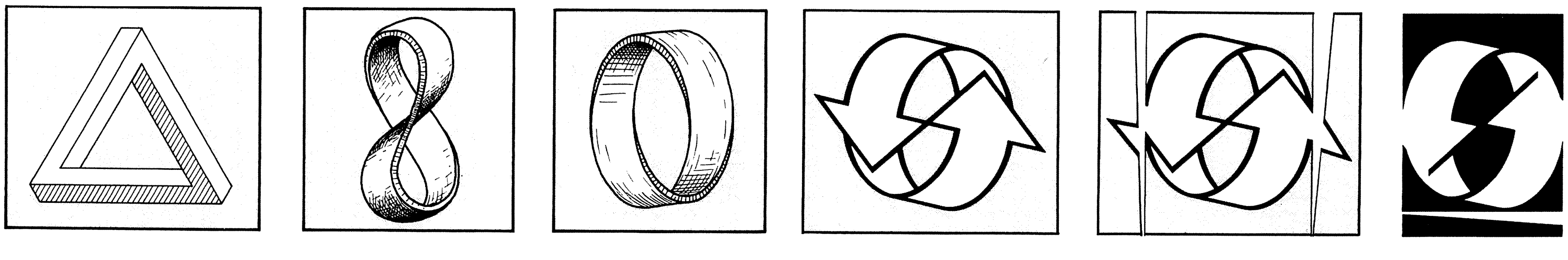
ANNUAL REPORT

Centrum voor Wiskunde en Informatica

Centre for Mathematics and Computer Science



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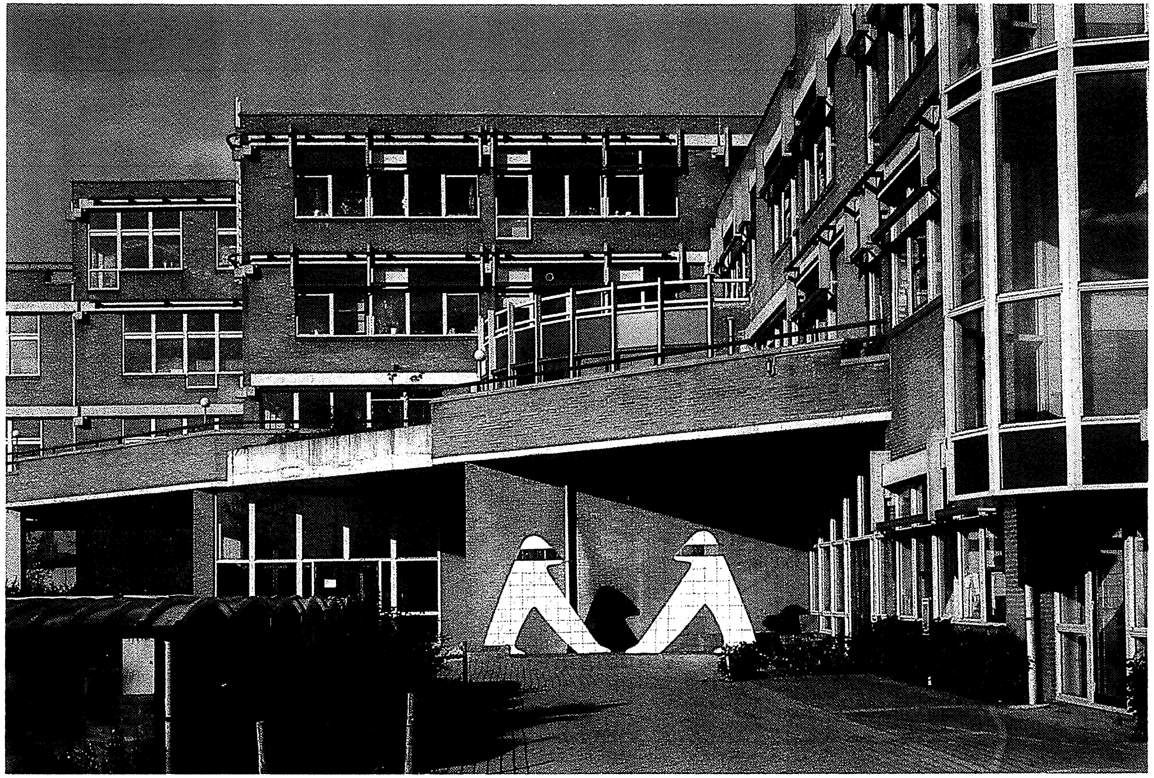
Centrum voor Wiskunde en Informatica
Centre for Mathematics and Computer Science

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



The Stichting Mathematisch Centrum was founded on february 11 1946, as non-profit institution aiming at the promotion of mathematics, computer science, and their applications. It is sponsored by the Dutch Government through the Netherlands Organization for the Advancement of Pure Research (ZWO).

Board of Directors

P.C. Baayen (scientific director)
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Centre for Mathematics and Computer Science (CWI)

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

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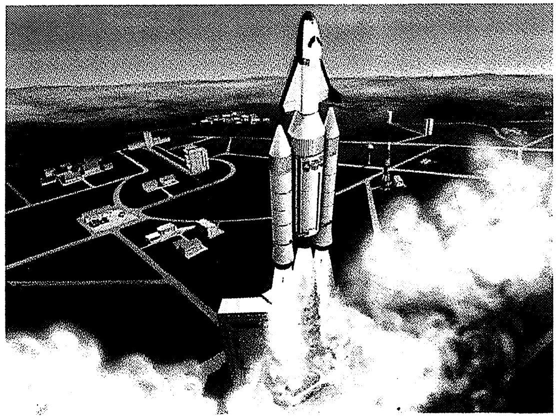
Introduction

Policy
During 1987, the Centrum voor Wiskunde en Informatica (CWI) matched its ongoing research programme with intensive planning for the future. There were a number of very good reasons for this. The supplementary grant under the Government's Information Technology Promotion Plan (INSP), will cease after 1988; and CWI wishes to ensure continuity for the expanded computer science research capacity made possible by this extra source of funding. On the other hand, the extra boost for computer science activities has left mathematical research lagging behind somewhat: restoration of an even balance is a priority.
A similar dichotomy is visible in another area. CWI policy has now for some years stressed strategic aspects of research and joint-effort with industry; but, at the same time we have to safeguard the institute's function as a centre of fundamental research. In recent years, the emphasis on the first activity, in particular in the field of computer science, has been to the detriment of the second (i.e. fundamental research).
These considerations led to CWI's Policy Document for the years 1988-1993, in which they are examined at some length. The document also gives the latest summary of current and planned projects.
For the same period a separate policy plan was produced dealing with the increasing importance of access to an up-to-date computer infrastructure to both researchers and support staff. Professor R. Dewar of the Courant Institute of Mathematical Sciences (New York) acted as consultant in the development of the plan.
Among features included in the Policy Document is regular evaluation of all research sectors by aptly named international visiting committees. In 1987 a start was made with three areas - statistics, stochastics and system theory. The advisory committees for each scientific department continue their work independently, alongside the activities of the visiting committees. The importance CWI attaches to national and international scientific contact and exchange was perhaps clearer in 1987 than ever in the past. Good examples of this in practice were the large number of visitors from home and abroad and involvement in congresses, workshops and colloquia (a number of which were jointly organized by CWI).

