages mentioned above, specialized packages have been developed for computations in specific algebraic areas; the oldest example is the Cayley package which specializes in group theory.

Lie groups were first studied by the Norwegian mathematician Sophus Lie (1842-1899). Lie groups and their associated algebras play a crucial role in several fields of theoretical physics and mathematics. CWI developed the LiE computer algebra package to carry out formal computations on reductive Lie groups and algebras.

Computer algebra at CWI

'LiE', developed at CWI, is another such package; it deals with reductive Lie groups and algebras, and their representations. Lie groups and algebras play a crucial role in several areas of mathematics and theoretical physics. In this area the theory provides numerous algorithms by which quantities of interest can be explicitly computed. However, without efficient implementations the practical utility of these algorithms is limited to a small number of relatively simple cases; even if one were to instruct one of the general purpose computer algebra packages to execute the algorithms (and that is certainly within their capabilities), the efficiency would be poor because these packages are not very specialized at performing the multitude of relatively trivial operations required (often combinatorial in nature), while their powerful symbolic facilities would remain largely unused. For this reason LiE was developed as a library of implementations of all the main algorithms in this specific area, programmed directly into an independent program. The program also shares with more general packages such features as are needed to make it a useful tool for practical computation: a flexible interactive interface, programmability, input and output facilities. On the other hand, a number of restrictions were deliberately made, which are not much of a limitation to the intended kind of computation and helped to keep the size of the project manageable: there is only a small number of data types and the program has no truly symbolic facilities. Within these restrictions and the specific area for which it is intended, LiE reached a fairly complete and stable state in 1992.

With the experience of having built a self-contained computer algebra package, attention has shifted to the wider perspective of exact computational methods, in particular in various areas of algebra. One direction of research is to find out which additional requirements are posed in areas where employing truly symbolic techniques is essential, and how these requirements can be met. In this way one hopes to be able to bridge the gap between specialized algebraic programs like LiE, and the more traditional general computer algebra packages which, while having the symbolic capabilities, do not handle abstract algebraic structures very well. As a specific area where these questions will be relevant, the focus has been put on Lie algebras, and the computational methods for determining their algebraic structure (these questions are beyond the scope of LiE, which only deals with representations of Lie algebras, and moreover only of reductive algebras). Another direction of interest is providing algorithms for computations in general Coxeter groups; this is a natural consequence of certain algorithms present in LiE which treat similar questions, but only for a more restricted class of groups. Thus, insight is gained into the best ways to make algorithms available to algebraists, and at the same time the (algorithmic) mathematical toolbox is enlarged.

Integrated toolbox

At a more global level questions have to be considered as to how the different parts in such a mathematical toolbox, extended with other tools such as typesetters, proof checkers, and knowledge bases, can be combined into an integrated environment in which a mathematician can effectively utilize them, without being continuously hampered by interface problems between the various parts. The multitude of programs already available, their different designs and specializations, and the new programs being developed continuously, clearly make it impossible to incorporate everything into one grand design; nor indeed is it practical to build separate interfaces between any pair of programs that one might wish to use cooperatively. The best solution to such problems, and one which has proved effective in other similar situations, is to design a general framework, which provides a systematic interface to the user and allows for basic operations of a general nature, but which permits programs that handle more specific tasks to be plugged in at will. For example, in UNIX there is the convention of writing programs (filters) which transform character streams in such a way that these can be combined by the UNIX shell into pipes, which perform more complicated tasks. At the same time conventions need to be established to guarantee a certain compatibility between the individual programs. For example, it is not sufficient to simply specify that communication takes place through character streams; there must also be some agreement on the representation of mathematical objects. Although this shows the basic direction, clearly different issues have to be treated if such a system is to support mathematical research than if the aim would be - say - to support document production, and this requires some new fundamental investigations. At CWI, the beginning of an attempt has been made to seriously attack these fundamental questions.

Mathematical Morphology

Research Programme	:	Image analysis
Researcher	:	H.J.A.M. Heijmans

Introduction

Among the major tasks in the field of image processing and analysis are feature extraction, shape description, and pattern recognition. Such tasks inherently require a geometry-oriented approach as they refer to geometrical concepts like size, shape and orientation. However, until recently the most important tools in image processing were of a probabilistic and analytic nature, and were based upon e.g. the correlation of signals and the frequency analysis of the Fourier spectrum.

Mathematical morphology is an approach to image processing which is based on set-theoretical, geometrical and topological concepts, and as such is particularly useful for the analysis of geometrical structure in an image. In contrast to the traditional approach of Fourier analysis, morphology is highly non-linear in nature, and poses several challenging mathematical problems. Below we shall briefly describe the historical development of this approach, explain its basic techniques, and discuss recent theoretical developments. Finally we outline the work carried out at CWI in this area.

What is mathematical morphology?

The word 'morphology' stems from the Greek words $\mu o \rho \phi \eta$ and $\lambda o \gamma o \varsigma$ meaning 'the study of forms'. The term is encountered in a number of scientific disciplines including biology and geography. In the context of image processing it is the name of a specific methodology designed for the analysis of the geometrical structure in an image. It was founded in the early sixties by two researchers at the Paris School of Mines in Fontainebleau, Georges Matheron and Jean Serra, who worked on a number of problems in mineralogy and petrography. Their main goal was the automatic analysis of the structure of images from geological and metallurgic specimens. They were particularly interested in the quantification of the permeability of a porous medium and the petrography of iron ores. Their investigations ultimately led to a new quantitative approach in image analysis, nowadays known as mathematical morphology. During the last two decades, this discipline has gained increasing popularity among the image processing community and has achieved the status of a powerful alternative to the classical linear approach. It has been applied in numerous practical situations, e.g. mineralogy, medical diagnostics, histology, industrial inspection, computer vision and character recognition.

Mathematical morphology has three aspects: an algebraic one, dealing with image transformations derived from set-theoretical and geometrical operations; a probabilistic one, dealing with models of random sets applicable to the selection of small samples of materials; and an integral geometric one, dealing with image functionals. Only the first aspect will be addressed here.

The central idea of mathematical morphology is to examine the geometrical structure of an image by probing it with small patterns, called *structuring elements*, at various locations in the image. By varying the size and shape of the structuring elements, one can extract useful shape information from the image. This procedure results in image operators which are well-suited for the analysis of the geometrical and topological structure of an image.

By its very nature, mathematical morphology is set-based, that is, it treats a binary image as a set. The corresponding morphological operators use essentially only three ingredients from set theory: set intersection, union, complementation, as well as translation. As a result such operators are translation invariant; additionally, they are highly non-linear. One of the basic intuitions of mathematical morphology is that the analysis of an image does not reduce to a simple measurement. Instead, it relies on a succession of operators which transform the image in order to make certain features apparent. Indeed, a picture usually contains an unstructured wealth of information; in order to analyze it, one has to distinguish meaningful information from irrelevant distortions. One has to extract what is of interest. In practice this amounts to transformations which reduce the original image to a sort of caricature. For example, in optical character recognition, one can simplify the task by first performing a *skeletonization* on a binary digital image representing a typed text, which reduces each connected component to a one-pixel-thick skeleton retaining its shape; this discards all (useless) information about the thickness of characters, and the reduced amount of information contained in such an image makes further recognition steps quicker and easier.

Theoretical developments

Although, originally, mathematical morphology was developed for binary images, from the very beginning there was a need for a more general theory. Such a theory needs to be powerful enough to handle for example grey-scale images and other object spaces such as the closed subsets of a topological space or the convex sets of a (topological) vector space.

Besides this enormous variation in object spaces there is yet another quite important generalization; namely, it is by no means obvious why morphological operators have to be translation invariant. In radar imaging, for example, rotation invariance is more appropriate (radar images are expressed in polar coordinates, with the observer at the origin). Furthermore, there are a number of situations where perspective transformations enter naturally. Think, for instance, of the problem of monitoring the traffic on a highway with a camera at a fixed position. It is obvious that in such a configuration the detection algorithms should take into account the distance between the camera and the object (e.g., a car).

Only recently it has been realized that complete lattices are the right mathematical framework for a general theory of morphology. (A complete lattice is a set with a partial order '$\leq$', such that every subset has a supremum and an infimum.) The main motivation for this generalization is that it unifies a number of particular examples into one abstract mathematical framework; they help to prevent the periodic 'reinvention of the wheel' which occurs too often in applied mathematics and engineering, where 'new ideas' are sometimes particular cases of 'old ideas' in pure mathematics. A second motivation intimately connected to the previous one is that an abstract approach provides a deeper insight into the essence of the theory (which assumptions are minimally required to guarantee certain properties?) and links it to other, occasionally rather old, mathematical disciplines. The efforts to build a general theory (partially carried out at CWI) have had a very pleasant side-effect: they have resulted in the design and validation of new types of morphological operators such as new classes of openings (for the definition of an opening, see below).

Research at CWI (general)

Research at CWI in the area of mathematical morpohology has focused on two themes: the development of a consistent complete lattice framework, and the construction of morphological filters. As regards the first of these, it is clear that the main requirement to be met by an abstract theory is that it covers all image classes relevant in the context of mathematical morphology. Other image classes are conceivable alongside binary images and grey-scale images on the continuous Euclidean space or the discrete grid. We discuss one of them in greater detail here.

In a number of situations a pixel image is not the optimal structure for representing an image. In histology, for example, one studies images of cells in a tissue. It seems reasonable to model such a population (of cells, in this case) as the vertices of a graph. For this purpose one can choose a neighbourhood graph constructed with the aid of the so-called *Voronoï diagram* as such graphs provide meaningful relationships between cells. Using classical morphological tools, one can then try to characterize quantitatively such notions as the average number of neighbours of a cell, size distribution of the clusters of cells of a given type, or cells sharing common characteristics. Such analyses can be done in the graph itself, which means that the actual distances between cells do not matter.

Although complete lattices provide the right

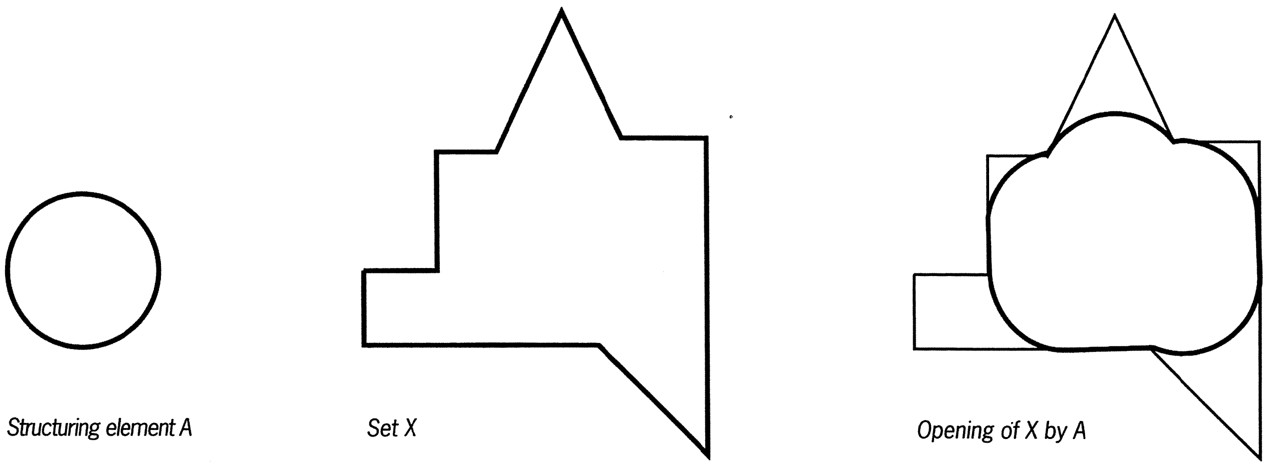


Figure 1

algebraic structure for mathematical morphology, they are too general for practical purposes. Topological and geometrical concepts are equally important in extracting quantitative geometric information from a scene. In the graph example discussed above, one can define a metric on the nodes by taking the neighbourship relations into account.

Another class of problems dealt with at CWI concerns the construction of morphological filters. By applying such filters, an image can be transformed (e.g., noise removal) so permitting meaningful measurements of the resulting image. Mathematically, a 'filter' is an operator ψ which is increasing (if $X \leq Y$ then $\psi(X) \leq \psi(Y)$) and idempotent ($\psi^2 = \psi$). Idempotence seems a sensible requirement for a filtering operation as it characterizes the successive stages of a series of transformations in image analysis. Indeed, if an operation is idempotent, then there is no point in repeating it, and so we must do something else, i.e. go to another stage. Conversely, a series of transformations must produce a clear result at one stage, and not stop halfway.

Given a filtering operator ψ which is not idempotent, one often applies it until the result ceases to change. This corresponds to a conditional loop, such as '**while** ... **do** ...'; provided such a loop eventually terminates, it implements an idempotent operation. However, in general there is no guarantee of convergence. At CWI a theory has been developed which says under what sort of conditions on the operator ψ, iteration leads to idempotence. This theory covers all the interesting cases occurring in practice.

Of particular interest are self-dual filters, which treat foreground and background identically. A well-known example of a self-dual image operator is the median operator. Take for example a binary image (1= black, 0= white). The median operator M associates with each pixel the median m of the nine neighbouring pixel values (central pixel included). Operating on the complementary image (black and white interchanged), M produces a median m^c, whose complement $(1 - m^c)$ equals m. Unfortunately, the median operator, which has a number of interesting statistical properties, and which is eminently suited for the removal of impulse noise, is not idempotent. The theory addressed above shows how to modify the median operator so that its iterates converge to a self-dual filter.

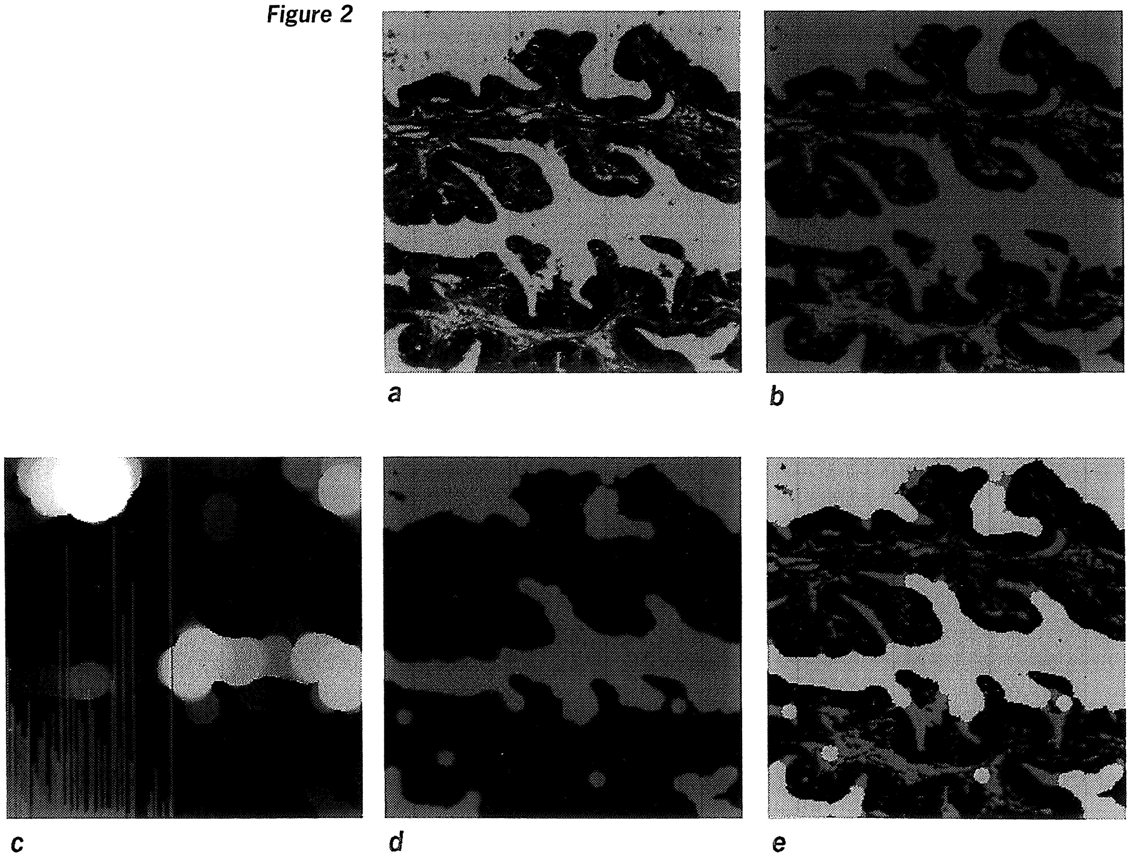
The opening transform

The key principle underlying mathematical morphology is to gain geometric information about a binary image by probing it with a specific small set (e.g., a disc), called the *structuring element*. The idea is perhaps best illustrated by discussing one operator in more detail, the *opening*, probably the most important operator in daily morphological practice. The opening is an operator which is increasing, idempotent and anti-extensive. The latter means that the transformed image is contained in the original one. Let A be a structuring element in $\mathbb{R}^2$, that is, $A \subseteq \mathbb{R}^2$. The opening of the set X by A, denoted $X \circ A$, is the union of all translates of A which are contained inside X:

$$X \circ A = \bigcup \{A_h \mid |h \in \mathbb{R}^2 \text{ and } A_h \subseteq X\}.$$

Here A_h denotes the translate of A along the vector h. The opening is obviously translation invariant: opening the translate X_h of the set X

Figure 2



leads to the same result as opening the original set and translating the outcome, i.e.

$$X_h \circ A = (X \circ A)_h.$$

The opening is illustrated in Figure 1.