New projects
The list of existing projects increased, with new projects starting up and progressing apace as in the case of *Processing and reconstruction of images,* following an in-depth reconnaissance phase. In autumn 1987, CWI organized a Dutch Mathematical Society Symposium on the subject of 'Mathematical Aspects of Image Processing' and a working party directed its attention to the problems of mathematical morphology. A start on the *Logical aspects of artificial intelligence* project meant a welcome reinforcement of AI-research: this had been a priority in the 1984 CWI Computer Science Research Development Plan, but lack of funds prevented an earlier start. In the field of numerical mathematics, CWI researchers were active in designing *Algorithms for vector computers,* carrying out *Semiconductor calculations* and studying *Adaptive grid techniques.* An interesting commission from the European Space Agency involved application of CWI expertise on the Euler equations to calculations involving the *Hermes* space shuttle. Research also began into *Computational statistics* (software applications for statistical research). Experience built up in the ABC Project (ABC is a simple, structured, user-friendly programming language developed by CWI) is proving valuable in new research into *Man-machine interfaces.* A start was also made on the self-explanatory Intelligent, Integrated, Interactive Computer Aided Design project *(IIICAD).*

Knowledge transfer - expert training - central role
In recent years CWI has devoted increasing time and attention to knowledge transfer and expert training. In particular, the traditional mediums of publication and presentation have been complemented by joint projects with industry and the practical-commercial application of CWI expertise. The two Shell fellowships (set up in 1986) were filled in 1987; the research involved concerns *Combinatorial algorithms for planning and scheduling* and *Inverse scattering and image processing of seismic signals.* In the graphic software sector, the Programmer's Hierarchical Interactive Graphics System (PHIGS) was offered to



An artist's impression of the Hermes spaceplane on the Ariane-5 heavy-lift launcher. The Pressurized Module COLUMBUS, together with Hermes and Ariane-5 will form the European space transportation system for the year 2000 and beyond. CWI contributes to ESA's Hermes project with ongoing research into the numerical solution of two-dimensional stationary Euler equations. (Courtesy European Space Agency ESA.)

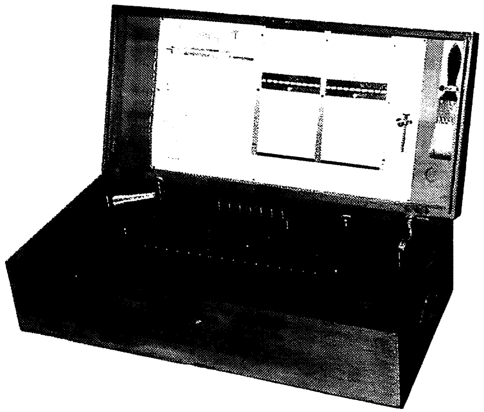
ISO and ANSI; and commercial rights for the Graphical Kernel System (S-GKS) were acquired by System Experts B.V.
A significant share of CWI's strategic-industrial research comes under the ESPRIT-Programme, with involvement in (project numbers in brackets) METEOR (432), GIPE (348), Parallel Architectures and Language for AIP - a VLSI directed approach (415), DIAMOND (1072) and VIP (1229 (1283)). Preparations were already underway in 1987 for CWI participation in ESPRIT II.
Turning to commissions, there were the development of a graphic system to manage Dutch Railways' marshalling yards, and a system to guide aircraft to loading/unloading areas at Schiphol Airport, Amsterdam. Some major banks expressed interest in cryptographic research.
A joint project started with the University of Twente in the area of flexible automation (the SPIN-project FLAIR). The ISNAS project, a joint effort involving six Dutch scientific bodies, was also launched in 1987. Work continued with the Ministry of Public Works on shallow-water equations (a project also involving the Delft Hydraulics Laboratory), and on extreme water levels at the North Sea coast.
A full list of 1987 publications is included, but it would be useful to mention a modest selection at this point. The CWI Monograph series continued with numbers 5 and 6: *One-Parameter Semigroups* by Ph. Clément and H.J.A.M. Heijmans, and *Program Correctness over Abstract Data Types with Error State Semantics* by J.V. Tucker and J.I. Zucker (which will appear in early 1988). J. Grasman's book *Asymptotic methods for Relaxation Oscillations and Applications* was published by Springer, and Th.J. Dekker, H.A. van der Vorst and H.J.J. te Riele produced *Algorithms and Applications on Vector and Parallel Computers* (pub. North Holland), a book based on the relevant national colloquium held at CWI during 1985 and 1986. Reidel published the first part (letters A and B) of the English translation of the *Russian Encyclopaedia of Mathematics,* a project involving major input from CWI. A quite different publication came in the form of the *Information Technology Atlas - Europe* (pub. North Holland), compiled by International Organisations Services B.V. (Amsterdam), J.C.P. Bus (CWI) and Wedgwood and Company, Ltd (London), together with the European Commission. Also deserving special mention is a book written by H.A. Lauwerier with a broad readership in mind - *Fractals: geometric figures in infinite repetition* (pub. Aramith, in Dutch).
CWI also (jointly) organized a number of conferences and workshops. In April, the fifth annual *Eurocrypt* conference on cryptography took place in Amsterdam. Also in April there was a conference in Noordwijkerhout on IIICAD, and in August CWI organized the annual Eurographics conference in Amsterdam. This was preceded by some specialist workshops. CWI was involved in the preparation of the programme for the PARLE-conference (on environments for parallel architectures and languages), held in June, in Eindhoven. In September, experts from Denmark (Univ. of Aarhus) and the Netherlands took part in a CWI workshop on image processing, whereas in November CWI organized a national colloquium on *Mathematical Mor-*

phology. Also in November, IIASA's *System and Decision Sciences* (SDS) Programme was highlighted, alongside with related research in the Netherlands, in a symposium at CWI, organized jointly with the Foundation IIASA-Netherlands. In December, a symposium on *Statistical Methods for Large Parameter Spaces* was organized jointly with the Dutch Association for Statistics. The year ended with the *Frontiers in Computing* conference in Amsterdam, organized by Frontiers in Information Technology (FIT) - an international umbrella organization set up and managed by CWI.

CWI has made a particular point of promoting knowledge transfer via courses. In addition to longstanding postgraduate courses on such subjects as *PROLOG* and *Software Engineering*, and the annual summer courses for secondary school teachers (1987 subject: *The PC and Maths at School*), CWI gave its first commercial course on *Vector and Parallel Computing*; twenty attended. CWI was also involved in the set-up of graduate training in computer science (a joint project with the two Amsterdam Universities and the University of Utrecht).

History

In 1987 CWI also took time to look back. The final events marking the institute's fortieth anniversary attracted considerable attention among both general public and the scientific community. The exhibition *Rekenen met Raderen* (Calculating with Clockwork) at Teylers Museum (Haarlem), which traced the history of pre-electronic computers, drew 15,000 visitors within three months. In June, *Om de Wiskunde* (Around Mathematics), a symposium jointly organized with a national working party on the history and social function of mathematics, dealt with the early years of the Centre and its role in post-war recovery. Speakers included the historian E.H. Kossmann and the economist J. Tinbergen. The founding of the Mathematical Centre (CWI's pre-1983 title) was also covered in 'Zij mogen uiteraard daarbij de zuivere wiskunde niet verwaarloozen' (Don't let them neglect pure mathematics), a book edited by G. Alberts, F. van der Blij and J. Nuis.



This 'Millionaire' calculator (circa 1920) formed part of 'Rekenen met Raderen' (Calculating with Clockwork), an historical exhibition on pre-electronic computers at Teylers Museum in Haarlem. The exhibition, one of the final events in the programme marking CWI's 40th anniversary, drew 15,000 visitors in three months before moving on to other Dutch cities. The 'Millionaire' was used by the late Adriaan van Wijngaarden (director of the Mathematical Centre 1961-1980) in preparing his Ph.D. thesis during the early 1940's. A similar machine was used by the celebrated Dutch physicist, H.A. Lorentz, in connection with the enclosure of the Zuyderzee ten years earlier. (The Millionaire appeared by courtesy of the Laboratory for Technical Mechanics, Tech. Univ. Delft.)