Consider the family of structuring elements rB, consisting of the spheres in $\mathbb{R}^2$ centered at the origin and with radius $r > 0$. The family of openings $\alpha_r(X) = X \circ rB$ satisfies the following semi-group property:

$$\alpha_r \alpha_s = \alpha_s \alpha_r = \alpha_r \quad \text{if } r \geq s.$$

This is due to the fact that a larger ball can be obtained as a union of smaller ones. This semi-group property forms the basis for a formal definition of a *size distribution*. The openings α_r formalize the intuitive idea of the sieving of a binary image according to the size and shape of grains within the image. As the mesh size of the sieve (the radius r) is increased, more of the image grains will fall through the sieve and the residual area of the filtered (sieved) image will decrease monotonically. These residual areas form a size distribution, called *granulometric size distribution*, that is indicative of the image structure. Its derivative is a density function, called the *granulometric size density*.

The opening transform of a binary image $X \subseteq \mathbb{R}^2$ is a function $F : \mathbb{R}^2 \rightarrow \mathbb{R}_+$ whose value $F(h)$ at the point h represents the radius r of the largest sphere which contains h and fits entirely inside X. In Figure 2 we depict: a grey-scale image (a); a binary image obtained by thresholding, i.e. declaring values below a certain threshold white, and above it black (b); its opening transform (c), displayed as a grey-scale image, and superimposed on it the histogram of its grey-values (which corresponds with afore-mentioned granulometric size density); a particular opening (d) of the binary image, obtained by thresholding the opening transform; a comparison (e) of the opened image (yellow) with its original. In this particular case the 5-7-11-chamfer metric has been used as an accurate discrete approximation of the continuous Euclidean distance.

Filtering and segmentation

One goal of image filtering may be the enhancement of the visual quality of a distorted image.

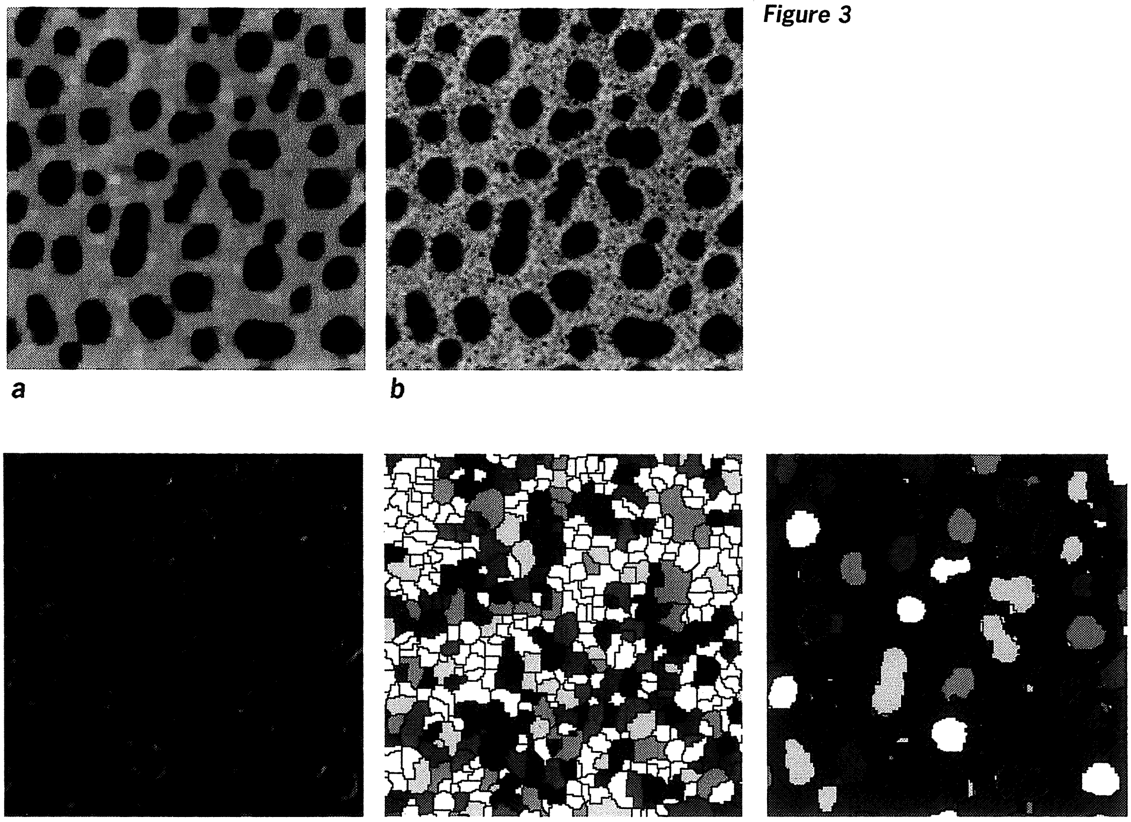


Figure 3

a b c d e

More frequently, however, its goal is to make the image more suitable for subsequent image processing tasks, such as segmentation. An original morphological method of segmentation is the 'watershed algorithm'. The basic idea is to regard an image as a topographic relief consisting of mountains (high grey-values) and passes (low grey-values). Imagine rain falling in such a landscape, and the water flowing along a steepest-descent path until it reaches a minimum level. Associated with this minimum is the catchment basin consisting of all positions such that all drops falling at this particular position reach the given minimum. The boundaries of the different catchment basins constitute the so-called watershed. Though watershed algorithms provide a powerful method for image segmentation they are, like many other segmentation techniques, sensitive to noise. This is illustrated in Figure 3 where we show: a distorted image (a); its gradient (c) (to which the watershed algorithm is applied); and the resulting segmentation (d). Due to the noise, the number of resulting regions is too large. Pre-processing the original image with some morphological filter (in this case with a so-called alternating sequential filter which is a composition of openings and closings, i.e. openings of the background) yields an image (b) whose segmentation (e) is better than the one for the original image.

Parallel Techniques in the Numerical Solution of Initial-value Problems

Research Programme	:	Discretization of evolution problems
Researcher	:	B.P. Sommeijer

Introduction

Many problems occurring in technical sciences are described in terms of time-dependent differential equations. As the analytical solution of such equations is rarely available, we have to resort to numerical methods for the approximate solution of the problem. Usually many time steps are needed to provide an accurate solution in time and, particularly for partial differential equations, this confronts us with a tremendous computational task. The power of traditional (i.e., sequential) computers is far from sufficient to cope with this huge task. The recent arrival of sophisticated vector- and parallel computers is certainly a step forward in the direction of a satisfactory treatment of these problems. However, many of the available numerical algorithms originate from the 'sequential' era and are not suited to take full advantage of these new architectures. Hence, research at CWI concentrates on the construction and analysis of new numerical methods, which are especially designed for these new computer types.

Background

Although parallel computers have been available for quite a few years, it is remarkable that the construction of parallel methods for the initial-value problem (IVP)

$$\frac{dy(t)}{dt} = f(y(t)), \quad 0 \le t \le T, \quad y \in \mathbb{R}^N,$$

$$f : \mathbb{R}^N \to \mathbb{R}^N, \quad \text{with } y(0) \text{ given}$$

received only marginal attention. In fact it is still in its infancy. A possible explanation is that the integration of an IVP is traditionally performed in a step-by-step way, which is sequential in nature. As a consequence, this approach offers little scope to exploit parallelism.

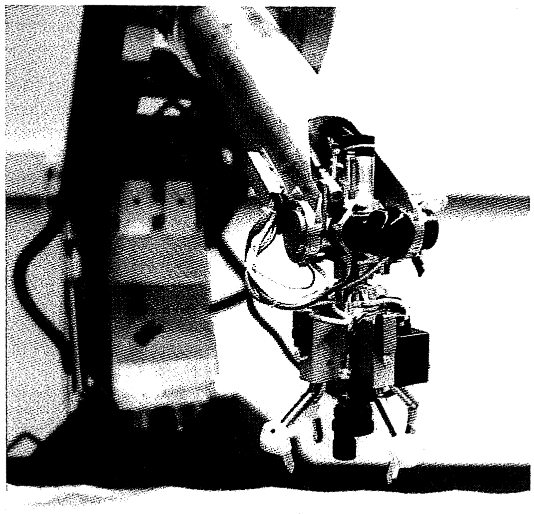
Nevertheless, there are some avenues: in the first instance, there is the rather obvious way to distribute the various components of the system of differential equations amongst the available processors. This is especially effective in methods which frequently need the evaluation of the right-hand side function f for a given vector y, so that the components of f can be evaluated independently of one another. This approach is termed *parallelism across the problem.* Many modern computer architectures are of the so-called vector-parallel type which means that they possess a number of vector pipes (typically 4, 8, or 16), which can perform calculations in parallel. Each vector pipe is very well suited to do arithmetic operations on (long) vectors and produces, after some start-up time, every clock cycle a result. Hence, for large values of N (the dimension of the IVP), the parallelism-across-the-problem approach can offer a significant speed-up. Moreover, this technique can be applied to any existing (i.e., sequential) IVP-solver, simply by cutting the long loops into smaller ones, the number of which equals the number of vector pipes.

However, this is not the end of the story; we can do a lot more: the above-mentioned kind of parallelism can easily be combined with another kind, called *parallelism across the method.* By this we mean that we try to exploit concurrency which is inherent in the method. Concurrent evaluations of the entire function f for various choices of its argument, and the simultaneous solution of various (non-linear) systems of equations are examples of parallelism across the method. Unfortunately, virtually no existing method for the numerical solution of an IVP possesses this property of inherent parallelism. Therefore, we have to construct new algorithms with the special aim that several concurrent sub-tasks of approximately the same computational complexity can be distinguished. Once such methods have been constructed, each sub-task can be assigned to a processor, or to a cluster of processors. Notice that this approach is also effective in case of a scalar differential equation (i.e., $N=1$). However, in case of large N-values, the vector capabilities of each processor (viz., vector pipe) can also be utilized, as both techniques are more or less independent.

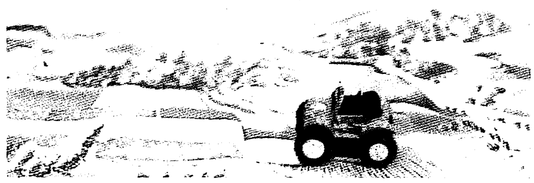
Finally, we mention a third approach, which is known as *parallelism across the time.* Contrary to the step-by-step idea, many time steps are performed simultaneously. In this way, numerical approximations to the IVP-solution are calculated in many points on the t-axis in parallel. In fact, these methods belong to the class of waveform relaxation methods. Experiments have shown that a substantial speed-up can be obtained by this technique provided that the number of steps (and hence the number of processors) is very large.

Research at CWI

Given that parallelism across the method is the most interesting and most promising approach, research at CWI has concentrated on this technique, which resulted in the construction of new algorithms. Here we have to distinguish between two types of IVPs: those which are called *stiff*, meaning that the solution consists of components varying slowly and rapidly in time, and those which do not have this property, termed *non-stiff.* Both types of IVPs require a completely different numerical treatment. Most simple are the so-called *explicit methods.* As the name implies, such methods are straightforward: the solution only needs evaluations of the right-hand side function f. In the case of non-stiff problems, an explicit method is an appropriate choice. However, these methods are very inefficient when dealing with stiff problems, since unavoidable rounding errors and discretization errors will be accumulated from step to step. This accumulation, which is called *numerical instability*, is more pronounced if the stiffness increases and



6 degrees-of-freedom anthropomorphic robot manipulator, used at the University of Amsterdam in neuro-computational research, at work in a visual tracking task. High-speed performance of numerical computations is crucial in many applications, like robotics, where a real-time response is required.



may easily destroy the numerical solution in a few time steps. There are two remedies to recover a stable integration process (i.e., bounded accumulation of errors): first, there is the possibility to reduce sufficiently the step size; for many stiff problems this leads to such a stringent restriction, that this remedy is not feasible from a practical point of view. A more realistic approach is to change to an *implicit method*, which can be given much better stability properties. Compared with explicit methods, implicit methods are more sophisticated and technically much harder to handle. Instead of evaluating the function f, a large and in general non-linear system of algebraic equations has to be solved by iteration in each integration step. The above considerations show that stability is the main concern in constructing a sequential as well as a parallel stiff IVP-solver.

Another aspect which is relevant both for stiff and non-stiff solvers is the *order of accuracy.* Obviously, the accuracy of the numerical approximation depends on the step size; if the error in the numerical result behaves (asymptotically) as the step size to some power p, then p is said to be the order of accuracy of the method. Many problems, especially those with a sufficiently smooth solution, are most efficiently solved by a high-order method. In such cases, the challenge in constructing a method is to obtain as high an

Carl David Tolmé Runge (1856-1927), left, and Martin Wilhelm Kutta (1867-1944), right, pioneered a very efficient and still widely practised method for the numerical solution of ordinary differential equations.

The implicit Runge-Kutta (RK) methods for numerical solution of ordinary differential equations have excellent stability properties, but are very costly when implemented on a computer. Precisely the reverse is true when it comes to Backward Differentiation Formulas (BDFs) of orders higher than two. Using parallelism one can combine BDF efficiency with RK stability.

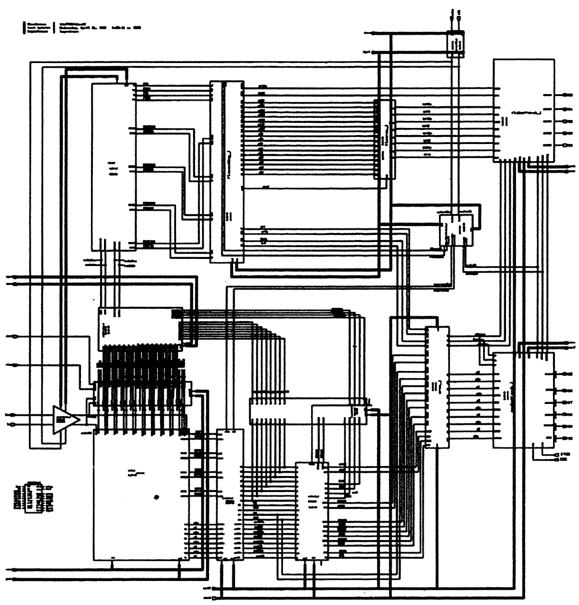
order as possible, relative, of course, to the required amount of arithmetic of the corresponding method. In terms of these two concepts - order of accuracy and stability - the results of the CWI research will be outlined below.

Non-stiff problems

Non-stiff problems are frequently encountered in e.g. celestial mechanics (orbit equations), control engineering problems (robotics), etc. It may also happen that problems which initially behave as non-stiff, eventually change to stiff, and/or vice-versa. For example, in orbit equations describing the motion of a number of planets, the stiffness is inversely proportional to the (smallest) mutual distance. Needless to say that in such situations an efficient solution process should be able to adapt the proper integration method.

A well-known class of methods for the numerical integration of non-stiff IVPs is the class of explicit *Runge-Kutta* (RK) methods. These widely used methods are quite popular for the following reasons: they are rather accurate and their implementation is straightforward (viz., they are self-starting and allow for an easy change of the step size). However, a disadvantage is that, for high orders of accuracy, the computational work per step (i.e., the number of times that the right-hand side function f has to be evaluated) grows faster than linearly if the order increases. Moreover, traditional RK methods do not allow for parallelism across the method since the argument y in the various f-evaluations depends on previous f-values and thus has to wait for their availability. However, it is possible to utilize the availability of a number of processors operating in parallel as follows. With each f-evaluation introduce some additional evaluations which can be calculated concurrently. By counting the number of f-evaluations that actually have been calculated in parallel as one single f-evaluation, it is possible to construct high-order accuracy RK methods for which the order equals the number of f-evaluations, for arbitrary order.

We have implemented such a parallel RK method on a 4-processor computer and found that this method is more efficient than the best sequential IVP-solver by a factor 2. Here we see that it is over-ambitious to hope for a speed-up with a factor s if we have s processors available. This reduction to 50% efficiency is due to the fact that we introduced an element of redundancy in the total computational volume in order to achieve parallelism across the method. However, because of the practical relevance of IVPs in technical applications, a speed-up with a factor two is certainly of great impact.



Circuit diagram of the Philips TDA8760 monolithic bipolar 10-bit AD converter. Uses include HDTV, video signal and radar pulse digitizing, and medical imaging. The circuit contains more than 2600 transistors, 400 resistors and 6 external capacitors. (Courtesy Philips Research Laboratories.)