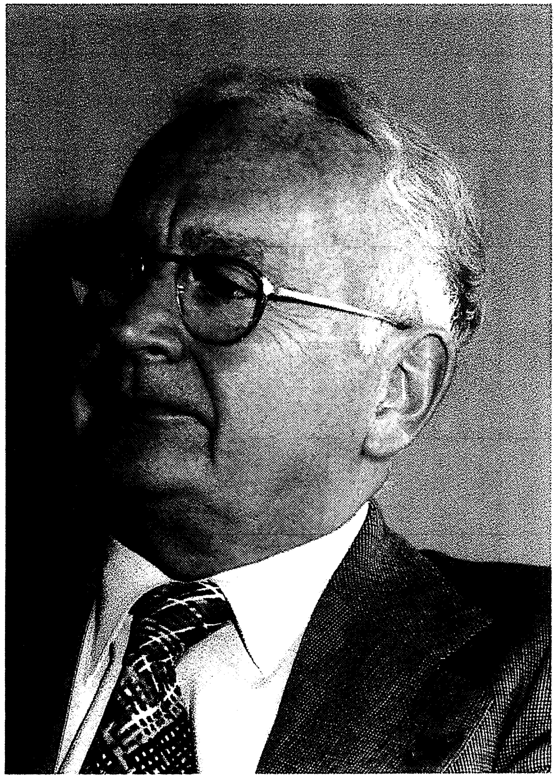
This annual report differs somewhat from its predecessors. In particular we have tried to present the research part in a form more accessible to non-specialist readers. We describe one project in each department in some detail and in general terms. The remaining projects appear only in summary form - title, short description, start-up year, research personnel and parties involved. However, this report goes into more detail on such matters as contract research, (inter)national programmes, knowledge transfer and central role. Hopefully, we have achieved our aim of improved accessibility and increased information.

P.C. Baayen
Scientific Director CWI

In Memoriam A. van Wijngaarden

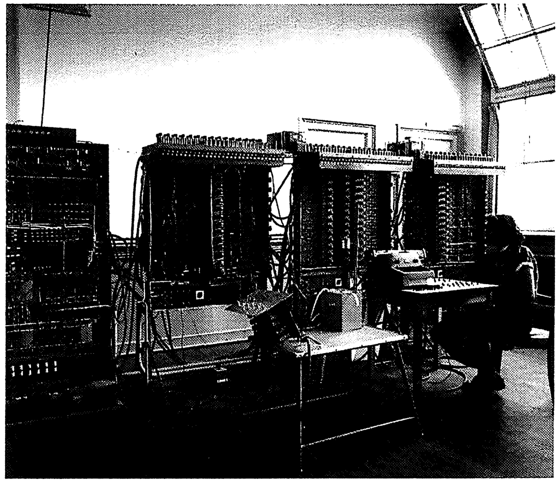
An era came to an end on February 7th 1987, with the passing away of Prof. Adriaan van Wijngaarden. He had been connected with the Mathematical Centre (CWI's pre-1983 name) almost since its foundation, first as head of the Computing Department, then from 1961 to 1980 as director, followed by a further year as advisor to the Board of Trustees and Board of Directors. Professor Van Wijngaarden was a pioneer of computer science with his roots in (numerical) mathematics; indeed, he embodied one of the principles on which the Mathematical Centre has always set great store: mathematics going hand in hand with computer science. The birth of computer science in The Netherlands, and its development into a fully fledged discipline, was in no small part due to his efforts. Internationally, Adriaan van Wijngaarden's contribution to the development of the programming languages ALGOL 60 and ALGOL 68, and his role in such organizations as IFIP, have been of lasting significance. We shall remember him with affection and respect.

Van Wijngaarden was born in Rotterdam on November 2nd, 1916. He studied mechanical engineering at the Technical University of Delft where he took his doctor's degree in 1945 on a thesis entitled 'Some Applications of Fourier Integrals to Problems of Elasticity'. Before he joined the Mathematical Centre (MC) on January 1st, 1947, he had held positions at the Technical University of Delft and at the National Aviation Laboratory (NLL). Immediately after his appointment as head of the nascent Computing Department, Van Wijngaarden went on a prolonged fact-finding mission to England and the USA in order to orientate himself about the newly developed electronic computer, and its use. In the course of this trip he came into contact with such computer pioneers as Wilkes, Turing, Wilkinson, Goldstine and Von Neumann. Upon his return, one of his conclusions was that the MC would do best to design and construct itself a computer. In 1952, under the leadership of Van Wijngaarden, the ARRA (Automatische Relais-Rekenmachine Amsterdam) - the first electronic computing machine in the Netherlands and one of the first on the continent of Europe - was completed at the MC. Members of the development team were B.J. Loopstra and C.S. Scholten, for a shorter period G.A. Blaauw, and at a later stage E.W. Dijkstra and W.L. van der Poel. The latter was at that moment employed by the Laboratory of the PTT (Post and Telecommunications Office), but worked in close collaboration with the MC. Of the total of five computers which the Netherlands



had in 1955, three (ARRA, FERTA and ARMAC) had been built under Van Wijngaarden's leadership at the MC, while the constructor of PTERA of the PTT - Van der Poel - was his first Ph.D. student, and later conferred Van Wijngaarden's own honorary doctor's degree at the Delft Technical University. (The fifth machine was a Ferranti computer at Shell.) In 1959 commercial interest for computer construction led, in cooperation with the life insurance company Nillmij, to the founding of an independent company: Electrologica (later incorporated in Philips Data Systems).

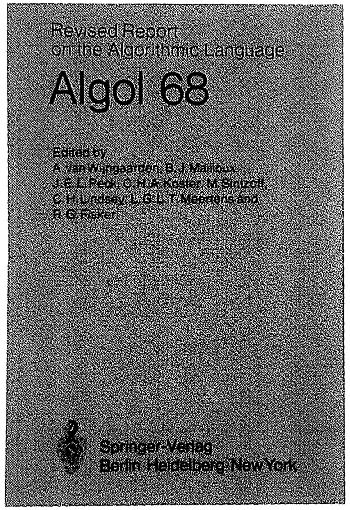
In the meantime Van Wijngaarden had already actually built up a computing service, which under his direct leadership - each morning he gave the 'calculator girls' a one hour lesson, and he was personally involved in setting up the calculation schemes - contributed considerably to the realisation of the goals of the MC. In this way, in a contract



for the NLL, for those days difficult and extensive calculations were made of the vibration (flutter) of aeroplane wings in subsonic streams.
During these 'calculating years' Van Wijngaarden was also active as a mathematician. He published many articles on various subjects in applied and numerical mathematics, and some in the area of the theory of numbers. His name lives on for numerical mathematicians in the Van Wijngaarden Transformation. Appreciation for his scientific work followed quickly: in 1952 Van Wijngaarden became 'special professor' at the University of Amsterdam and in 1958 'professor extraordinary' in a chair on 'Numerical Mathematics and Computer Methodology'. In 1959 he was elected to the Royal Dutch Academy of Sciences. Many of his pupils

Largely due to Van Wijngaarden's efforts, the first electronic computing machine in the Netherlands (named ARRA) and one of the first on the continent of Europe, was completed at the Mathematical Centre in 1952.

have leading functions in research and industry. At the moment 10 of his 15 former Ph.D. students hold themselves a professorship.
Already in the period when he was involved in the construction of computers, but even more after the actual production process had been passed on to commercial interests, Van Wijngaarden's scientific interest focussed on the mathematics of programming. Together with his co-worker E.W. Dijkstra he made essential contributions to the development of ALGOL 60 and he was the great pioneer of ALGOL 68. The contribution of each of the four authors of the ALGOL 68 report were characterized concisely by Van Wijngaarden as follows: 'Koster: transputter; Peck: syntax; Mailloux: implementation; Van Wijngaarden: party ideologist'. The report itself, translated into Bulgarian, Chinese, German, French and Russian, stands from a scientific point of view, in its severity and sharpness of definition, at a lonely peak of mathematical elegance and thoroughness. As part of the ALGOL 68 project Van Wijngaarden developed his elegant and forceful concept of two-level grammars (called after him W-grammars). The design of ALGOL 68 has had an enormous influence on the development of later programming languages and on programming theory and practice in general.
Van Wijngaarden's interest, for that matter, was not limited to algorithmic languages. He was fascinated by language in general - and in particular by the interface between computer and natural language. He was very keen on the correct and cultivated use of language, and had a special feeling for puns and etymology. He also contributed actively as a member of the Working Group on Frequency Research of the Dutch Language. His love for language, however, did not prevent him from concluding his scientific career in 1981 with a lecture entitled 'Languageless programming'.
Already at the end of the fifties Van Wijngaarden was actively devoting his organizational talents to both national and international matters. Because also of his courteous and forthcoming way of dealing with people he played an important part in the founding of the Dutch Computer Society in 1959 and of the International Federation for Information Processing (IFIP) in 1960. He held important functions in both organizations for