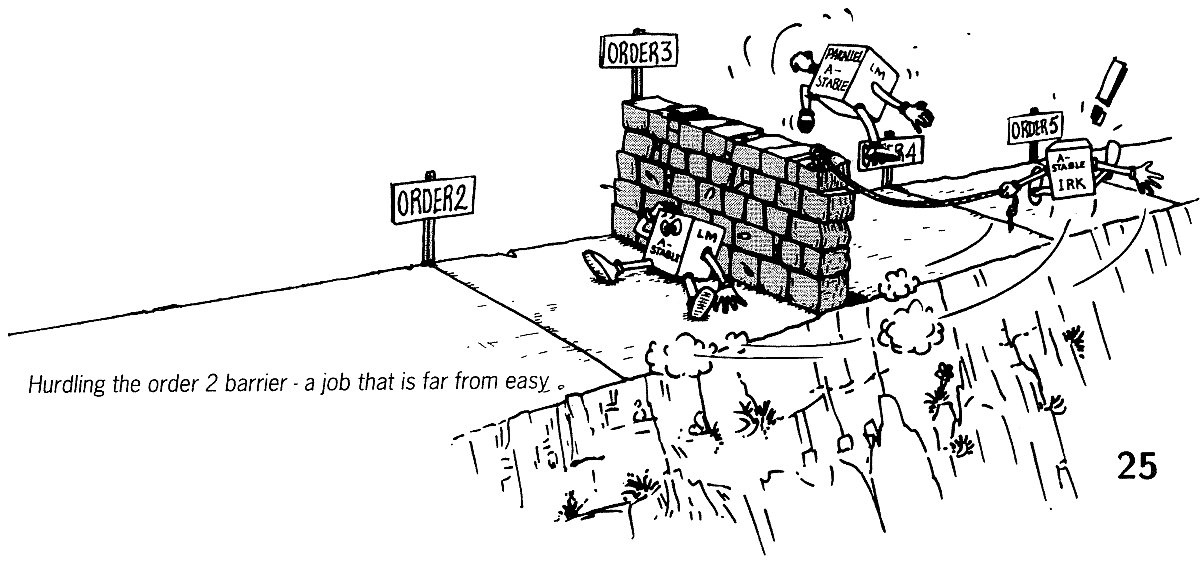
Electrical circuits are modelled by large systems of stiff ordinary differential equations. These types of simulation present a monumental computational task. Only the very fastest, i.e. parallel, computer architectures plus appropriately designed numerical algorithms can cope here.

Stiff problems

The mathematical formulation of chemical reactions often leads to stiff differential systems because, typically, the reaction speeds of the various components differ several orders of magnitude. Also the description of an electrical circuit usually gives rise to a stiff IVP. Furthermore, many semi-discrete partial differential equations (like reaction-diffusion problems) can be considered as systems of stiff ordinary differential equations.

Nowadays, the majority of the stiff IVPs is numerically integrated by means of the so-called *Backward Differentiation Formulas* (BDFs). These (sequential) methods are relatively cheap per step (which explains their popularity), but suffer from the disadvantage that a high order of accuracy cannot be combined with good stability properties. Parallel variants of these methods have been constructed and analyzed at CWI, which require the same computational effort on a parallel machine as a BDF on a sequential computer. These variants combine good stability behaviour with a high order.

Sequential Runge-Kutta methods have also been suggested for stiff IVPs in the literature; because of the stiffness, these methods are necessarily implicit. From a theoretical point of view, these implicit RK methods have ideal numerical properties: arbitrarily high orders can be combined with excellent stability behaviour. The reason that they have never been able to compete with the BDFs is that the implicit RK methods are extremely expensive per step when implemented on a (sequential) computer. In this context, parallelism across the method has been exploited to give these methods a renewed chance. CWI has designed parallel methods which significantly reduce the computational work per step, and still maintain the outstanding numerical qualities of these methods.



Hurdling the order 2 barrier - a job that is far from easy.

For implicit methods the use of parallelism is even more effective than for explicit methods, since the sub-tasks which are assigned to the various processors consist of a considerable computational load

(e.g., to find the solution of a non-linear system of equations). This keeps the processors busy for a relatively long time, thus reducing the negative influence of synchronization and communication on the performance.

Based on these techniques, a parallel IVP-solver has been implemented on a 4-processor machine and has been compared with the best sequential stiff solvers. Comparison with the best sequential RK-based code shows a speed-up with a factor 6 to 8. Comparison with the best BDF-based code shows a speed-up with a factor 2 where the poor stability of the BDF method does not hamper the integration process, and a speed-up with a much larger factor when the IVP causes the BDF code to run into stability-induced difficulties. And hence, in this case, a side-effect of this kind of parallelism is that the robustness of the methods (and the resulting software) is increased, a feature which is equally important as speed-up.

Semantics

Research Programme	:	Semantics
Researcher	:	J.W. de Bakker

History

Programs are written in a programming language, and serve as a means to instruct a computer to perform a given task. As linguistic entities, programs have form and meaning. In the specification of their form, one employs syntactic rules, usually in the form of some grammatical formalism. In semantics, one is concerned with defining meanings of programs in terms of a mathematical model. For $\mathcal{L}$ a programming language (the reader may think of PASCAL, LISP or PROLOG as typical examples), one looks for a set $\mathcal{P}$ of mathematical objects and a meaning function $\mathcal{M} : \mathcal{L} \rightarrow \mathcal{P}$ (*) such that, for each $s \in \mathcal{L}$ (each program), one determines its meaning $\mathcal{M}(s) = p$ as object in $\mathcal{P}$. In general, this is a rather demanding endeavour. Programming languages are complex entities, and so are the computations specified by the programs of the language. Accordingly, ever since the advent of high-level programming languages (say from 1960 onwards), a rich body of methods and tools has been developed to be used in semantic design.

In the period 1960 to 1970, the emphasis was on the use of general techniques from the theory of computability for the formal definition of (syntax and) semantics of programming languages, e.g. based on (generalized) Markov algorithms, or Van Wijngaarden's two level grammars. Indeed, thanks to the universality of these definitional systems, it was not surprising that complete formal definitions could be given. What was lacking in these definitions was sufficient abstraction from representational (and often arbitrary) detail. Sheer symbol manipulation was often the prevalent approach.

Owing to the pioneering work of Dana Scott around 1970, the study of semantics returned to the treasured principles of mathematical logic, viz. (i) definitions should be *compositional* (a classic principle due to Frege) and (ii) definitions should clearly separate the linguistic realm from the mathematical structure(s) (the domain(s) of interpretation) to which the linguistic constructs are mapped (the $\mathcal{P}$ from definition (*) above). These principles are fundamental for the style of so-called denotational semantics, which has remained one of the major methodologies in semantics till the present day. An even more seminal contribution of Scott was the design of semantic models for the lambda calculus (cf. CWI Annual Report 1991) - and many more related languages -, couched in the framework of a general theory of (lattice-theoretic) domain equations. Jointly with his coworker, the late Christopher Strachey, Scott laid the foundations for the semantic analysis of a host of -mostly sequential- programming languages.

Subsequently, extensions of the general theory were proposed by Gordon Plotkin, especially to cover the notions of nondeterminacy and parallelism as well. Around 1980, two further innovative developments took place. Firstly, the notion of so-called *structural operational semantics* (SOS) was introduced by Plotkin. Its origin can be traced back to automata theory : a transition system $(S, A, \rightarrow)$ consists of a set of *states* S, a set of *actions* A, and a transition relation $\rightarrow \subseteq S \times A \times S$. In automata theory, one would write $\delta(s, a) = s'$, in the SOS-oriented semantics the same fact is written as $s \xrightarrow{a} s'$ (†). Plotkin's idea was to instantiate the abstract set of states S to a concrete set, viz. the set $\mathcal{L}$ of statements in a programming language, and to read (†) as: statement s performs an a-step and then turns into the statement s' - which may, in turn, make a b-step, etc. The formalism of transitions such as (†) turned out to be especially fruitful in the study of *concurrency*, initiated around 1980 in the work of Milner on CCS (a Calculus for Communicating Systems) and Hoare on CSP (Communicating Sequential Processes).

We next discuss two related areas which have been of prime importance in the history of semantics. Firstly, so-called *algebraic semantics* has gained a central status - as third methodology - alongside the methods of denotational and operational semantics. Here, the theory is built on the foundations of universal algebra (such as the notions of initial and final algebra) and equational logic. Algebraic semantics has turned out to be quite valuable, in particular for a logical underpinning of abstract data types (abstract versions of the data structures of programming). In addition, there are deep connections with the theory of rewriting, the theory of concurrency (cf. CWI Annual Report 1989), and with (the vast variety of) specification formalisms (cf. CWI Annual Report 1987).

A second area of research neighbouring on that of semantics is the theory of program correctness, verification and transformation. Historically, this work dates back to Floyd's inductive assertion method (1967), Dijkstra's structured programming and weakest preconditions (early seventies), and Hoare's axiomatic method for simple sequential languages (1969). Though partly more of a logical/syntactic flavour, this area exploits semantic modelling in the investigation of the soundness of formal systems to prove program correctness or to deduce program transformations. Also, the steps prescribed in refining a program from an abstract specification to an executable - and hopefully efficient - implementation require semantic justification.

So much for the history of semantics. Some evidence for the world-wide recognition of the developments sketched above may be inferred from the fact that five of the pioneers named above (Dijkstra, Hoare, Floyd, Scott, Milner) are recipients of the Turing award of the American Association for Computing Machinery (the Turing award being the Nobel prize of the computer science profession).

Current developments

All four areas listed above - denotational semantics, operational semantics, algebraic semantics, program logics - are topics of vigorous current activity. In denotational semantics, one observes an increased presence of the language of category theory, especially in the more advanced parts of domain theory. Moreover, interesting applications are being developed in the design of semantics driven implementations. *Abstract interpretation* is used as a technique to investigate those properties of programs which may be derived from their 'execution' in restricted - mostly finite - models, e.g. to ascertain termination properties (so-called strictness analysis). SOS-style semantic specifications are at present investigated in a language independent fashion, e.g. by analyzing the feasibility of 'automatically' deriving a denotational semantics or a system of (equational) axioms from a given SOS definition.

Semantics is partly driven by its intrinsic foundational questions, and partly by external developments such as technological advances and associated software innovations. The scene of programming language design has expanded considerably in the decade of the 1980s. The group of the traditional imperative languages (ALGOL, PASCAL), together with an occasional functional language (LISP), formed the starting point of a rapidly growing variety of programming paradigms. Languages for concurrency played a central role in the 1980s. Next, the field of functional languages gained in impact, with the language ML as, possibly, the most influential contemporary representative. *Logic programming* (LP, cf. CWI Annual Report 1988) is an area of much current interest, not in the least thanks to the influential Japanese fifth generation project. One relatively fresh protagonist on this scene is the paradigm of object-oriented (OO) languages, a belated offspring of the 1960s language SIMULA. Smalltalk and C^{++} are more contemporary instances of OO languages.

All these language families pose their own problems and often require 'special-purpose' mathematical tools. For example, functional languages rely heavily on the (theory of the) typed lambda calculus, and LP is a programming variant of Horn clause logic, itself a version of resolution logic (which is, in turn, a way of viewing first order predicate logic). Finally, it may be in order here to draw attention to the growing interest for the interface between the semantics of programming languages and that of natural languages as studied in computational linguistics (cf. CWI Annual Report 1990).

Semantics has grown in the 1980s, both in depth and in width, and it is facing ever new challenges to assimilate the continuous stream

Operational semantics for a simple language $\mathcal{L}$

We present the syntax and operational semantics for a simple imperative language. Let $(v \in)$ *Var*, $(e \in)$ *Exp*, $(b \in)$ *Test* be the (unspecified) syntactic classes of *variables*, *expressions* and *tests*. As syntax for $(s \in) \mathcal{L}$ we use

$$s ::= v := e \mid \mathbf{skip} \mid (s_1 ; s_2) \mid \mathbf{if}\ b\ \mathbf{then}\ s_1\ \mathbf{else}\ s_2\ \mathbf{fi} \mid \mathbf{while}\ b\ \mathbf{do}\ s\ \mathbf{od}.$$

Let $(\alpha \in)$ *Val* be the domain of values (e.g., integers, truth values), and let $(\sigma \in) \Sigma = \mathit{Var} \to \mathit{Val}$ be the set of *stores*. $\sigma[\alpha/v]$ denotes a store which is like σ, but for its value in v which equals α. Let E denote termination, and let $(r \in)$ *Res*, the set of *resumptions*, be given as $r ::= \mathrm{E} \mid (s : r)$. *Transitions* are written as $< r, \sigma > \to < r', \sigma' >$. The transition system $\mathcal{T} = (\mathit{Res}, \Sigma \times \Sigma, \to)$ has as rules

- $< (v := e) : r, \sigma > \to < r, \sigma[\alpha/v] >$, with α the value of e in σ
- $\dfrac{< s_1 : (s_2 : r), \sigma > \to < r', \sigma' >}{< (s_1 ; s_2) : r, \sigma > \to < r', \sigma' >}$
- $< \mathbf{while}\ b\ \mathbf{do}\ s\ \mathbf{od} : r, \sigma > \to < \mathbf{if}\ b\ \mathbf{then}\ s ; \mathbf{while}\ b\ \mathbf{do}\ s\ \mathbf{od}\ \mathbf{else}\ \mathbf{skip}\ \mathbf{fi} : r, \sigma >$

(We omit the obvious rules for the **skip** and **if**... **fi** statements.) Let $\Sigma^\infty = \Sigma^* \cup \Sigma^\omega$ be the set of finite or infinite sequences of stores, with ε the empty sequence, and let $(p \in) \mathbf{P} = \Sigma \to \Sigma^\infty$. The operational semantics $\mathcal{O} : \mathit{Res} \to \mathbf{P}$ is the (unique) function satisfying $\mathcal{O}(\mathrm{E})(\sigma) = \varepsilon$, $\mathcal{O}(s{:}r)(\sigma) = \sigma' \cdot \mathcal{O}(r')(\sigma')$, for $< s{:}r, \sigma > \to < r', \sigma' >$ derivable from $\mathcal{T}$. Then $\mathcal{O}[\![s]\!] \stackrel{def}{=} \mathcal{O}(s : \mathrm{E})$ gives the *operational semantics* for $\mathcal{L}$.

Remark: Uniqueness of the $\mathcal{O}$ as specified above relies on an argument involving the completeness of the metric space **P**, contractiveness of the operator used (implicitly) to define $\mathcal{O}$, and Banach's fixed point theorem.

Denotational semantics for $\mathcal{L}$

Let $(p \in)$ *Cont* be the set of *continuations* - the semantic counterparts of the syntactic resumptions. Here, $\mathit{Cont} = \mathbf{P}$ ($\mathcal{L}$, **P** are as in Box 1). We define $\mathcal{D} : \mathcal{L} \to (\mathit{Cont} \to \mathbf{P})$ as the unique function satisfying

$$\begin{aligned}
\mathcal{D}(v := e)(p)(\sigma) &= \sigma[\alpha/v] \cdot p(\sigma[\alpha/v]),\ \alpha \text{ as in Box 1} \\
\mathcal{D}(s_1 ; s_2)(p)(\sigma) &= \mathcal{D}(s_1)(\mathcal{D}(s_2)(p))(\sigma) \\
\mathcal{D}(\mathbf{while}\ b\ \mathbf{do}\ s\ \mathbf{od})(p)(\sigma) &= \sigma \cdot \mathcal{D}(\mathbf{if}\ b\ \mathbf{then}\ s ; \mathbf{while}\ b\ \mathbf{do}\ s\ \mathbf{od}\ \mathbf{else}\ \mathbf{skip}\ \mathbf{fi})(p)(\sigma)
\end{aligned}$$

(omitting the obvious clauses for **skip** and **if**... **fi**). Existence and uniqueness of $\mathcal{D}$ follow, again, by an argument based on Banach's theorem. Let $\mathcal{D}[\![s]\!] = \mathcal{D}(s)(\lambda\sigma . \varepsilon)$. For our simple $\mathcal{L}$, $\mathcal{O}$ and $\mathcal{D}$ coincide, as stated in

Theorem: $\mathcal{O}[\![s]\!] = \mathcal{D}[\![s]\!]$, for each $s \in \mathcal{L}$.
Proof (sketch): Put $\mathcal{E}(\mathrm{E}) = \lambda\sigma . \varepsilon$, $\mathcal{E}(s : r) = \mathcal{D}(s)(\mathcal{E}(r))$, and show that $\mathcal{E}$ satisfies the defining equations for $\mathcal{O}$ (Box 1) □

As soon as $\mathcal{L}$ includes more interesting features, this simple relationship ceases to hold, due to the lack of compositionality for the transition system based $\mathcal{O}$.

of foundational insights and technological advancements.

Contributions of CWI

Parallelism or *concurrency* has been a major focus of semantic research at CWI in the past decade (cf. CWI Annual Report 1986). An overview is contained in [2]. Characteristic for a good deal of our approach is, on the one hand, the reliance on topological structures in the semantic modelling, and on the other, the large variety of forms of parallelism considered. Not only the more traditional concurrency in an imperative setting, but also parallel versions of LP and OO have been studied in depth. In the period under review a total of six Ph.D. theses were completed on the theory of parallel processes in relation to the design and semantics of parallel languages in the style of imperative, dataflow, LP and OO programming, with one further thesis on the proof theory for parallel OO. At present, the main topics in our research are (i) full abstraction - how abstract should a denotational semantics be in relation to a given operational semantics; (ii) category-theoretic investigations in comparative domain theory; (iii) generalized finiteness conditions in topological models; (iv) predicate- versus state- transformations as theoretical underpinning for a study of refinement.

A substantial part of CWI research in this field over the years has been embedded in international or national collaborative projects. In the first category, we participated in the ESPRIT sponsored project Parallel Architectures and Languages (1984-1989, see [1] for a selection of its results on semantics) and the ESPRIT Basic Research Action Integration - integrating the foundations of functional, logic and object-oriented programming (1989-1982, cf. [4]). Currently, our foundation-laying work is supported by the SCIENCE-MASK project - Mathematical Structures in Concurrency Semantics, and a (national) SION project entitled 'Non-well-founded sets in the semantics of programming languages'. Nationally, we have collaborated for many years with the groups led by Prof. G. Rozenberg (Leiden University) and Prof. W.P. de Roever (Eindhoven University of Technology), first in the SION-sponsored National Concurrency Project (LPC, 1984-1988), and next in the NFI-project REX - Research and Education in Concurrent Systems, 1988-1993. REX has funded a series of international schools/workshops. [3] contains the proceedings of the 1992 meeting on semantics. As final event, terminating ten years of highly fruitful cooperation, in 1993 a School/Symposium will be organized entitled *A Decade of Concurrency - Reflections and Perspectives.* As in the past, the proceedings - the seventh in the LPC/REX history - will be published in Springer's Lecture Notes in Computer Science series.

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Computational Learning and DNA Sequencing

Research Programme	:	Algorithms and complexity
Researcher	:	J.T. Tromp

Introduction

By 'learning' we mean the construction or modification of a 'mental representation' of reality on the evidence of external experience. This 'mental representation' should enable us to predict real phenomena, recognize and classify similar experiences, generalize, deduce, and so on. The executing agent should be a machine (effectiveness) and preferably fast (feasibility). We distinguish:
- root learning: information is presented in the way it will later be used;
- learning by being told: information is provided in abstract form and must be integrated in the world model of the student and be adapted for applications;
- learning by examples: information is provided by the environment in the form of specific examples which can be generalized to abstract concepts or rules - this also covers the situation where the student experiments on his or her environment to obtain the required examples;
- learning by analogy: information is provided in a form analogous with later needs; the student must discover the analogy.

We are primarily interested in learning by examples, which boils down to the following strong poetic image: 'the eye of the understanding is like the eye of the sense; for as you may see great objects through small crannies or levels, so you may see great objects of nature through small and contemptible instances', [Francis Bacon].

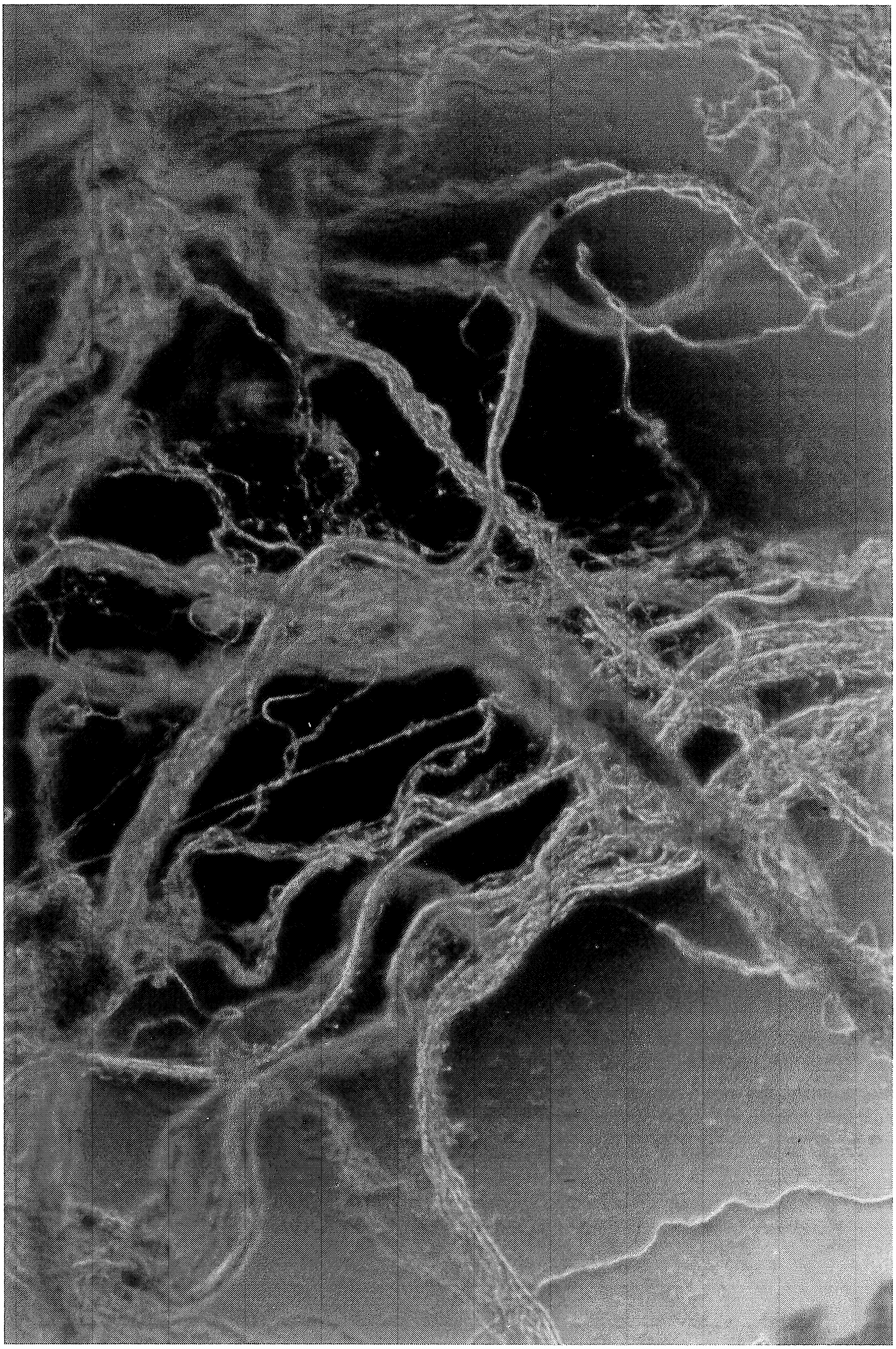
In almost all cases, automatic learning involves compression of a large body of observations into a short description such as a simple law. This procedure is an application of the philosophical dictum known as Occam's Razor: 'if more than one hypothesis explains the data, then choose the simplest hypothesis.' For instance, the laws of mechanics of Newton compress 2000 years of observations on earth and the heavens. The more compact a description is, the better it predicts.

Compact descriptions play a central role in any reasonable theory of learning. Compression of information leads to descriptions with high so-called 'Kolmogorov complexity'. This notion is as important a tool in computer science, mathematics, physics and other sciences, as is information theory. CWI pioneered the area of applications of Kolmogorov complexity (learning and inductive reasoning, combinatorics, formal languages, complexity of computation, thermodynamics of computation, chaos), set out in the first comprehensive treatment and textbook [1] on theory and applications by Paul Vitányi (CWI) and Ming Li of the University of Waterloo in Canada.

This research turns out to have impact on aspects including philosophy (solving the induction problem related to the unknown prior in Bayes' rule); technology of computation (energy-free computing by reversible computation); linguistics (human language); physics (solving paradoxes from statistical thermodynamics, and development of a quantitative chaos theory); mathematics (new proof methods in combinatorics); and machine learning (new models and algorithms).

DNA sequencing

Let us consider an example from biology. In the billion dollar 'Human Genome Project' the goal is to chart the human chromosome. This is quite a formidable task. A DNA molecule can be represented as a string over the set of nucleotides $\{A, C, G, T\}$. Such a character string ranges from a few thousand symbols long for a simple virus to approximately 3×10^9 symbols for a human being. Determining this representation



A microscopic view of some DNA strands.
(Courtesy Généthon; photo: Philippe Plailly)

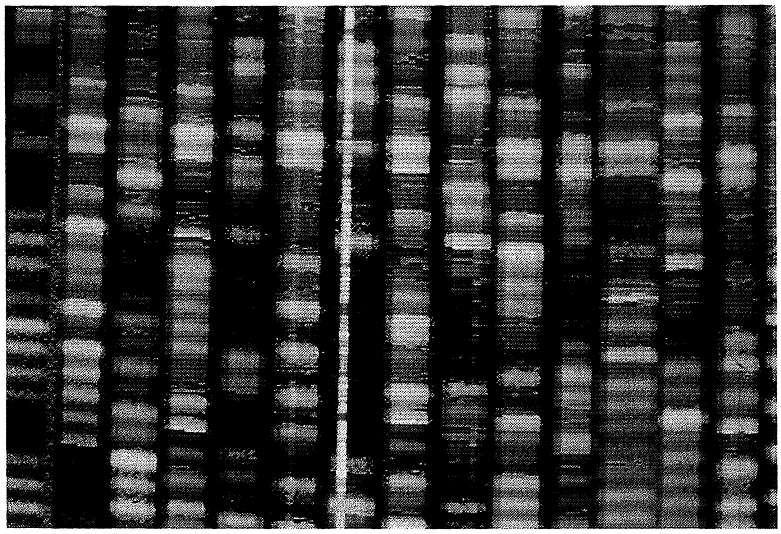
for different molecules, or *sequencing* the molecules, is a crucial step towards understanding the biological functions of the molecules. With current laboratory methods, only small fragments (originating from unknown locations in the molecule) of at most 500 nucleotide bases can be sequenced at a time. Then from hundreds, thousands, sometimes millions of these - possibly overlapping - fragments, a biochemist *assembles* a superstring, thus trying to approximate the original molecule. To this end a simple algorithm, 'greedy merge', has been in use for more than ten years. It seems to perform well in practice, but until now one has not succeeded in proving why. In abstracting away from the practical issues involved in this construction process as well as nature's peculiarities such as the alphabet of 4 bases, we arrive at the following problem:

Given a finite set of strings, we would like to find their shortest common superstring. That is to say we want the shortest possible string s such that every string in the set is a substring of s.

Example. Suppose we want to find the shortest common superstring of all words in the following sentence: 'Alf ate half lethal alpha alfalfa'. The word 'alf' is a substring of both 'half' and 'alfalfa', so we can immediately eliminate it. Our set of words is now $S_0 = \{$ ate, half, lethal, alpha, alfalfa $\}$. A trivial superstring is 'atehalflethalalphaalfalfa' of length 25, which is simply the concatenation of all substrings. A shortest common superstring is 'lethalphalfalfate', of length 17, saving 8 characters over the previous one (a compression of 8).

Unfortunately no general method is known for solving this problem quickly. The related problem of deciding, given a set of strings and an integer k, whether there exists a common superstring of length at most k has been shown to be 'complete' for the class of decision problems known as NP. It shares this dubious honour with the SAT problem of deciding whether a given boolean formula can be satisfied by some truth-assignment, and the TSP problem of deciding whether a hypothetical salesman can tour a set of cities within a given total distance. The best known algorithms for these decision problems more or less try out all possibilities and this leads to an exponential running time, which is considered unfeasible.

This means that we should content ourselves with finding a reasonably short superstring, perhaps in the belief that on the instances that arise in DNA sequencing practice this has a good chance of yielding a good enough representation of the actual molecule. What we want is a good *approximation* algorithm that can be run quickly (i.e., in polynomial rather than exponential time).



DNA electrophoresis for sequencing analysis by fluorescence. *(Courtesy Généthon; photo: Philippe Plailly)*

A simple greedy algorithm is routinely used to cope with the job. This algorithm, here called GREEDY, repeatedly merges the pair of (distinct) strings with maximum overlap until only one string remains.

Looking at what GREEDY would make of the above example, we see that it would start out with the largest overlaps from 'lethal' to 'half' to 'alfalfa' producing 'lethalfalfa'. It then has 3 choices of single character overlap, two of which lead to another shortest superstring 'lethalfalfalphate', and one of which is 'lethal' in the sense of giving a superstring that is one character longer. In fact, it is easy to give an example where GREEDY outputs a string almost twice as long as the optimal one, for instance on input $\{c(ab)^k, (ba)^k, (ab)^k c\}$.

It has been an open question as to how well GREEDY approximates a shortest common superstring, although a common conjecture states that GREEDY produces a superstring of length at most two times optimal.

From a different point of view, Li considered inferring a superstring from randomly drawn substrings in the Valiant learning model. In a restricted sense, the shorter the superstring, the smaller the number of samples needed to infer that superstring. Therefore finding a good approximation bound for shortest common superstring implies efficient learnability or inferability of DNA sequences.

Previous work by Tarhio and Ukkonen, and by Turner established some performance guarantees for GREEDY with respect to the 'compression' measure. This basically measures the number of symbols saved by GREEDY compared to plainly concatenating all the strings. It was shown that if the optimal solution saves l symbols, then GREEDY saves at least $l/2$ symbols. But, in general this implies no performance guarantee with respect to optimal length, as in the best case this only says that GREEDY produces a superstring of length at most half the total length of all the strings.

One of the results of CWI research in this field is that the superstring problem *can* be approximated within a constant factor, and that algorithm GREEDY in fact produces a superstring of length at most $4n$. (Here 4 is the constant factor and n the length of the shortest superstring.)

Approximation

In 1988, Papadimitriou and Yannakakis developed a theory about finding approximate solutions to optimization problems. The notion of completeness for the class NP is based on the notion of many-one reduction: a problem A reduces to a problem B when we can decide membership of x in A by transforming x into a problem instance y and asking instead whether y is in B. For instance, it is possible, given a set of cities with their mutual distances and a bound k, to transform the problem instance into a (not much larger) boolean formula, such that the cities can be toured within total distance k if and only if the formula has a satisfying truth assignment. We say that TSP many-one reduces to SAT. A problem is called *hard* for a class if all problems in that class can be reduced to it. In analogy to the many-one reduction for decision problems, Papadimitriou and Yannakakiş introduced the notion of L-reduction between optimization problems which intuitively preserves linearity of approximation, and defined syntactically the class MAX SNP. It is known that every problem in this class can be approximated within *some* constant factor. A problem is MAX SNP-hard if every problem in MAX-SNP can be L-reduced to it. Our investigations into the superstring problem also showed it to be MAX SNP hard. Combination with later work by Arora et al. [2] shows that this means there are limits on how well it can be approximated.

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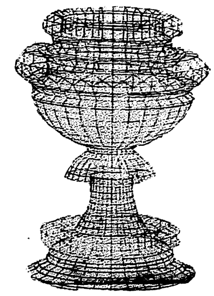
Object Boundaries from Scattered Points

Research Programme : Intelligent CAD systems (terminated in 1992)
Researcher : R.C. Veltkamp



Perspective Study of a Chalice by Uccello (1397-1475).

The research project described here concerns the construction and manipulation of 2D or 3D closed object boundaries from a set of points. These points are scattered points, i.e. no structural relationship between them is known in advance and they have an arbitrary position.

At CWI we have considered four stages of this task:

1. Given a set of scattered points, construct a geometric structure on the points.
2. Given a geometric structure on a set of scattered points, find a closed polygonal or polyhedral boundary through all points.
3. Given a closed object boundary, construct a hierarchy of approximations and localization information.
4. Given a closed polygonal or polyhedral object boundary, construct a smooth boundary.

Introduction

In many applications in geometric modelling, computer graphics, object recognition, distance map image processing, and computer vision, input data is available in the form of a set of 2D or 3D coordinates which are points on the boundary of an object. Such points can be synthetic or measured from the boundary of an existing object. Figure 1 shows an example of a set of 2D points from the boundary of Uccello's chalice, which serves as the cover picture of the journal 'Computer Aided Geometric Design', and a collection of 3D points from the surface of an Indian mask from the Man Museum in Ottawa, measured by a laser range system. A collection of points, however, is an ambiguous representation of an object, and can therefore not be used directly in many applications. It is often essential to have a representation of the whole boundary available, whereby the representation unambiguously defines a valid object. The boundary constructed from a set of points can, for example, be used for the initial design of an artifact, for numerical analysis, or for graphical display.

Internationally and in The Netherlands much work has already been done on the construction of boundaries from points and the subsequent manipulation of these object boundaries. By far most techniques used assume that the points lie on some regular, often rectangular, grid structure. This a priori knowledge makes boundary construction, approximation, and smoothing (the stages 2, 3 and 4 mentioned above) considerably easier than it would be without that information.