In the 1960's Van Wijngaarden was the driving force behind the design of ALGOL 68, which has had an enormous influence on programming theory and practice afterwards.

many years.
During the fifties and sixties the computer work of the two Amsterdam universities (the Free University and the University of Amsterdam, VU and UvA) was done at the MC. When, about 1970, this started to form too great a burden for the institute, it was decided to found SARA, a joint computer centre for VU, UvA and the Mathematical Centre. Van Wijngaarden, who was one of those who took the initiative for this unique form of cooperation, was a member of the board of SARA until the end of 1980.
Appreciation for the scientific and organizational contributions which Van Wijngaarden has given to the development of computers, information technology and electronic information processing, is apparent from the many invited professorships he has held and from the decorations bestowed upon him. He spent various periods as visiting professor at the University of New York, the University of California at Berkeley, and the University of Chicago.
He was honoured nationally in 1973 when he was appointed Knight of the Order of the Dutch Lion, in 1979 he received an honorary doctorate at the Technical University of Delft (when his first Ph.D. student Van der Poel conferred his degree) and in 1981 upon leaving the MC the award of the 'Silver Medal' of the City of Amsterdam. Foreign awards were the 'Medaille d'argent de la ville de Paris' (1959), an honorary doctorate of the Institut National Polytechnique in Grenoble (1979), the Wilhelm Exler Medaille of the Österreichische Gewerbeverein in Vienna (1981) and the Computer Pioneer Award of the IEEE (1986).
Van Wijngaarden had a charming and lovable personality. At the same time he was a perfectionist. He characterized his working method as that of an engineer: 'Engineers don't start by talking: what on earth would they be supposed to say? They make the design for a project and then say: do you want it?'. These were the lines on which Van Wijngaarden lived and worked: with great style, aiming at perfection, but at the same time with attention and personal interest for the people around him. Here we would like to express our sincere gratitude for everything that was done for the Mathematical Centre and the scientific world by Adriaan van Wijngaarden, Dutch mathematician and computer scientist.

P.C. Baayen
J. Nuis
Directors CWI

Organization

The Centre for Mathematics and Computer Science (CWI) is the research institute of the Stichting Mathematisch Centrum (SMC), which was founded on 11th February 1946. SMC falls under The Netherlands Organization for the Advancement of Research (NWO), the main source of funding.
In line with its statutory purpose 'to foster the systematic pursuit of pure and applied mathematics in The Netherlands', SMC immediately set up an institute for fundamental research, the Mathematical Centre. From the outset this institute played an important role in the development of computer science in The Netherlands. A change to the present name, CWI, in September 1983, reflected the major expansion of research in this field. On the national level this growth led to the setting-up in 1982 of the Stichting Informatica Onderzoek in Nederland (SION), an independent NWO research organization for computer science. SION and SMC share premises at CWI, their formal connection is embodied in a Permanent Consultation Commission.

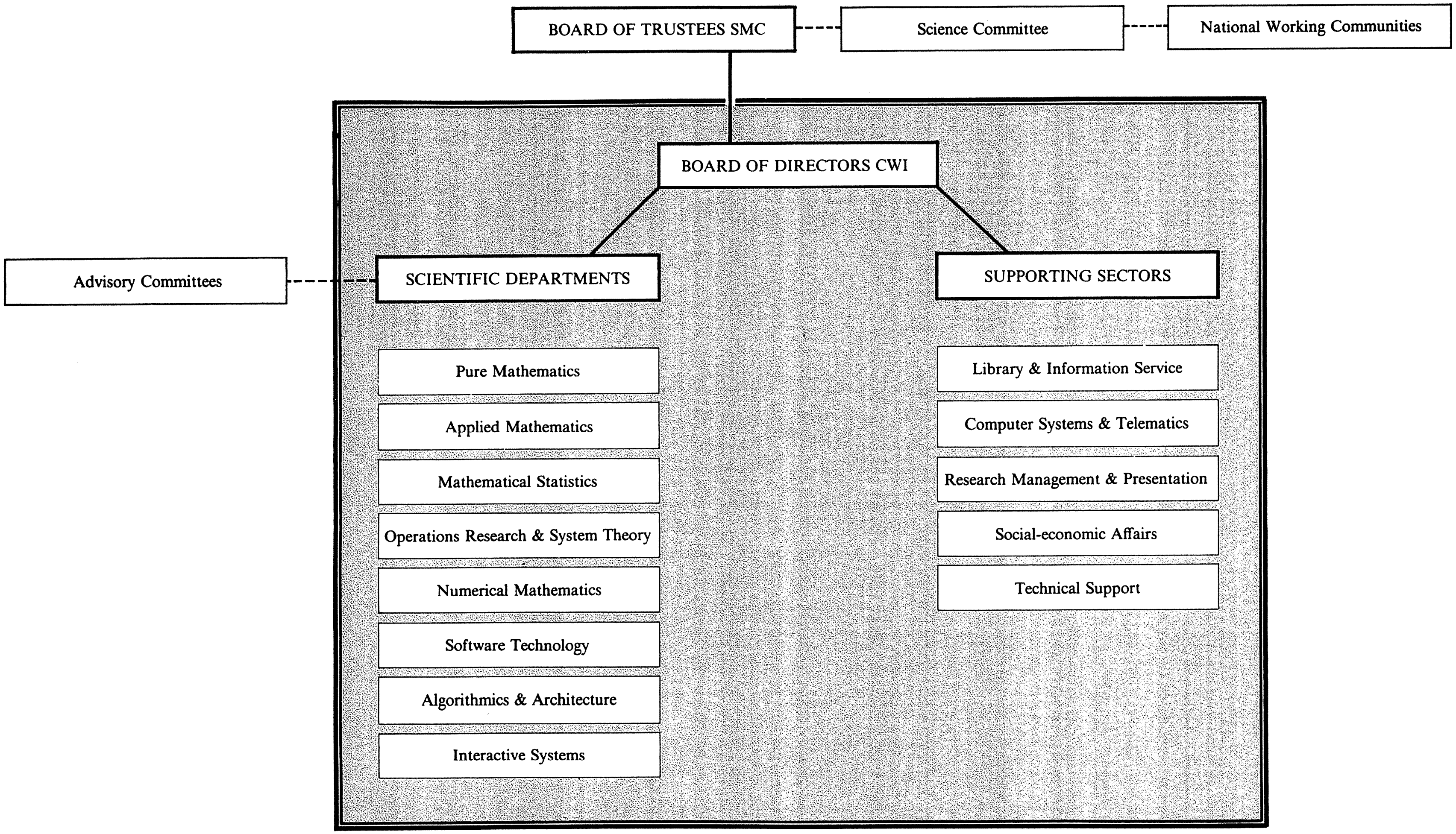
SMC also finances research projects at Dutch universities. These projects are organized in eight national working parties in the following fields:

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

SMC 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.

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.
CWI research is organized in eight scientific departments. The structure is less rigid than it appears, given considerable inter-departmental collaboration. This is a matter of deliberate policy, not only in the selection of research topics, but also in the selection of the permanent scientific staff. There are also a number of supporting service departments. The organization of SMC and CWI is shown on the opposite page.

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



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

Department of Pure Mathematics

M. Hazewinkel (head of department)
H. den Boer
J.T.M. van Bon
J.N.E. Bos
G. Brassard
A.E. Brouwer
D. Chaum
A.M. Cohen
I. Damgård
J.H. Evertse
J.A.M. van de Graaf
T.H. Koornwinder
J. van de Lune
S. Mjølsnes
S.N.M. Ruijsenaars
G.C.M. Ruitenburg
J.K. Scholma
R. Sommeling
J. de Vries

trainee:
W.H.L. Neven

LOCAL RECOGNITION OF GEOMETRIES

Introduction
In synthetic geometry, one attempts description of a geometry using some of its fundamental properties (axioms); the oldest example being Euclid's axiomatic description of the affine plane. Axioms chosen should be the most elegant and easily verifiable. A particular aspect of the problem of choosing a set of axioms is the extent to which a geometry is characterized by local axioms (i.e. axioms referring uniquely to a given point and its neighbourhood). The CWI study of this question covered a class of geometries associated with groups of Lie type. These studies increase our insight both into geometry and the theory of such groups, many of which play an important role in modern theoretical physics.