The way in which the boundary points are acquired may give useful information in order to construct the whole boundary, but can also make the construction method very dependent on the specific data source. If it is not known how the data is obtained or if a single construction method is to be used for data from various types of sources, no structural relation between the input points may be assumed, except that they all

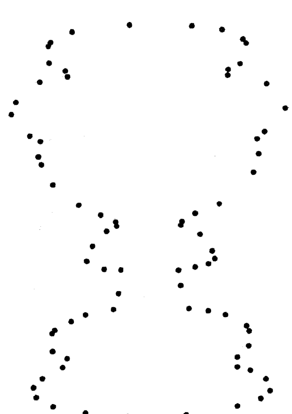


Figure 1: *2D boundary points of a chalice, and 3D boundary points of an Indian mask.*

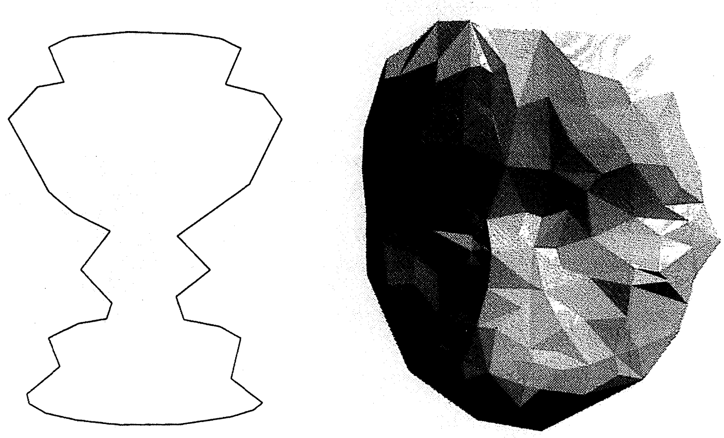


Figure 2: *Polygonal chalice boundary, and polyhedral mask boundary.*

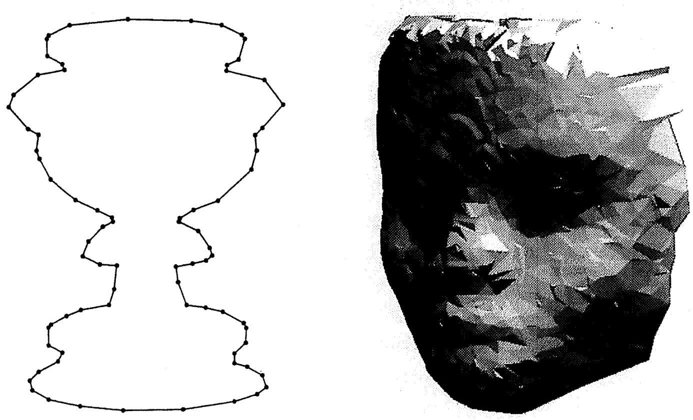


Figure 3: *Polygonal and polyhedral approximations.*

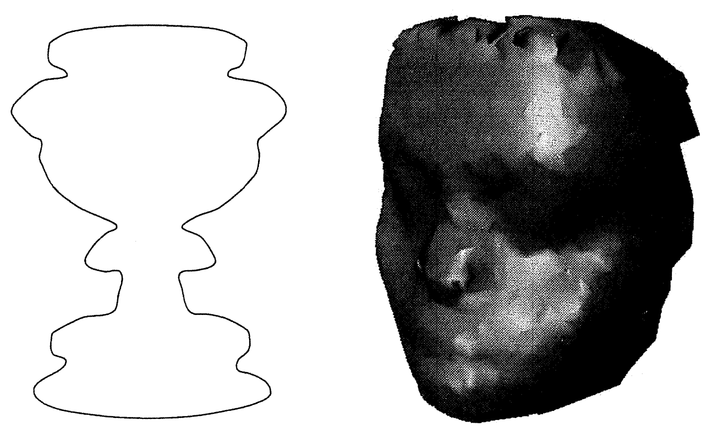


Figure 4: *Smooth chalice curve and mask surface.*

lie on the boundary of an object. The order of the points in the input then provides no information on their topological relation to each other. In particular, they do not lie on a regular grid, but are scattered points. Our project is about the development of new techniques to construct and manipulate closed boundaries of 2D and 3D objects from scattered points.

Boundary construction

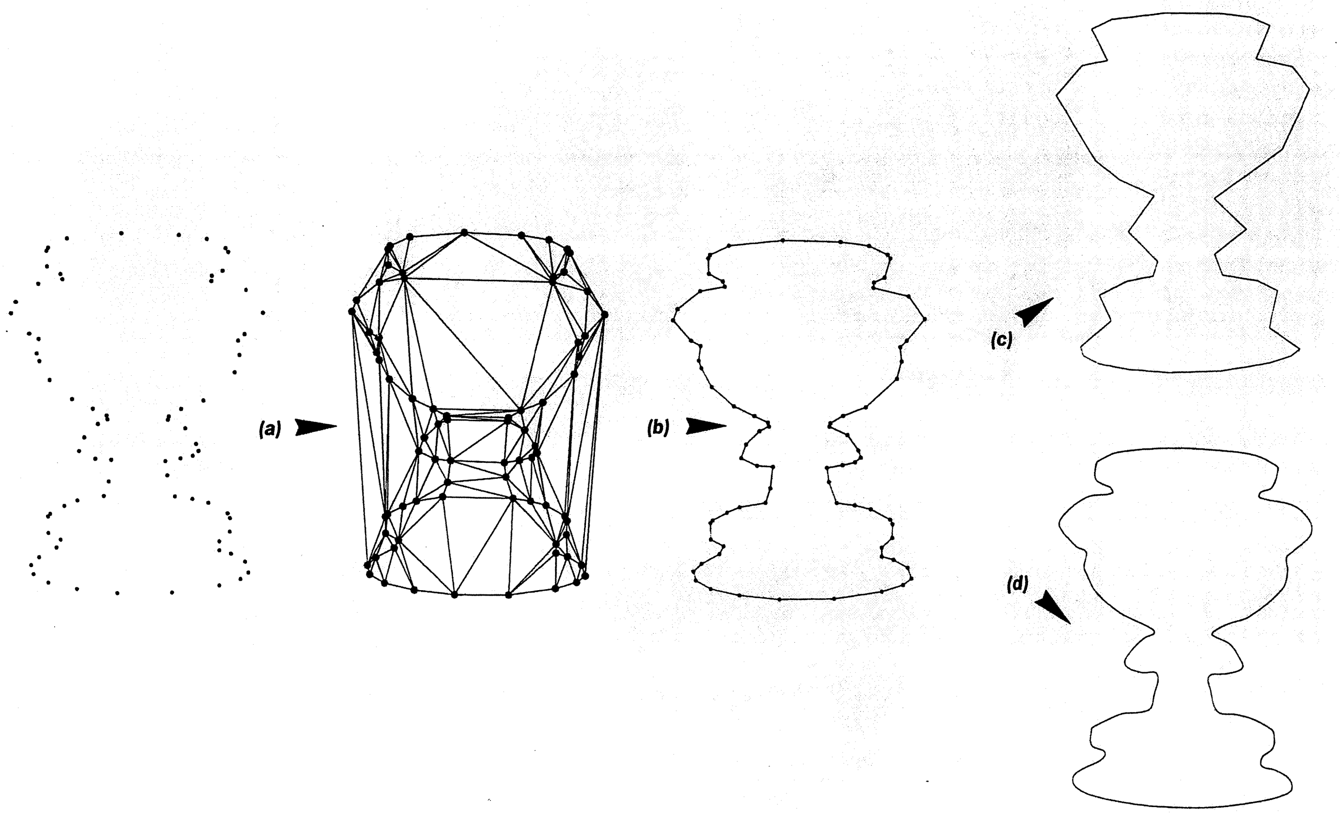
The simplest boundary through a set of points is one that consists of linear segments: line segments for a 2D polygonal boundary, and triangles for a 3D polyhedral boundary (in 3D, a triangle is the unique polygon that is always flat). Figure 2 shows a polygonal and polyhedral boundary of the points from Figure 1. In both the polygonal and the polyhedral boundary, points are connected by edges. It is not feasible to try all possible boundaries through a given set of points by considering all edges between points because of the combinatorial explosion of the number of possible solutions. For example in 2D, a boundary through N points must consist of N line segments, and there are $\binom{N}{2}$ possible edges. Trying all sets of N edges out of $\binom{N}{2}$ results in at least $\Omega(N^N)$ combinations, which is too much to be of practical use.

One possible solution to this problem is to first describe some structure of the set of points by a geometric graph, and then derive a boundary from this structure using the inherent geometric information. At CWI we developed the so-called γ-neighbourhood graph. This geometric graph is a neighbourhood graph in the sense that data points are connected to each other if no other data points lie in some parameterized neighbourhood. This parameterization makes the γ-neighbourhood graph very flexible. Indeed, it unifies a number of geometric graphs such as the Convex Hull and the Delaunay Triangulation into a continuous spectrum of geometric graphs.

The object boundary is now extracted from the γ-neighbourhood graph by removing connections from the outside until all points lie on the boundary. The selection of the connections to be removed is based on the geometric information in the γ-neighbourhood graph. Figure 2 shows the resulting object boundaries obtained from the point sets in Figure 1.

Approximation

In many real applications, a boundary constructed



The four project stages:
***a.** Given scattered points, find a geometric structure.*
***b.** Given the geometric structure, find the boundary.*
***c.** Given the boundary, find an approximation.*
***d.** Given the boundary, find a smooth boundary.*

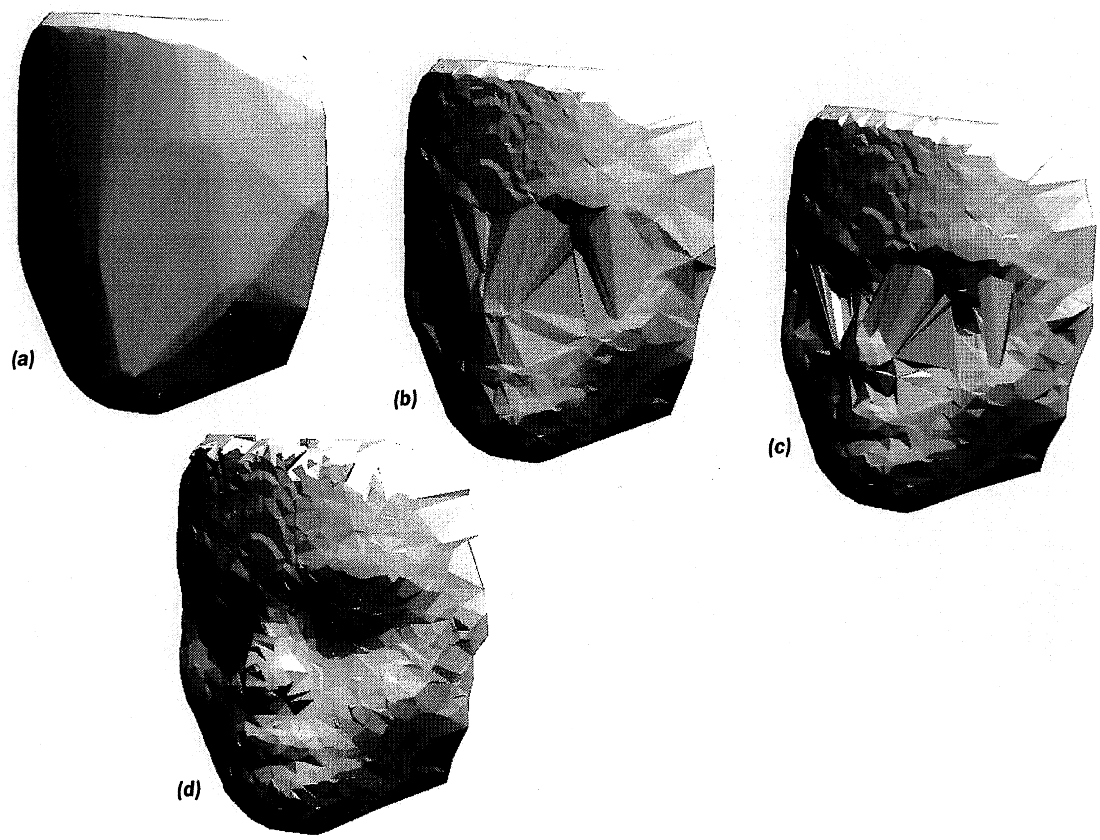
from a set of points consists of thousands of faces. For example, the constructed boundary of the mask in Figure 2 is made up of some three thousand triangles. However, an approximation of the object is often sufficient. In animation for example, the motion blur prohibits the perception of much detail, so that an approximated object is sufficient and is also faster to display. A polygonal approximation of the chalice and a polyhedral approximation of the mask are shown in Figure 3.

Localization provides bounding area or volume information. Such information is useful for efficient operations such as collision detection for robot motion planning. The fact that boundaries constructed from experimental data often consist of many segments, and that a hierarchy of approximations together with localization information is very efficient for many applications, prompted the inclusion of this subject in the project.

Our goal is to devise a scheme whose definition is readily generalized from 2D to 3D, and is very efficient in use. This is not as easily obtained as it may seem, in that many existing methods do not meet these demands. For example, a simple bounding area for a piece of a polygon is a rectangle. The generalization to 3D suggests the use of a block, but the intersection test for two blocks may require thirty-six intersection tests between the sides of the blocks. On the other hand, the test for intersection of two circles or spheres only requires the calculation of the distance between the two centres: if the distance is smaller than the sum of the two radii, there is an intersection. Indeed, circles and spheres have been used as bounding areas and volumes since the early days of geometric modelling and computer graphics. The application of circles and spheres to the approximation and localization of polygons and triangular polyhedra in a hierarchical way was elaborated last year.

Smoothing

In 1992 we considered the task of smoothing the constructed object boundaries. Polygonal boundaries are C^1-discontinuous at the vertices, exhibiting abruptly changing directions of the tangent line. Given an ordered set of vertices, i.e. a polygon, a smoother boundary curve is often desired, consisting of curved line segments



In 3D, the reconstruction of an object boundary from the geometric structure on the scattered points is much like the process of sculpting. Given the initial structure, parts are successively cut away until the final shape passes through all points.

that interpolate the vertices of the straight line segments and are smoothly connected at the vertices. Analogously, the polyhedral boundaries are C^1-discontinuous at the edges, where the tangent planes instantly change orientation. Here too we frequently need a smoother surface, consisting of curved triangles that interpolate the flat triangles' vertices and are smoothly connected along the edges. There are many, varied reasons why smoothing is needed: in car body it is aesthetics; in aircraft and ship hull design the need comes from the laws of aero- or hydrodynamics; and in boundary *re*-construction the reason is the smoothness of the original boundary. Figure 4 shows a tangent line continuous chalice boundary curve which interpolates the vertices of the polygonal boundary, and a tangent plane continuous mask boundary surface which interpolates the triangle vertices of the polyhedral boundary.

Smooth boundaries are most easily constructed by piece-wise polynomials. Three polynomial schemes are most widely used in Computer Aided Geometric Design: the Coons, B-spline and Bézier schemes, especially for rectangular surface patches. Triangular interpolants are dominant in 3D scattered data interpolation, and the Bézier formulation for curves naturally generalizes to a triangular form. (Bézier curves and surfaces were independently developed by De Casteljau at the Citroën and by Bézier at the Renault automobile company. However, as De Casteljau's development was never published, this curve and surface scheme was named after Bézier.) The Bézier formulation is a convenient method to describe other polynomial schemes as well as to develop new schemes.

Because the Bézier scheme has useful geometrical interpretations, and results in a piecewise, triangle-by-triangle, surface representation, the interpolation methods developed in our project are in Bézier form. The polynomial degree of tangent plane continuous triangular surfaces is usually four or five. The problem we considered is the development of a tangent line/plane continuous interpolation scheme which is local, i.e. only depends on nearby vertices, while keeping the polynomial degree as low as three. This is easily done for curves, but is more involved for surfaces. The solution we derived is based on the subdivision of triangles in Bézier form.

The Amsterdam Hypermedia Model
a description of structured, multimedia information

Research Programme : Multimedia kernel systems
Researcher : L. Hardman

Introduction
One of the benefits of encoding information electronically is the potential for integrating dynamic media such as sound and video into online presentations. The information can also be structured, allowing the reader to interactively navigate through the presentation. Unfortunately, this richness brings with it the problem of making the same information accessible to readers using a wide range of hardware. Therefore, a description of the information is required which can be interpreted independently of any particular hardware platform used by a reader. In order to provide this, two fundamental types of relationships require to be described in addition to the media items being used to communicate the message: timing and structural relations. Timing relations specify the presentation dependencies among media items, possibly stored at different sites. Structural relationships define logical connections among items the reader will find relevant.

Models for hypertext and multimedia already exist, where the former describe structural relations and the latter timing relations. Neither is able to express the full complexity of a hypermedia presentation – a combination of hypertext structuring and multimedia timing. The goal of our work is to enable the specification of hypermedia presentations, including logical and temporal relations, in a platform independent way. Figure 1 shows an example of a typical hypermedia presentation. By using a model which captures the author's intentions, rather than platform-dependent presentation details, and interpreting these at play-time the author is spared work and the presentation can be played on a range of hardware platforms.

In order to capture sufficient information for specifying a hypermedia presentation we need to look at models of both hypertext and multimedia and combine the information required by both paradigms. The Dexter hypertext reference model [1], developed by a group of hypertext system designers, describes the structural relations required for static media. Our own previous work describes a model for timing relations between collections of static and dynamic media composed to form multimedia presentations. The Amsterdam Hypermedia Model builds on these two bases and presents a model for structured, multimedia information.

Once a hypermedia presentation has been described using our model, its description could be interpreted for playing on different target platforms. While we do not prescribe a language for specifying a presentation conforming to our model, it could be expressed in a system-independent language such as the HyTime (Hypermedia/Time-based Document Structuring Language) international standard, based on SGML (Standard Generalized Mark-up Language).

Hypermedia model requirements
An author's requirements for a hypermedia model are straightforward. An author wishes to assemble separate items of different media into a presentation, and specify choice points where a reader can either continue with the current presentation or jump to a different presentation. Such an 'authoring' process can be broken down into specifying how media items are grouped together, what the timing relations between media items are, how individual items appear on the

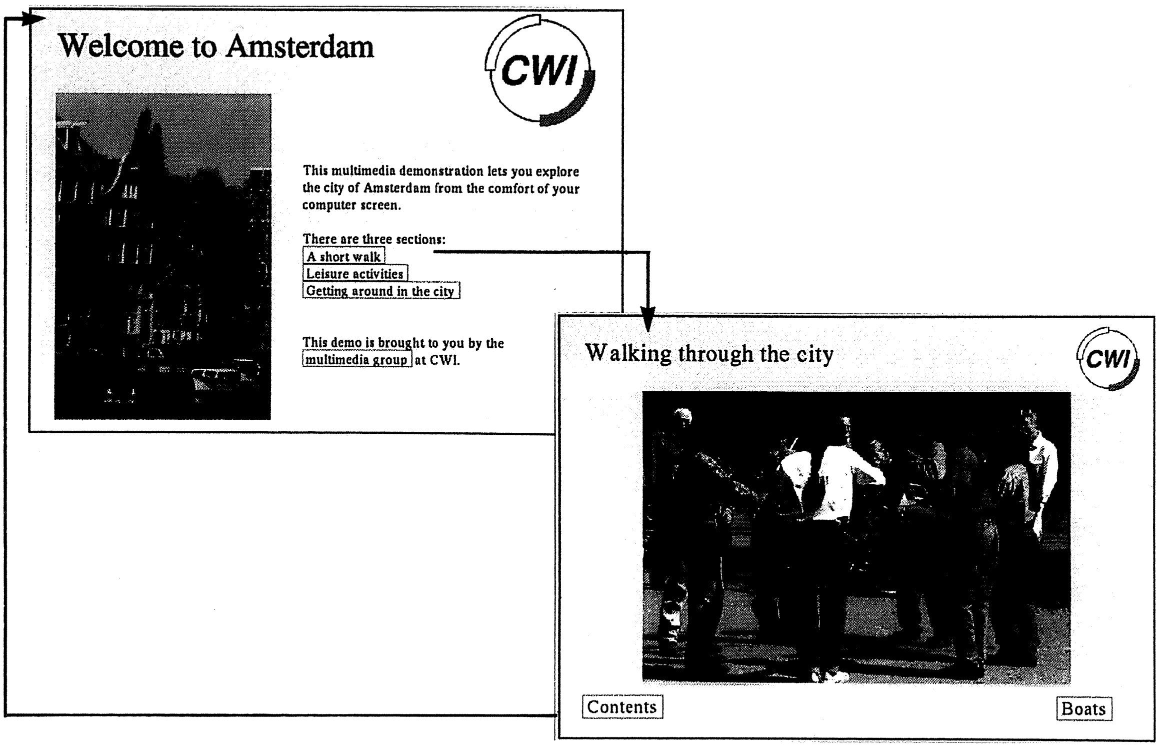


Figure 1. *A typical hypermedia presentation. The screen on the left shows the contents screen of a hypermedia tour of Amsterdam. The reader can choose the desired part of the tour from the items set in bold text. The A short walk - heading takes the reader on a short walk through the city - from which a scene is shown on the right of the figure. This is built up from fragments of text, a picture of the CWI logo and a video of musicians playing in the Leidseplein. The Boats button takes the reader to the following scene. The Contents button allows the reader to jump back to the main contents screen of the Amsterdam tour.*

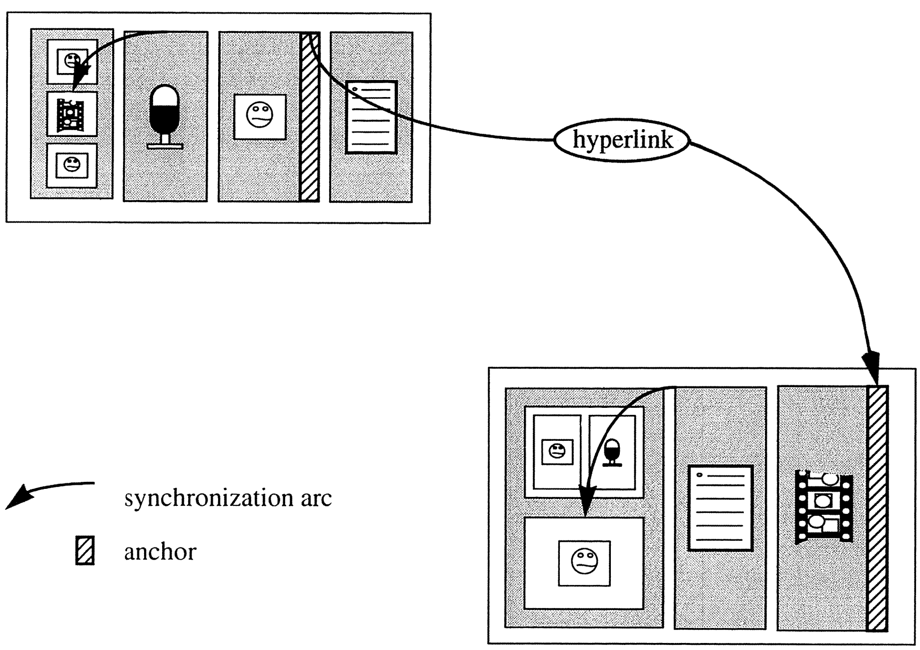


Figure 2. *Two linked composite components. Two composite components (each of which is a multimedia presentation) are connected by a hyperlink between source and destination anchors. A synchronization arc gives timing constraints within a composite component. The presentation on the left of the figure is played from beginning to end, unless the reader selects the anchor; if so, the presentation on the right is started up.*

screen and where the choice points are for jumping to other presentations. It is these specifications which need to be captured in our hypermedia model.

- *Composition*: When creating a presentation the author should be able to group items together, for example, a spoken commentary accompanying corresponding subtitles. We will refer to this grouped object as a *composite component*. This enables the author to manipulate the grouped object in its own right, rather than having to work with the individual items composing it. This is where many current multimedia authoring systems do not support the author – the items making up a presentation always have to be treated separately.

- *Synchronization*: A composite component can contain items of any media type, static, such as text and graphics, and dynamic, such as audio and video. When grouping items into a composite component timing relations between the items need to be specified. This timing information needs to be included in our model. In the example shown in Figure 1 all the visual items are started simultaneously and the music starts slightly later. A more complex example might be where a series of video clips are to be shown with accompanying music and subtitles, where the author wants to wait until the background music fades away before going on to the next video in the sequence.

- *Styles for multimedia*: In order to display the media items comprising a presentation the visual characteristics need to be specified for every item. Although this is possible on an individual basis, we can use an approach similar to the use of styles in word processors. These allow the author to define a number of styles and then assign one of these to each of the paragraphs in the document. In the case of multimedia there is a close parallel, where media items play different roles in the presentation, for example subtitles should be at the bottom of the screen in an unobtrusive font, a main picture should occupy most of the screen, and titles should be in a larger font at the top of the screen. We can help the author by providing the equivalent of word processor 'style' specifications for the different media.

- *Hyperlinks*: While playing through a presentation author-created choice points can be presented to the reader via the use of hyperlinks. The reader can follow the hyperlinks, by selecting an active anchor on the screen (often by pointing with a mouse and clicking), to other presentations or different parts of the same presentation, see for example Figure 1. When the reader follows a hyperlink there is a choice of whether the current presentation is replaced or not, and if not whether it should be paused or continued. A restriction in most current systems is that the complete presentation is replaced when the reader follows a hyperlink. Our hypermedia model needs to record from where and to where the reader can jump.

In order to meet these requirements we have developed the Amsterdam Hypermedia Model. This model allows the expression of both structural aspects of hypertext and dynamic aspects of multimedia in one comprehensive model.

The Amsterdam Hypermedia Model

Figure 2 gives a intuitive description of the model, showing a hyperlink between two presentations. While the reader is watching the presentation represented by the left-hand composite component, active screen areas are present which can be clicked on at any time. (Examples of active areas are the buttons and bold headings shown in Figure 1.) If the reader chooses one of these, the corresponding hyperlink is followed and the presentation on the right of Figure 2 will be started up.

Items are grouped together into composite components, which in turn can be treated as items in higher-order groupings. Items can be included in several composites. The timing information between the items comprising the component, the *children* of the component, is stored with the component. Timing information between two arbitrary descendant items of a component is specified by referencing the descendants and stating the timing relation between them, e.g. a delay of a number of seconds.

A *channel* is an abstract output device for playing media items, allowing the specification of default presentation characteristics for the items allocated to that channel. Examples of such specifications for text are a default font, size and style and the position and size of the window. For video they would include a window and an associated colour map. A component specifi-

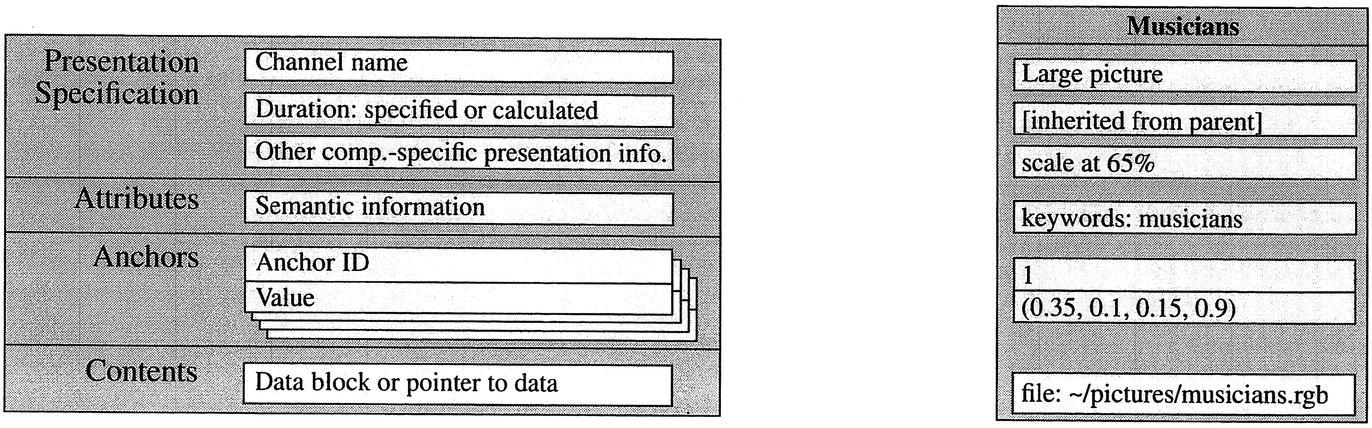


Figure 3. *Amsterdam Hypermedia Model atomic component. The example on the right corresponds to the musicians picture to the right of Fig. 1. For a description of the individual parts see the bulleted points in the main text.*

cation records to which channel an item is allocated. A typical use of channels is to combine several of them into a reusable layout. For example, the two screens at the top of Figure 1 use the same layout, where the pictures and sound items are different.

For supporting jumps between different presentations we use a hyperlink and anchor construction, where an anchor is used as the end of a hyperlink. A hyperlink defines a direct relationship between two parts of a presentation. Selecting the hyperlink allows the reader to move around the information in the presentation. The *anchor* is a part of the media item, for example a text string or a rectangle in a picture. When the reader clicks on the anchor with the mouse the corresponding hyperlink is followed to a different part of the presentation, see for example Figure 1. Composite anchors can be constructed to give the effect, for example, that a picture of a leaf and the word 'leaf' are both anchors associated with the same hyperlink. When following a hyperlink the currently playing presentation can be replaced partially or fully, for example see Figure 1.

Data model

We present the data model as a means of expressing the information required for describing a hypermedia presentation. Our model is an extension of the Dexter hypertext reference model, which was developed by a group of hypertext system designers to capture the essence of hypertext structures. Using our own previous work on a model for multimedia, we have combined the two, defining a data model sufficiently rich to describe hypermedia presentations. This model describes the information required for specifying the structural and time-based connections within and among presentations and suggests how this information should be stored.

A distinction is made in the data model between atomic and composite components. An atomic component is one which contains, or has a pointer to, a media item which can be presented to the reader. A composite component is a grouping of atomic and/or composite components. Figure 3 shows the data structure of an atomic component, and Figure 4 the data structure of a composite component. A description of the purpose of each part of a component follows.

- *Presentation specification*: Information about how the media item is to be presented. The channel name indicates on which channel the item is to be played, and carries with it most of the presentation information needed for the item. Exceptions to the channel defaults can also be recorded (in the example in Figure 3 the picture is to be scaled at 65%). Timing is also a presentation attribute, and in the case of a static picture can be inherited from the parent component. For a composite component explicit synchronization relations can be stated between any two descendants.

- *Attributes*: A semantic description of the information. The model makes no assumptions about the form or the use of the information, but provides a place to store it.

- *Anchor*: A means of indexing into the data of a component. They are used for attaching hyperlinks to components, for example within text an anchor is a character string, within video it is an area on the screen which may change with time. In a composite component an anchor is a list of pointers to other anchors,

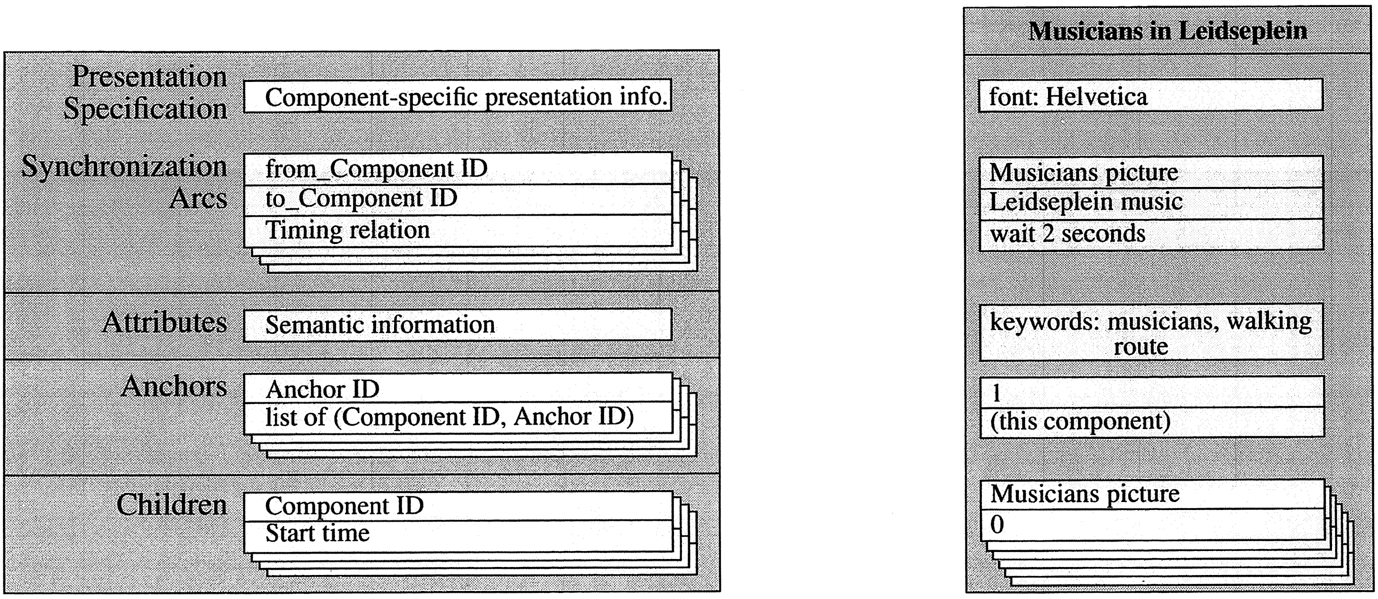


Figure 4. *Amsterdam Hypermedia Model composite component. The example on the right corresponds to the complete musicians scene to the right of Fig. 1. For a description of the individual parts see the bulleted points in the main text.*

being eventually dereferenced to anchors in atomic components.

- *Contents* (only in atomic component): The actual data of the media item, or a pointer to data.
- *Synchronization arc* (only in composite component): Explicit timing relation between two descendant components.
- *Children* (only in composite component): The atomic or composite components making up the composite component.

The model we have presented gives no suggestions for *how* a hypermedia presentation should be authored, and indeed it is not expected that an author of a hypermedia presentation would ever see the values in the data model directly – an authoring environment would calculate many of these automatically and give the author direct access to others.