Projective geometry
Here, for ease of presentation, the term 'geometry' is understood as a pair P,L, consisting of a set P of *points* and a collection L of certain subsets of P, called *lines.* The principle of describing a geometry by means of a well-chosen set of axioms can be illustrated by the example of a *projective geometry.* Such a geometry can be thought of as coming from ordinary n-dimensional Euclidean space as follows: define the point set P of the geometry as the collection of all lines through a point O and its line set L as the collection of all planes through O. (In order to view a line of our geometry as a set of points, identify a plane through O in Euclidean space with the set of lines through O contained in it). The properties of this geometry P,L can be studied by projection onto a hyperplane not containing O (hence the term 'projective'). This satisfies the following axiom [Pasch]:
If two lines l, m meet in precisely one point, and two lines p, q meet both l and m in distinct points, then p and q have a point in common.

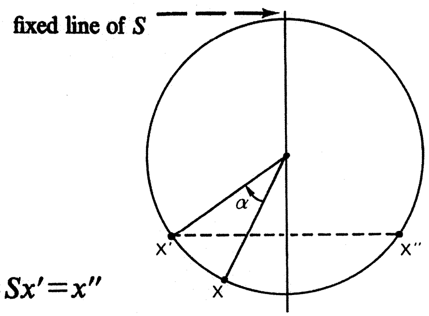
Now, a theorem (Veblen and Young) states that *any* geometry in which there is a line through every pair of points (every pair is 'colinear') and which satisfies [Pasch] and certain additional conditions (such as: every line having at least three points, and there being at least two planes), is a projective geometry coming from a vector space whose dimension is at least 4. This implies that every statement in a projective geometry established by reference to the generating vector space, could also be verified by the simple use of point/line arguments and [Pasch].

Geometries of Lie type
There is a host of known geometries meriting an axiomatic description, including geometries associated with *groups of Lie type;* these received particular attention at CWI.

In general, given a group of Lie type G and a suitable subgroup H, there is a natural choice of line on the coset space G/H turning the space into a *geometry of Lie type.* Projective geometry recurs as the special case where G is the group of all linear transformations of an n-dimensional vector space, and H the isotropy group of a one-dimensional linear subspace. Other 'suitable' subgroups of G are the isotropy groups of higher-dimensional subspaces; the resulting 'Grassmannian' geometries appear in many parts of mathematics.

Local axioms
Firstly we need a precise definition of 'neighbourhood'. In a geometry P,L the distance

A group is a set of elements in which any two elements may be combined ('multiplied') to yield a third element; there is a unit element which, multiplied by any element, leaves that element unchanged; and a 'division' operation, which is the inverse of multiplication; the multiplication is associative. In Lie groups the elements are labeled by one or more continuous parameters (such as the rotations around a given axis, where the continuous parameter is the rotation angle). Groups of Lie type encompass these groups, but may also contain discrete elements.



$S{\cdot}R_\alpha x = Sx' = x''$

As an example, consider the transformations of the points on a circle by a clockwise rotation over a given angle α around its centre (R_α), or by reflection with respect to a fixed line through the centre (S). The set $\{R_\alpha, R_\alpha{\cdot}S\}$ ($0 \leq \alpha < \pi$), forms a group G, as is easily verified. The subset $\{R_0$ (the unit element), $S\}$ forms a *subgroup* H of G, which leaves the intersection points of the symmetry axis and the circle invariant (the *isotropy group* of these points). Any element of G belongs to one and only one *coset* of H, obtained by multiplying the elements of H with some $g \in G$. In this example the cosets are $\{R_\alpha, R_\alpha{\cdot}S\}$. The cosets form a space G/H which can be identified with the circle via $\alpha \rightarrow \{R_\alpha, R_\alpha{\cdot}S\}$.

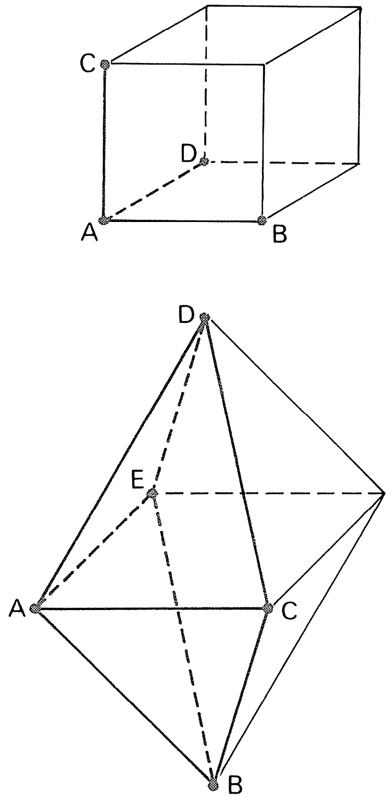
between two points A and B is defined as the length of the smallest sequence of points from A to B, such that any two consecutive points of the sequence are colinear. The distance between two colinear points is 1. The *h-neighbourhood* of a point A is the set X of all points whose distance to A is at most h, together with all lines bearing at least two points of X. If P,L is the unique space such that the h-neighbourhood of every point is isomorphic to a fixed space X, we say that P,L is *h-recognizable.* Now we can pose the following question. Given a geometry P,L, what is the minimal value h for which P,L is h-recognizable?

Also, a set of axioms is said to be *h-local* if it can be verified using only the knowledge of the h-neighbourhood of each point. Thus, given an h-recognizable geometry, it makes sense to ask for an h-local set of axioms.

Graphs

Geometries where all lines carry only two points, are called *graphs*. Some very special graphs are *regular polytopes*; they form one of the tools for understanding geometries of Lie type. Examples of regular polytopes are the cube and the octahedron. Although a regular polytope is essentially an object in Euclidean space, we shall interpret it as a geometry of points and lines, disregarding the ambient space.

Now, the 1-neighbourhood of a point γ in the octahedron consists of a quadrangle together with the point γ, colinear to all the points of the quadrangle. The octahedron is the only graph all of whose points have such a 1-neighbourhood, so the octahedron is 1-recognizable. But the 1-neighbourhood of a point of the cube consists of three disjoint points,



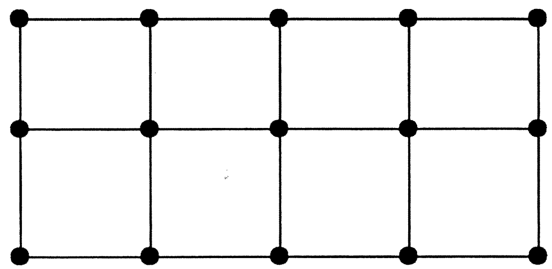
One way of understanding Lie type geometries is the study of regular polytopes, two examples being the cube and the octahedron. The 1-neighbourhood of a point A (coloured points and lines) is shown for both. The octahedron is the only graph where all points have this particular 1-neighbourhood. In the case of the cube the 1-neighbourhood of a point (A) contains three disjoint points (B, C and D) and there are many graphs with this property.

and there are many graphs all of whose points have such a 1-neighbourhood.
Now, the following axiom system [A] characterizes the cube:

- every point lies on 3 lines;
- each line has 2 points;
- every pair of points at distance 2 lies in 1 quadrangle;
- if p is a point and Q a quadrangle not containing p, then the set of points in Q colinear with p is either empty or a singleton.

The only graph that satisfies [A] is the cube. In order to verify [A] for an arbitrary graph, it is sufficient to know the structure of the 2-neighbourhoods of its points (knowing only the 1-neighbourhoods will not do). Thus [A] is 2-local and the cube is 2-recognizable.
The simplest regular polytope, the tetrahedron or 'simplex', is a graph in which any two points are colinear. [Pasch] is trivially satisfied in a simplex. It is sometimes referred to as the 'thin' projective space (the term indicates certain minimal conditions, e.g.: just two points on a line, two lines through a point, etc.). Since the 1-neighbourhood of any point of the simplex is the graph itself, any axiom system is 1-local, quite similar to projective geometry.