Future work

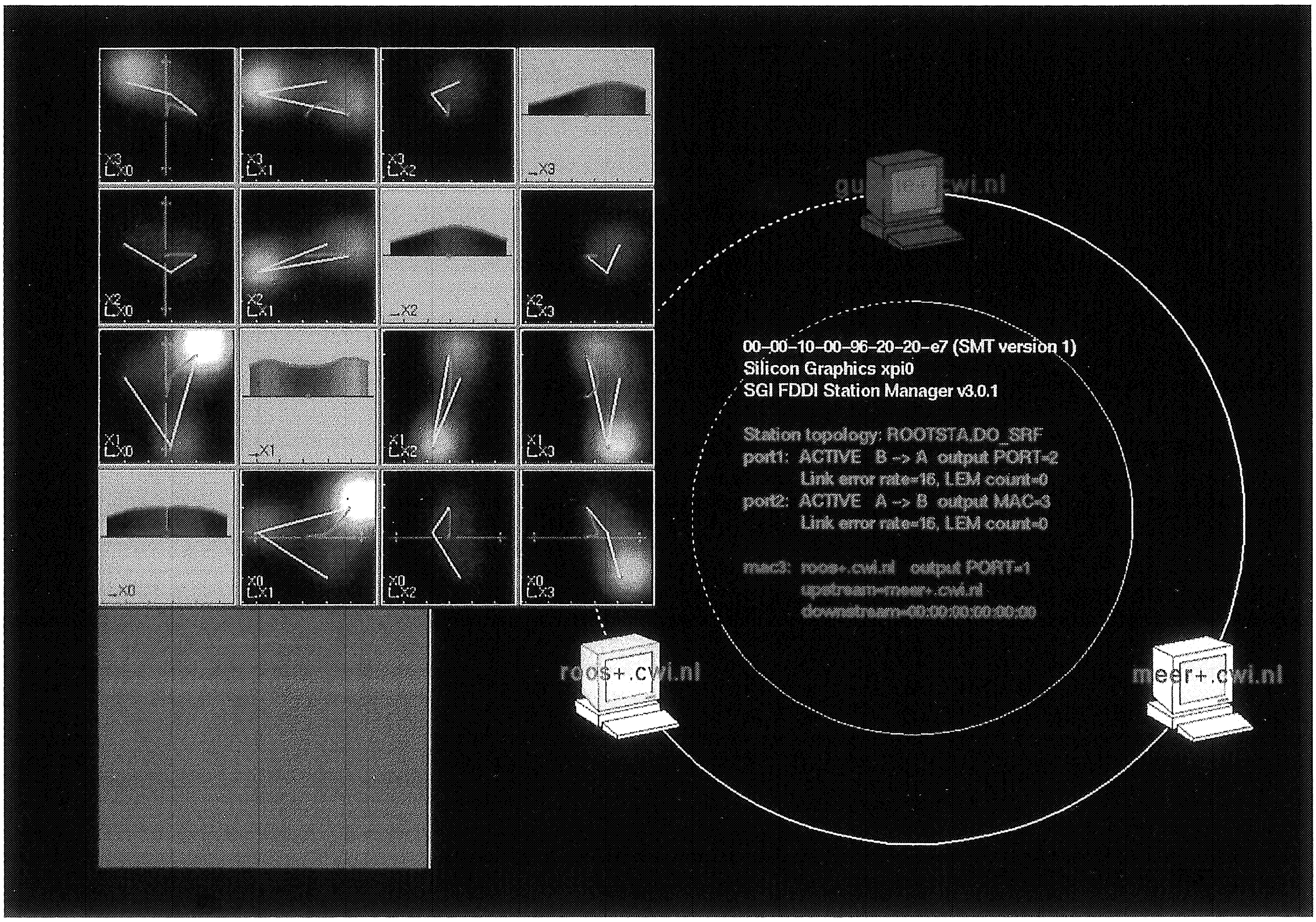
The Amsterdam Hypermedia Model enables the system-independent specification of multiple dynamic media combined into presentations which can be explored by a reader interactively. We have built a working prototype which supports composite components, channels, hyperlinks and synchronization arcs.

One of the directions for our work is to generate hypermedia presentations on the fly, i.e. dynamically, based on selecting data items from a store and assembling them into a presentation. By providing high-level constructs and making explicit the issues in creating a presentation we will be able to reduce the search space required by a presentation generator. An example application for this is in the field of management games, where players require access to background information depending on the state of a simulation.

Reference

1. FRANK HALASZ, MAYER SCHWARTZ (1990). The Dexter Hypertext Reference Model. *NIST Hypertext Standardization Workshop*, Gaithersburg, MD, January 16-18.

COMPUTING EQUIPMENT RESOURCES



Distributed Scientific Visualization.
Connectivity plays a predominant role within CWI's central computing facilities. Medium to high speed networks are used to connect workstations and servers, enabling easy access to central facilities for all users. Moreover, many research groups at CWI are presently developing distributed algorithms and environments which rely on high speed networks.
The illustration shows a distributed visualization algorithm in action. The grey scale window on the top left is a scatterplot representation of a four-dimensional scalar potential function. The mouse is used to navigate through the four-dimensional space. Although the visualization is done locally at a workstation, the tremendous volume of computation is performed on remote compute servers. The window on the right displays a visual tool showing three compute servers connected together by a high speed fibre optic (FDDI) cable. This type of visual tool is used to gather valuable statistics, including processor utilization and sustained data throughput. In turn, these statistics are used to derive computational and rendering metrics. In this particular case the sustained performance of the depicted configuration is about 100 Mflops and approximately 60 Mbytes of data. The raw rendering speed will reach some 400 K triangles per second.

Research Workstations:

SGI Indigo-LG1 (R4000)
(11 @ 58.3/60.5 SPECmark92[1])
30k triangular meshes

SGI Indigo-LG1 (R3000)
(24 @ 22.4/24.2 SPECmark92[1])
20k triangular meshes

SGI Indigo-XS/XS-24 (R4000)
(33 @58.3/60.5 SPECmark92[1])
40k triangular meshes

SGI Indigo-XS/XS-24 (R3000)
(68 @ 22.4/24.2 SPECmark92[1])
30k triangular meshes

SGI Indigo-Elan (R4000)
(1 @58.3/60.5 SPECmark92[1])
120k triangular meshes

SGI 310-VGX (R3000)
(1 @22.4/24.2 SPECmark92[1])
200k triangular meshes

SUN SLC/ELC
(37 @ 10/8.4 SPECmark92[1])
(monochrome)

SUN SparcStation 1, 1+
(2 @ 12/10.2 SPECmark92[1])
(colour)

Portable Research Computers
(2 Tadpole Sparcbooks)
(4 Mac Powerbooks)

Miscl. Research/Administration
(NCD, DS-3000, VS2000)
(MacPlus/PC's)

Compute/Data Servers:

Cray-S/MP
1 SPARC CPU @40.4/52.5 SPECmark92[1]
28 i860 APP @48.3/58.6 SPECmark92[1]

Siemens MX300
(Library Information System)

Network Services:

4 Building-Wide Ethernets
1 Experimental FDDI Ring

Annex Terminal Controller
Cisco Terminal Controller
72 Telebit Trailblazer Modems

Print Services:

1 Compugraphic 9600 Phototypesetter
1 OCE-6750 Laserprinter
2 Agfa-3400PS laserprinters

4 HP Laserjet Printers
9 Mac Laserwriter Printers

File Servers:

SGI PowerServer 4D/260
(6 @ 25 Mhz R3000)
64MB memory, 6.0 GB disks

SGI PowerServer 4D/420
(2 @ 40 Mhz R3000)
64MB memory, 6.0 GB disks

SGI PowerServer 4D/260
(6 @ 25 Mhz R3000)
64MB memory, 6.0 GB disks

SUN 4-490
(2 @ 40 Mhz R3000)
64MB memory, 6.0 GB disks

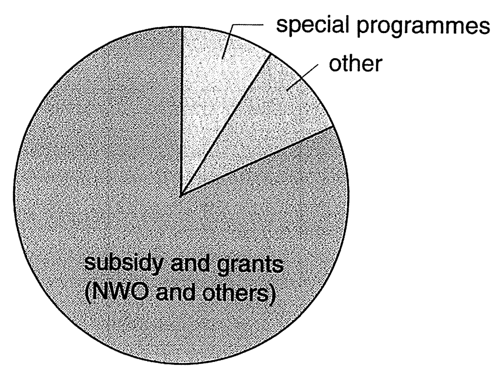
[1] SPECmark92 figures for integer and floating point performance, respectively.

FINANCIAL AND OTHER DATA

FINANCES 1992

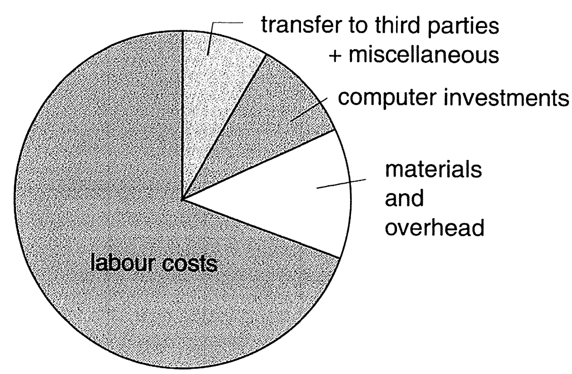
In 1992, SMC spent Dfl. 25.14 million, of which about Dfl. 2.81 million was allocated to university based research and Dfl. 22.33 million to CWI. The expenses were covered by a subsidy from NWO (Dfl. 20.63 million), other subsidies and grants (Dfl. 2.09 million), from the international programmes (mainly EC programmes, e.g. ESPRIT, SCIENCE and RACE) (Dfl. 2.00 million), and from national programmes (Dfl. 0.03 million). Finally, an amount of Dfl. 2.05 million was obtained as revenues out of third-party-services and other sources.
During 1992 CWI also employed over twenty researchers in externally financed positions. These are not included in the adjacent financial summary.

income CWI

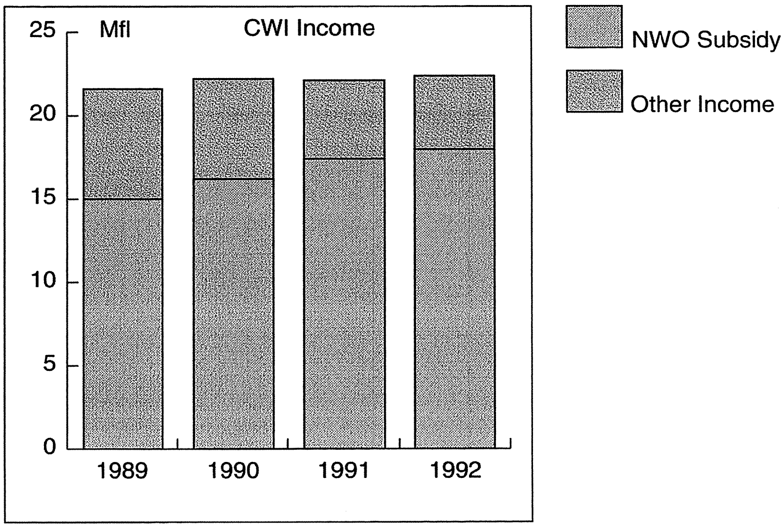


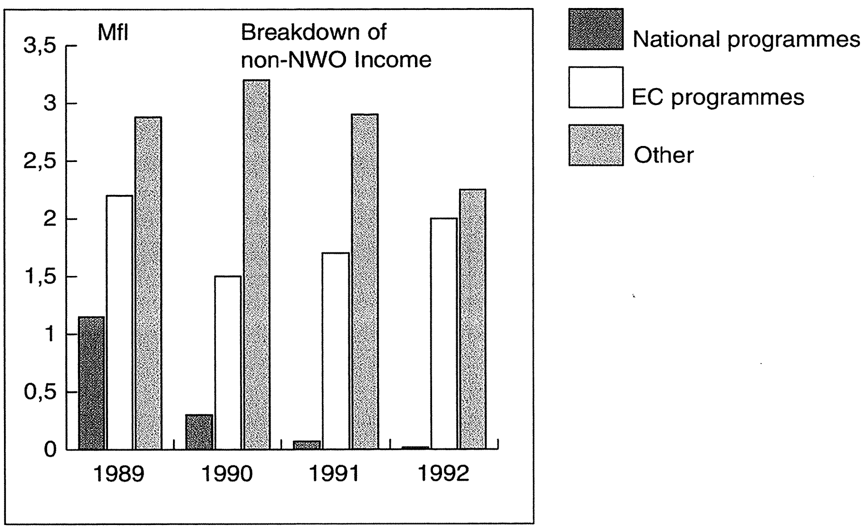
	university based	CWI	SMC
	*Dfl. 1000		
INCOME			
subsidy and grants			
- NWO	2666	17960	20626
- other	-	209	209
national programmes	-	29	29
international programmes	-	2001	2001
other revenues	96	2051	2147
total income	2762	22250	25012
EXPENSES			
labour costs	2259	15447	17706
materials and overhead	12	2732	2744
computer investments	200	2256	2456
transfer to third parties	336	1655	1991
miscellaneous	-	244	244
total expenses	2807	22334	25141

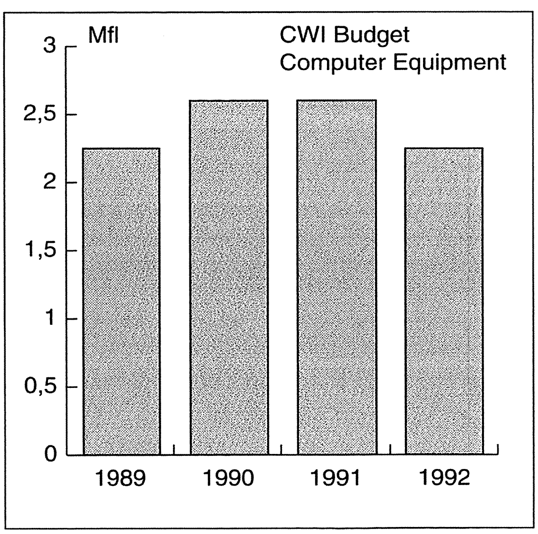
expenses CWI

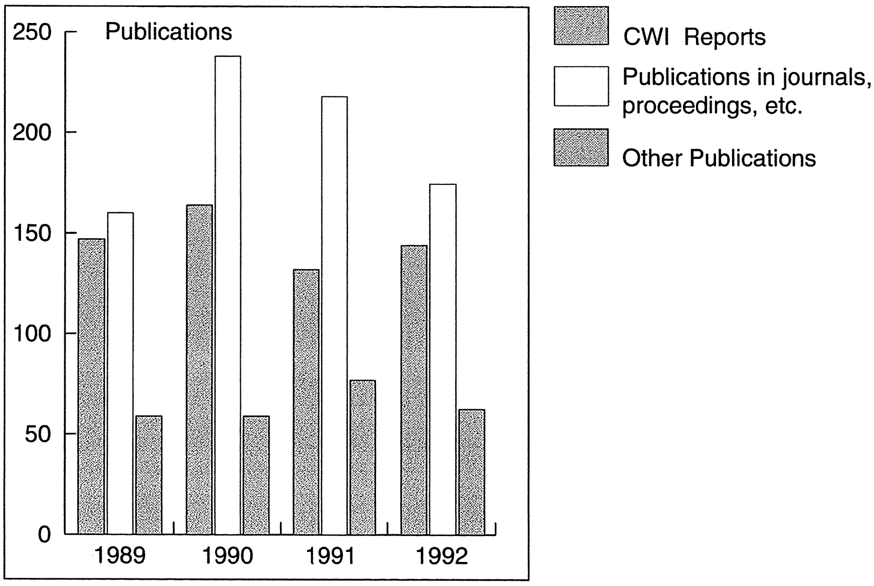


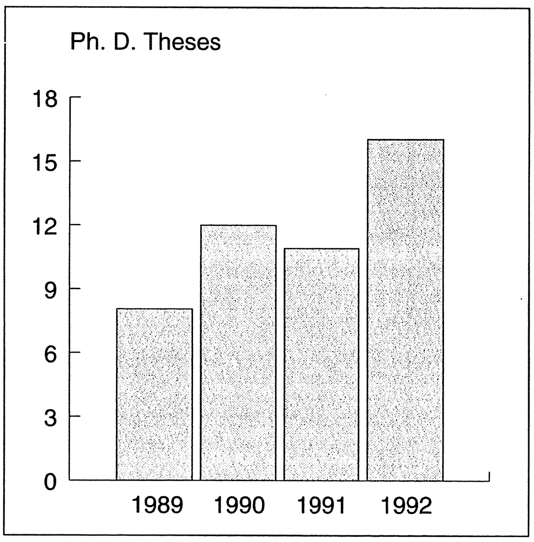
FINANCES 1989 -1992











Library (ultimo 1992)

40 000	books
1 500	subscriptions on journals
100 000	reports

Ph.D. THESES

Author	Title	Thesis advisor(s)+)
J. Rekers	Parser Generation for Interactive Environments	P. Klint
B.P. Sommeijer	Parallelism in the Numerical Integration of Initial Value Problems	P.J. van der Houwen
J.A. Hoogeveen	Single-machine Bi-criteria Scheduling	J.K. Lenstra
M.M. Fokkinga	Law and Order in Algorithmics	L.G.L.T. Meertens L.A.M. Verbeek (UT)
E.D. de Goede	Numerical Methods for the 3D Shallow Water Equations on Supercomputers	P.J. van der Houwen A.W. Heemink (UvA)
J.M.A.M. van Neerven	The Adjoint of a Semigroup of Linear Operators	O. Diekmann
J. Molenaar	Multigrid Methods for Semiconductor Simulation	P.W. Hemker
J.N.E. Bos	Practical Privacy	J.H. van Lint (TUE)
R.R.P. van Nooyen	Some Aspects of Finite Element Methods for Semiconductor Simulation	P.W. Hemker
M. Kuijper	First-order Representations of Linear Systems	J.M. Schumacher
A. Ponse	Process Algebras with Data	J.A. Bergstra J.C.M. Baeten (TUE)
E.J.L.J. van Heyst	Special Signature Schemes	J.H. van Lint (TUE)
P.J. Veerkamp	On the Development of an Artifact and Design Description Language	J. Treur (VUA)
J.A.P. Heesterbeek	R_0	O. Diekmann J.A.J. Metz (RUL)
P.A. Zegeling	Moving-Grid Methods for Time-dependent Partial Differential Equations	P.J. van der Houwen
R.C. Veltkamp	Closed Object Boundaries from Scattered Points	J. van den Bos (EUR) M.H. Overmars (RUU)

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

UT = University of Twente
UvA = University of Amsterdam
TUE = Technical University Eindhoven
VUA = Free University Amsterdam
RUL = State University of Leiden
EUR = Erasmus University Rotterdam
RUU = State University of Utrecht

CWI RESEARCH PROGRAMMES

Algebra, Analysis & Geometry

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

Programme leader: M. Hazewinkel

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

Programme leader: O. Diekmann

Operations Research, Statistics & System Theory

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

Programme leader: A. Schrijver

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

Programme leader: O.J. Boxma

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

Programme leader: J.H. van Schuppen

Image analysis
Research on the analysis of digital images and spatial data: fundamental study of stochastic

models, statistical procedures, and stochastic and geometric algorithms; applications to consulting problems in spatial statistics and image analysis; software implementation.