Grassmannians
The 'thin' Grassmannians are the graphs defined by means of a set of n elements as follows: the points are the subsets of size k, and the lines are the pairs of points meeting in a subset of size $k-1$. The 1-neighbourhood of a point γ in this graph has the shape of the point γ itself, together with a k by $n-k$ 'grid', all of whose points are of course colinear with γ. We rephrase this as: 'the thin Grassmannians are locally a k by $n-k$ grid'. The notion of a grid is illustrated in the picture below of a 3 by 5 grid. Here



any two points on the same horizontal/vertical level are regarded as colinear.
The graphs which are locally a 4 by 4 grid, have been determined at CWI (Blokhuis & Brouwer). In addition to the expected thin Grassmannian of subsets of size 4 in a set of size 8, there were more graphs with this local structure. Therefore knowledge of the 1-local structure is not sufficient to characterize this thin Grassmannian, i.e. it is not 1-recognizable, and the best one may hope for is 2-recognizability. This holds for thin Grassmannians in general. Conversely, many axiom systems for these graphs are, indeed, 2-local.
The Grassmannians themselves (and not only the 'thin' ones) also have 2-local axiom systems (Cohen, finalizing earlier work of Cooperstein). It is surprising that, although the diameter (the greatest distance realized) in Grassmannians grows with k, all are 2-recognizable.

Some special regular polytopes
In Euclidean space of any dimension >3, there are regular polytopes resembling octahedron and cube: the *hyperoctahedron* and *hypercube*. They are the thin versions of the geometries related to groups of classical Lie type (the orthogonal, symplectic and unitary groups). The hyperoctahedron behaves as the octahedron: its diameter is 2 and it is locally a hyperoctahedron of smaller dimension, so that 1-local axiom systems exist. Johnson & Shult derived such a system from a known global system for the corresponding geometries of Lie type. In the Lie geometry analogues of the hypercube the diameter grows with the dimension. Work by Brouwer & Wilbrink and Brouwer & Cohen resulted in an 8-local axiom system (finite case; in the general case, quotients of the Lie geometry also arise). In Euclidean 4-dimensional space, there is an additional interesting regular polytope, related to the geometry of Lie type F_4: this has 24 points and is locally a cube. There is another graph (in fact the only one) with this local structure, obtained from the 3 by 5 grid by interchanging its points and lines. Thus, here again the geometry is not 1-recognizable. However, work by Cohen and Cooperstein implies that very little additional knowledge of 2-neighbourhoods is necessary to characterize these geometries. Also 2-local axiom systems have been given characterizing

the so-called root group geometries of exceptional Lie type E_6, E_7, E_8.
The regular polytopes not covered in the above discussion, viz., the icosahedron, dodecahedron, and the 4-dimensional 600-cell, do not correspond to Lie geometries.

Group theory without groups
The local approach to geometries of Lie type is inspired by group theory, so much so that the work is sometimes referred to as group theory without groups. Finite simple groups are often characterized by 'local information', for example the knowledge of 1- and 2-neighbourhoods in geometries whose points are certain involutions of the group and in which a line is the set of points contained in an elementary abelian subgroup. The results discussed above may have applications in group theory.

New directions
A slight change of the local approach also allows for geometries obtained from those of Lie type by removing a suitable big subspace (hyperplane). In the case corresponding to the hyperoctahedron, a 1-local axiom system has been given (Cohen & Shult).
Finally, since there is no restriction on finiteness in most of the above results, one might try to extend them to geometries of affine Lie type. A 2-local axiom system for geometries of affine type E_8 has been found (Cohen).

PROJECTS

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

Discrete mathematics and cryptography
There are two subprojects:

- Algebra, geometry and combinatorics (1972).

  A.M. Cohen, J.T.M. van Bon, A.E. Brouwer, R. Sommeling.

  The research is concerned with Chevalley groups and the associated geometries and, more generally, with geometries of Buekenhout-Tits type.
  It is also concerned with some algebraic/discrete mathematical aspects of Lie groups, e.g. the classification of finite subgroups of exceptional Lie groups. In addition, there is research in coding theory, the theory of designs and the theory of graphs (especially distance-regular graphs).

- Cryptography (1980).

  D. Chaum (NFI), J.N.E. Bos, J.H. Evertse, J.A.M. van de Graaf, H. den Boer (NFI).

  Most of the research in this group aims at the creation, development, and description of 'secure' communication protocols and to provide the mathematical proofs that they are indeed secure. In addition attention is paid to actual implementation questions and the evaluation of proposals for such protocols of others.

Univ. Rotterdam, Free Univ. Brussels, Univ. Michigan, Univ. Eindhoven, Univ. Freiburg, Cal. Tech. Pasadena.

Analysis
The purpose is harmonic analysis on (pseudo-)Riemann symmetric spaces, the study of special functions and their group theoretic interpretation, the study of (zero patterns of) special analytic functions and various problems of a number theoretic nature.

- Analysis on semisimple Lie groups and symmetric spaces and the connection with special functions (1972).

  T.H. Koornwinder, J. van de Lune, G.C.M. Ruitenburg.

- Special functions and classical analysis (1972).

  T.H. Koornwinder, J. van de Lune, H.J.J. te Riele (CWI Dept. of Num. Math.), G.C.M. Ruitenburg.

Univ. Leiden.

Algebraic mathematical physics
The investigation of algebraic (and algebraic-geometrical), combinatorial and representa-

tion theoretical aspects of completely integrable Hamiltonian systems (both quantum and classical), the exactly solvable models from lattice statistical mechanics and parts of gauge theory and representation theory which are related to this.

- The generalized hard hexagon model (1984).

  M. Hazewinkel.

- Relations between finite degree of freedom, infinite degree of freedom, lattice, classical, quantum and relativistic integrable models (1985).

  M. Hazewinkel, S.N.M. Ruijsenaars (Huygens), J.K. Scholma.

Univ. Twente, Philips Telecomm. Hilversum, Univ. Utrecht.

Dynamical systems
Research on dynamical systems, with emphasis on topological and measure-theoretic aspects. Later on possibly also chaotic and stochastic aspects (e.g. stochastic (partial) differential equations and their applications) will be studied (1976).

J. de Vries.

Department of Applied Mathematics

H. Lauwerier (head of department)

O. Diekmann	B. de Kerf	K. Soni
B. Dijkhuis	J.A.J. Metz	R.P. Soni
P.P.B. Eggermont	J.B.T.M. Roerdink	H.E. de Swart
A. Grabosch	H.N.M. Roozen	N.M. Temme
J.A.P. Heesterbeek	K.E. Schuler	M. Zwaan
H.J.A.M. Heijmans		

DYNAMICS OF PHYSIOLOGICALLY STRUCTURED POPULATIONS

Introduction

In studying the dynamics of populations it has become increasingly clear that models, where all individuals are treated as if they were the same, are usually unsuited to a quantitative confrontation with real data. There is also a general wish to tune the mathematics more to the biological mode of examining problems. Hence, the considera-tion of 'physiologically structured' popula-tions, where individuals differ in size, age, en-ergy reserves, etc. These models are more realistic, though mathematically far more complicated - and interesting.