Subjects:
- Stochastic geometry
- Applied spatial statistics and stereology
- Bayesian and likelihood-based image analysis
- Mathematical morphology and discrete image transforms
- Software development

Programme leader: A.J. Baddeley

Numerical Mathematics

Discretization of evolution problems

Fundamental and applied research into numerical methods for evolutionary differential equations. Both ordinary and partial differential equations are covered. In many cases of practical interest, these two problem classes can be linked numerically via the Method of Lines. Attention is given to theoretical analysis on stability and convergence issues and to applying specific algorithms to important problems from actual practice.

Subjects:
- Adaptive grid methods
- Three-dimensional flux modelling
- Parallel initial-value-problem algorithms
- Algorithms for atmospheric flow problems

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

Boundary-value problems, multigrid and defect correction

The design, development and analysis of methods for the numerical approximation of solutions of problems described by (elliptic and hyperbolic) partial differential equations or integral equations, as arise in, e.g., structural mechanics, fluid dynamics and electricity. The research focuses on defect correction and multigrid methods. Applications include: complex systems of non-linear equations; compressible Navier-Stokes equations, in particular in relation with aerodynamics; separation of biological material in a centrifuge.

Subjects:
- The analysis of defect correction and adaptive techniques for convection-diffusion problems
- Application of multigrid techniques to fluid dynamics problems
- Singular perturbation problems
- Parameter identification in ordinary differential equations

Programme leader: P.W. Hemker

Large-scale computing

Research into the general aspects of implementation of mathematical and numerical algorithms for modern vector and parallel architectures. In particular, multigrid methods for the Euler/Navier-Stokes equations and the solution of number-theoretical problems with a numerical component and with applications in cryptography are investigated.

Subjects:
- Parallel numerical algorithms
- Computational number theory

Programme leader: H.J.J. te Riele

Software Technology

Semantics

Investigation of theory and applications of programming language semantics, in particular: the study of a category-theoretic perspective on the various domains employed in semantic modelling, with extensions of the metric methodology as developed by the Amsterdam Concurrency Group over the past decade; applications of concurrent programming, emphasizing imperative, logic and object-oriented programming; program refinement, state and predicate transformer semantics.

Subjects:
- Research and Education in Concurrent Systems (REX)
- Non-well-founded sets and semantics of programming languages
- Mathematical structures in concurrency semantics (Science-MASK)
- Foundations and applications of semantics
- Program refinement, predicate transformer and state transformer semantics
- A calculus of neural networks

Programme leader: J.W. de Bakker

Concurrency and real-time systems

Research into software engineering, in particular the discovery of technically sound methods of specification , design and verification of distributed and concurrent computer systems. The emphasis is on the theory of concurrent processes, process algebras, structural operational semantics, temporal and modal logics, and correctness of real-time and distributed systems.

Subjects:
- Specification and Programming Environment for Communications Software (RACE-SPECS)
- Broadband Object-Oriented Service Technology (RACE-BOOST)
- Calculi and Algebras of Concurrency: Extensions, Tools and Applications (ESPRIT BRA-CONCUR II)
- Real-time specification and programming

Programme leader: F.W. Vaandrager

Extensible programming environments

Incremental generation of type checkers and evaluators from formal static and dynamic semantics definitions. Generation of incremental programming environments from formal language definitions. Generation of compilers for parallel computers.

Subjects:
- Incremental program generation
- Generation of interactive programming environments (ESPRIT-GIPE II)
- Compiler generation for parallel machines (ESPRIT-COMPARE)

Programme leader: P. Klint

Algebraic and syntactic methods

Foundational research directed primarily, but not exclusively to term rewriting systems. The emphasis is on the study of oriented equational axiom systems, enabling rigorous consistency proofs and - in principle - executability of concurrent calculi, and on term graph rewriting.

Subjects:
- CONcurrency and Functions: Evaluation and Reduction (ESPRIT BRA-CONFER)
- Extensions of orthogonal rewrite systems – syntactic properties
- SEMAntics and pragmatics of generalised GRAPH rewriting (ESPRIT BRA working group SEMAGRAPH

Programme leader: J.W. Klop

Logic and language

The study of various correctness properties of logic programming and PROLOG, and the relation between logic programming and non-monotonic reasoning, addressing both proof theoretical and semantic issues. Furthermore, the study of topics in natural language analysis from a formal point of view, inspired by the analysis of programming languages.

Subjects:
- Logic programming and non-monotonic reasoning
- Formal aspects of PROLOG and logic programming (ESPRIT BRA-COMPULOG II)
- Structural and semantic parallels in natural languages and programming languages
- Non-monotonic reasoning and semantics of natural language

Programme leaders: K.R. Apt, D.J.N. van Eijck

Algorithmics & Architecture

Algorithms and complexity

Study and design of algorithms for non-conventional computer networks and distributed information systems, covering the design, construction and use of hardware, as well as applications. In particular, realistic models for multicomputers, design and analysis of algorithms suitable for distributed computations, and fundamental research in complexity theory.

Subjects:
- Distributed algorithms
- Machine learning

Programme leader: P.M.B. Vitányi

Cryptography

The research concerns all aspects of cryptology related to information security. This involves the construction and analysis (from the point of view of crypto-analysis, information theory and complexity theory) of cryptographic protocols and their underlying algorithms, and the mathematical proofs of their soundness and reliability. Emphasis is placed on protection of individual privacy in protocols for the transmission of messages, payment systems, and their treatment of personal data by various organizations.

Subjects:
- Non-traceable public-key cryptography
- Effective implementation techniques for cryptography
- Conditional Access For Europe (ESPRIT-CAFE)

Programme leader: D. Chaum

Constructive algorithmics

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

Subjects:

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

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

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

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

Programme leader: M.L. Kersten

Interactive Systems

Computer graphics
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. Current activities include visualisation and extending the present architecture for support of vast amounts of new input data which can nevertheless be treated interactively.
Subjects:

- Architectures for graphics interaction
- Real-time image coding
- Scientific visualisation and computer steering

Programme leaders: A.A.M. Kuijk, R. van Liere

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

- MANIFOLD – language and systems
- MANIFOLD – cases

Programme leader: F. Arbab

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

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

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

Computer Systems & Telematics

Multimedia kernel systems
Study of a small number of fundamental problems associated with the systems-level support for multimedia data manipulation, viz. distributed multimedia. It concerns the definition, manipulation and support of multimedia data across collections of computers in a cooperative manner. Research issues include: the specification of multimedia presentations in a transportable, multi-machine environment; the definition of hyper-information links into data; protocol rules for machine-machine and interpersonal multimedia communication; distributed resource allocation algorithms.
Subjects:

- Transportable multimedia document specifications
- CWI Multimedia Interchange Format (CMIF)
- Dynamic, hyper-structured multimedia document generation
- MAnagement Games Utilities Support (MAGUS)
- Multimedia distributed operating systems
- Multimedia CoProcessor (MmCP)

Programme leader: D.C.A. Bulterman

Multidisciplinary Programmes

Mathematics & the Environment

This programme combines all CWI research groups with applications to the environmental sciences.

Subjects:

- Mathematical techniques for the study of the population biology of infections
- System identification of compartmental systems - a mathematical tool in public health and environmental protection
- Analysis of bootstrap resampling schemes, with applications to environmental data sets
- Adaptive-grid software for PDE's in environmental problems
- EUSMOG: Algorithms for air pollution models used in smog-prediction
- Parallel solution techniques for a 3D coupled shallow-water/transport model
- CRAY Y-MP software for a 3D transport model for shallow seas

Programme leader: J.G. Verwer

Multimedia

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

Subjects:

- Aspects of the definition
- Manipulation
- Presentation of multimedia data

Programme leader: D.C.A. Bulterman

INTERNATIONAL AND NATIONAL PROGRAMMES

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

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

European Programmes

ESPRIT

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

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

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

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

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

ESPRIT Basic Research

CONCUR (3006): Theories of Concurrency: Unification and Extension
September 1989 - March 1992
Universities of Aalborg, Amsterdam, Edinburgh, Eindhoven, Oxford and Sussex, SICS, INRIA
Coordinator
J.C.M. Baeten

INTEGRATION (3020): Integrating the Foundations of Functional, Logic and Object-oriented Programming
July 1989 - March 1992
CNRS-ENS, Imperial College, UNINOVA Lisbon, Univ. Pisa, Philips Research Laboratories, Linköping Univ.
Coordinator
J.W. de Bakker

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

CONFER (6454): Concurrency and Functions: Evaluation and Reduction
October 1992 - October 1995

INRIA Rocquencourt, ECRC GmbH, Univ. Edinburgh, CNRS-ENS, Imperial College, INRIA Sophia Antipolis, Univ. Pisa, SICS
J.W. Klop

COMPULOG II (6810): Formal Aspects of Prolog and Logic Programming
August 1992 - August 1995
Univ. Leuven, ECRC GmbH, RWTH Aachen, Univ. Saarland, Univ. Pisa, Univ. Rome (La Sapienza), Univ. Rome (Tor Vergata), UNINOVA Lisbon, Univ. Uppsala, Imperial College, Univ. Bristol, Univ. Edinburgh
Coordinator
K.R. Apt

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

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

RACE

RIPE (1040): RACE Integrity Primitives Evaluation
November 1988 - October 1992
Siemens AG, Philips Crypto BV, PTT Research, Universities of Leuven and Aarhus
Prime contractor
D. Chaum

SPECS (1046): Specification and Programming Environment for Communication Software
January 1988 - January 1993
GSI-TECSI, Alcatel Alsthom Recherche, Alcatel Austria-Elin Forschungszentrum Gmbh, Alcatel Standard Electrica SA, Centro Studi e Laboratori Telecomunicazioni Spa, Compagnie IBM France,France Telecom CNET, GPT Ltd, PTT Research, INRSC, Dublin City univ., ABB Corporate Research, Alcatel Bell NV
J.C.M. Baeten

BOOST (2076): Broadband Object-Oriented Service Technology
January 1992 - January 1995
MARI Computer Systems Ltd, IPSYS Software Plc, Bull S.A., Société Francais de Genie Logiciel S.A., GIE Emeraude, Detecon Technisches Zentrum, Intrasoft S.A., Telefonica, Intecs Sistemi Spa, Standard Elektrik Lorenz AG, Alcatel SEL, Centro de Estudos de Telecomunicaçoes, Univ. College of Wales
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 Zurich, Scuola Normale Superiore Pisa, Univ. Delft
O. Diekmann

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

MASK: Mathematical Structures in Semantics for Concurrency
September 1, 1992 - September 1, 1995
Univ. Pisa, INRIA, Univ. Udine, Univ. Mannheim, Univ. Koblenz
Coordinator
J.J.M.M. Rutten/J.W. de Bakker

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

Other programmes

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

National Programmes

SPIN (Stimulation Project Team Computer Science)

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

SION (Netherlands Foundation for Computer Science)

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

Incremental program generators
March 1990 - August 1994
P. Klint

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

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

Extensions of orthogonal rewrite systems - syntactic properties
January 1992 - January 1996
J.W. Klop

Declarative procedural aspects of non-standard logics
August 1992 - August 1996
K.R. Apt

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

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

NFI (National Facility Computer Science)

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

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

Research and Education in Concurrent Systems (REX)
January 1988 - July 1994
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 - November 1994
TNO/IBBC, Univ. Amsterdam
P.J.W. ten Hagen

Formal methods for the description of information systems and their analysis (ISDF)
September 1989 - September 1994
Universities of Eindhoven, Leiden, Limburg and Twente
M.L. Kersten

ALADDIN - Algorithmic Aspects of Parallel and Distributed Computing
January 1992 - January 1996
Univ. Utrecht
P.M.B. Vitányi

Systematic design of user interfaces
January 1990 - January 1994
Free Univ. Amsterdam, Univ. Delft, Univ. Bra-

bant, Univ. Twente
S. Pemberton

STW (Foundation for the Technical Sciences)

Statistical analysis of debugging and error counting models in software reliability
March 1989 - March 1993
Univ. Utrecht
K.O. Dzhaparidze

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

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

IOP (Innovative Research Programmes)

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

RESEARCH STAFF

Analysis, Algebra & Geometry

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Operations Research, Statistics & System Theory

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Analysis, Algebra and Geometry

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Numerical Mathematics

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Software Technology

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Algorithmics and Architecture

M. Bordegoni (Italy)
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E. Hughes (USA)
A. Israeli (Israel)
G. Kuper (USA)
M. Livny (USA)
S. Moran (Israel)
A. Panconesi (USA)
T.P. Pedersen (Denmark)
D. Peled (USA)
A. Shaham (Israel)
A. Shamir (Israel)
H. Shin (Korea)
H. Venter (South Africa)

Interactive Systems

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B. Servolle (France)
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S. Thiébaux (France)
R. Valent (France)

Computer Systems & Telematics

P. Strandjev (Bulgaria)
Z. Zolnai (Yugoslavia)
G. Piccolo (USA)

PUBLICATIONS

Department of Analysis, Algebra and Geometry

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

Papers in Journals and Proceedings

M. HAZEWINKEL (1992). Riccati and soliton equations. K. ITO, T. HIDA (eds.). *Gaussian Random Fields*, World Scientific, 187-196.

M. HAZEWINKEL (1992). Idiosyncratic remarks by a bibliomaniac. 6: Classics, masters, and handbooks. *Acta Appl. Math., 26*, 87-102.

M. HAZEWINKEL (1992). Hyperalgebra. *Handbook of Algebra Newsletter nr. 2.*

Reports

AM-R9207 T.H. KOORNWINDER. *On Zeilberg's algorithm and its q-analogue: a rigorous description.*

AM-R9208 M.A.A. VAN LEEUWEN. *The Robinson-Schensted and Schützenberger algorithms. Part I: new combinatorial proofs.*

AM-R9209 M.A.A. VAN LEEUWEN. *The Robinson-Schensted and Schützenberger algorithms. Part II: geometric interpretations.*

AM-R9210 M. HAZEWINKEL. *On cocommutative bialgebras.*

AM-R9211 M. HAZEWINKEL. *'Hilbert 90' for polynomial matrices.*

AM 2: **Modelling and analysis**

Papers in Journals and Proceedings

J.A.P. HEESTERBEEK (1992). The influence of certain co-factors on the spread of HIV. J.C. JAGER, E.L. RUITENBERG (eds.). *AIDS Impact Assessment, Modelling and Scenario-Analysis*, Elsevier Science publishers, 73-81.

M.C.M. DE JONG, O. DIEKMANN (1992). A method to calculate - for computer - simulated infections - the threshold value, R_0, that predicts whether or not the infection will spread. *Prev. Vet. Med., 12*, 269-285.

A.B. OLDE DAALHUIS (1992). Computing with Daubechies' wavelets. *CWI Quartely, vol. 5, no. 1*, 63-72.

A.B. OLDE DAALHUIS (1992). Hyperasymptotic expansions of confluent hypergeometric functions. *IMA J. Appl. Math., 49*, 203-216.

A.M. DE ROOS, O. DIEKMANN, J.A.J. METZ (1992). Studying the dynamics of structured population models: a versatile technique and its application to Daphnia. *Amer. Nat., 139*, 123-147.

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Department of Numerical Mathematics

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

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Department of Algorithmics and Architecture

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AA 2: **Cryptology**

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AA 3: **Computer systems and ergonomics**

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