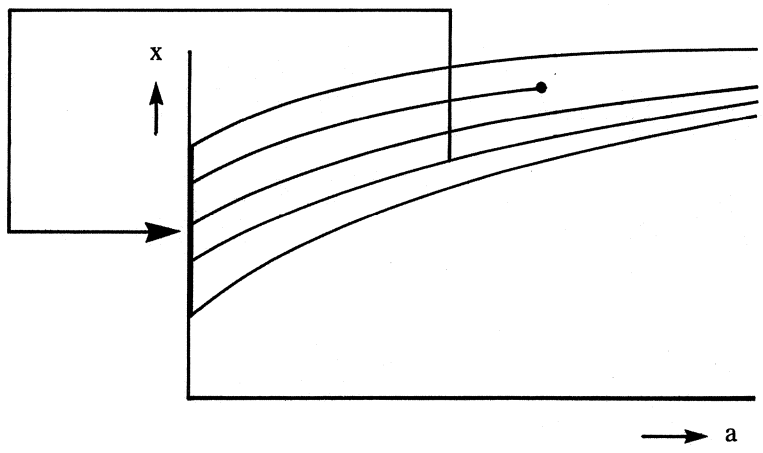
CWI's joint project with the University of Leiden aims to develop a general modeling methodology for physiologically structured populations, to create an exchange between this methodology and the theory of dynamical systems, and to study biologically relevant special cases in detail.

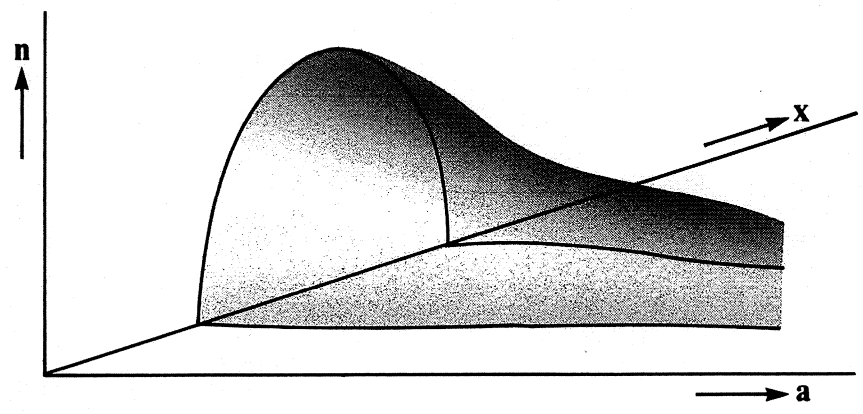
Models with physiological structure

As in any experiment, a given mathematical model necessarily entails a good deal of simplification. The ultimate aim is to help un-ravel the natural network of cause and effect by studying mechanisms in their bare essen-tials, unobscured by all the wonderful detail present in the natural state. The classical lumped models of population dynamics, where all individuals are considered identical, constitute a good example of this simplified approach. It is a useful ploy when the essen-tials of the population process under study can be captured in a few empirically mean-ingful parameters incorporating the gross in-teractions between individuals. A simple ex-ample is a cell culture where the substrate is continuously replenished. Individuals, howev-er, are usually far from identical; and quanti-ties like per capita birth and death rates are no more than 'population properties', i.e. averages over the whole population. Many mechanisms, which determine individual behaviour relevant for population dynamics, are directly related to individual differences. Thus food scarcity affects reproduction by keeping individuals for longer in the non-productive size range. Despite the quite justified tendency towards simplification there is a need for modeling strategies and corresponding mathematical tool boxes which take into account both the total size of a po-pulation and its physiological structure. Here 'structure' refers to any subdivision on the basis of one or more traits of the individuals and the adjective 'physiological' serves to sin-gle out traits such as size, which reflect dynamical processes in the individual.

Model construction

The first task is then to give a proper defini-tion, in terms of certain variables, of that state of an individual known as the *i-state*. The *i*-state should capture all properties of the individual which are relevant for the dynamics of the population. An example of a possible variable is the size of an individual: it plays a role because e.g. reproduction takes place only above a certain size. Supposing that the probability of producing offspring, the number of offspring, the probability of dying, and an individual's feeding rate all depend exclusively on its size and the current food conditions - then size would be a candi-date to characterize the *i*-state. But, size alone may not be sufficient: e.g. if the way size alters in time depends on other intrinsic fac-





Left:
The i-state space of a physiologically structured model, involving age (a) and size (x). Termination of a life-line is indicated by ●, production of offspring by ⌑

Right:
The frequency distribution of a population, represented as a surface above the i-state space. The mathematical model equations describe the change in time of this surface.

tors like age, then a comprehensive characterization of the *i*-state requires their incorporation also.
Now, consider a simple case where the *i*-state is completely specified by the size (x) and age (a) of the individual, the latter taken to be the physical time up to an additive constant. Each individual then traverses a trajectory in the $x-a$ plane, starting at a point of creation (birth) and terminating at a point of annihilation (death, cell division, or other 'jump' transitions). At any time the total population is then represented as a cloud of points in the $x-a$ plane, called the *p*-state. Its changes in time represent the dynamics of the population: more precisely the *p*-state is the frequency distribution of the individuals over the space Ω of all possible *i*-states. All relevant population quantities can be calculated as integrals of this frequency distribution with some weighting function. Thus, the total number of individuals is given by $N(t)=\int_\Omega n(t,x,a)dxda$, and the total biomass by $M(t)=\int_\Omega m(x)n(t,x,a)dxda$, where n is the population density in the point (x,a) and m the biomass as a function of size.
A complete recipe for the construction of a deterministic physiologically structured model then reads as follows:

- Track down an appropriate set of *i*-state variables (e.g. size and age) and determine the corresponding *i*-state space Ω.
- Determine the (deterministic) motion through the *i*-state space (growing, ageing) in dependence on the *i*-state itself and the environmental conditions.

- List the (stochastic) jump transitions (death, birth), again in dependence on *i*-state and environment.
- Use simple bookkeeping arguments to write down, on the basis of the *i*-model, an equation for the rate of change of the *p*-state. (Assume that numbers are so large that we can describe stochastic processes in terms of rates - as is usually done in chemistry.)
- Specify the way in which environmental variables (like substrates) are influenced by the population (e.g. via consumption).

Formulating a model may already - on its own - provide clarification, but to take full advantage of the exercise we must:

- analyze the resulting *p*-equations to distil relevant biological information.

Some approaches

The traditional and oldest example of a model in the sense described above is the linear age-dependent model of human demography introduced by Lotka and Sharpe in 1911. In the late sixties and early seventies several influential papers considered traits like size and chemical composition in the description of populations of unicellular organisms. The first five points of the recipe mentioned above were fully covered in these papers, but the last point was usually restricted to a crude numerical integration.

In about 1983, R.M. Nisbet and W.S.C. Gurney (Glasgow) started to develop *stage structure models,* characterized by the fact that individuals within the same stage have identical physiological and behavioural properties. They did so partly to be able to use efficient numerical methods for delay equations and partly because they wanted models with only a few parameters, tailored to experimental data. Since the birth term is always characterized by a non-local dependence in *i*-state space (e.g. mothers aged 24 produce offspring of age zero), the *p*-equations are first order partial functional differential equations. As a consequence their analysis requires a somewhat abstract point of view, which explains the jerky start of a mathematical theory. The book on age-dependent models published by G.F. Webb in 1985 marks the beginning of a new period dominated by *semigroup methods.* Meanwhile methods which are similar in spirit, but different in important details, have been developed by W. Desch & W. Schappacher (Graz), G. Greiner (Tübingen) and at CWI in cooperation with Ph. Clément (Delft), M. Gyllenberg (Helsinki) and H.R. Thieme (Heidelberg).

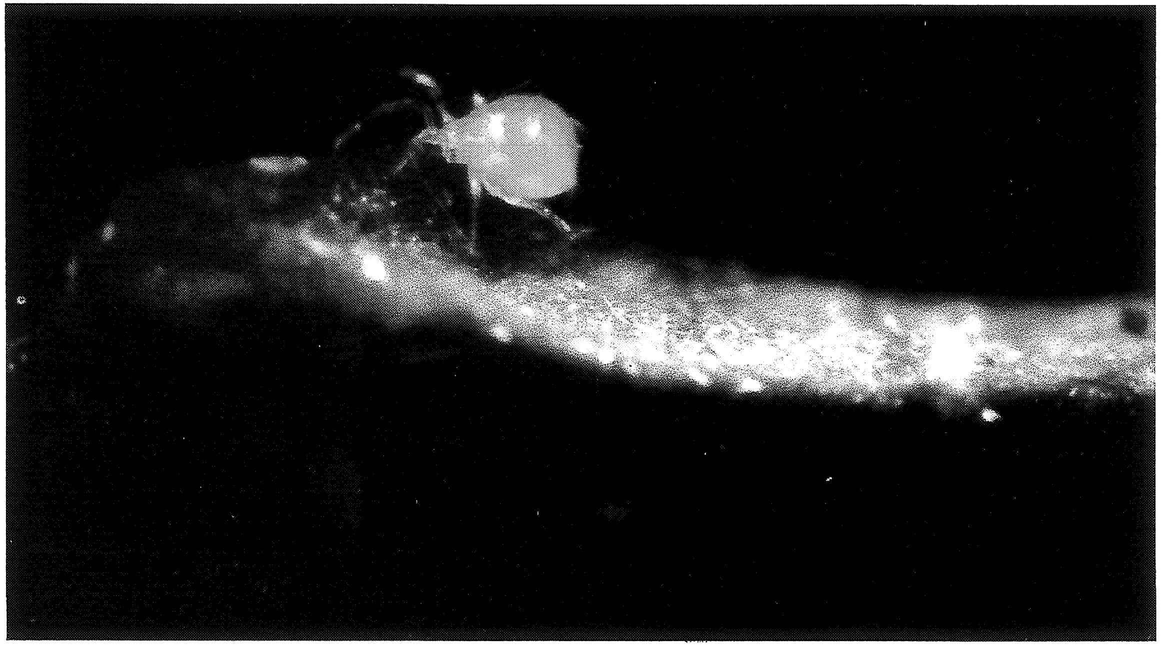
Dynamical systems

The work at CWI is characterized by simultaneous attention focused on a unifying modeling methodology dealing with general traits, and the abstract, functional analytic approach to dealing with the equations. This point of view is propagated in the Springer Lecture Notes in Biomathematics 68, edited by J.A.J. Metz and O. Diekmann and published in 1986. It also served as the guiding principle in organizing an international workshop at NIOZ on the Dutch island of Texel in 1986, which brought together scientists whose disciplines ranged from experimental biology to pure mathematics.

A general aim of the CWI project is to incorporate the class of partial functional differential equations, which model structured populations, into the qualitative theory of dynamical systems, in order to get at our disposal the usual stability and bifurcation results. As occurs more often, the specific application sheds a new light on the existing theory and necessitates extensions which are, in retrospect, mathematically quite natural. Thus in 1987 considerable attention was given to the development of a perturbation theory for dual semigroups which is more widely applicable, e.g. when investigating retarded functional differential equations. In the present context the idea is to take the space of regular Borel measures as the *p*-state space, and to work with both the norm and the weak $\star$ topology (and in fact a third, the so-called sun topology) to describe continuity and differentiability properties of orbits. The advantage is that a large class of problems then becomes semilinear, and hence easy to analyze, when so viewed.

Case studies

Apart from the general theory, attention is focused on case studies motivated by concrete biological questions. S.A.L.M. Kooijman (Free University, Amsterdam and TNO, Delft) developed various energy budget



Phytoseiulus persimilis *Athias-Henriot: Adult female (length about 1 mm). This predatory mite has proved a very successful tool in the fight against spider mites, which can cause considerable damage to vegetables grown under glass in this country. These mites are the subject of several recent population studies. (Photo: K. Hofker, Leiden.)*

models for Daphnia populations. He and his colleagues used these to sharpen the insight derived from toxicity tests at TNO. F. van den Bosch, A.M. de Roos (Leiden) and W. Gabriel (Plön) studied the effects of cannibalism on population survival. Models for the spread of diseases in populations with age- and social structure are a hot topic internationally. They will be the subject of a CWI colloquium in 1989.

At CWI considerable attention is given to models for the interaction of predator and prey populations in a patchy environment. Here a local colony is considered as an 'individual' characterized by the local densities of predator and prey. Despite local extinctions on short time scales the populations may persist on large geographic and long time scales. The aim is to understand the way in which different factors contribute to the overall dynamic pattern; this is also relevant to biological control. The general model corresponds with a highly nonlinear, infinite-dimensional dynamical system with very many parameters. As a direct solution to this situation is next to impossible, we have derived various simplified caricatures by using time-scale arguments and special choices of sub-models, (joint work with M.W. Sabelis, Leiden). Networks of models are thus obtained; and qualitative insights, derived from the simplest elements, may be used to direct quantitative simulation studies, and to guide the interpretation of the outcome of such studies. In this connection it should be noted that A.M. de Roos (Leiden) has recently developed an efficient numerical method for solving general structured population equations.

In summary we can say that the modeling methodology is well established, that the number as well as the power of our mathematical tools is rapidly increasing, and that many biologically intriguing questions await a penetrating analysis.

PROJECTS

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

Dynamical systems with stochastic perturbations
The investigations concern:

- Spectral atmospheric models;
- Stochastic population dynamics;
- Random walks on random networks.

Characteristic of the first two topics is the study of the expected sojourn time of the system in the neighbourhood of a stable equilibrium. In the third topic it is analyzed how the diffusion approximation is derived from the transition randomness of the network on large time properties. (1982).

J.B.T.M. Roerdink, H.N.M. Roozen, H.E. de Swart (STW), B. de Kerf.

Univ. Amsterdam, KNMI, NIOZ, Univ. Utrecht, Univ. California La Jolla.

Asymptotics and applied analysis
This project includes research on asymptotic expansions of integrals, and solving problems on analysis and asymptotics (with numerical aspects) from physics, biology, and statistics (1975).

N.M. Temme, B. Dijkhuis.

Univ. Groningen, Univ. Utrecht, NIOZ, Univ. Winnipeg, Univ. Knoxville.

Nonlinear analysis and biomathematics
Analysis of differential equations (both ordinary, partial and functional) and integral equations which correspond to a mathematical description of biological processes. Whenever appropriate due attention is paid to the modeling aspects. (1975).

O. Diekmann, A. Grabosch, J.A.P. Heesterbeek, H.J.A.M. Heijmans, H.A. Lauwerier, J.A.J. Metz.

Univ. Leiden, Univ. Delft, Univ. of Tech. Helsinki, Free Univ. Amsterdam, Univ. of Strathclyde Glasgow, Univ. Leiden, Univ. Heidelberg, Virginia Polytech. Inst. and State Univ., Philips Telecomm. Hilversum.

Processing and reconstruction of images

- Research by means of mathematical and numerical analysis, mathematical statistics and computer science in support of methods for the processing and reconstruction of images;
- Development of algorithms and software;
- Contact with medical investigators, biologists, physicists and laboratories.

(1985).

J.B.T.M. Roerdink, H.J.A.M. Heijmans, H.A. Lauwerier, N.M. Temme, M. Zwaan.

Acad. Hospital Utrecht, Philips Medical Systems Best, Shell KSEPL Rijswijk.

Department of Mathematical Statistics

R.D. Gill (head of department)
L.G. Barendregt
H.C.P. Berbee
A.L.M. Dekkers
K.O. Dzhaparidze
S.A. van de Geer
P. Groeneboom
L.F.M. de Haan
C.C. Heesterman
R. Helmers
A.W. Hoogendoorn
R.A. Moyeed
A.P. van der Plas
M.J. Rottschäfer
S. Tardif
W. Vervaat
E.A.G. Weits

trainees:
G. van Osta

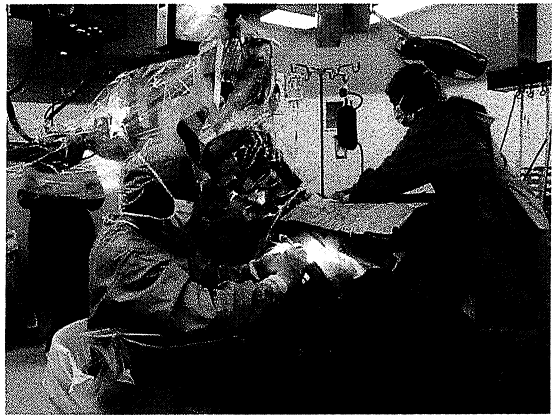
SEMIPARAMETRIC STATISTICS

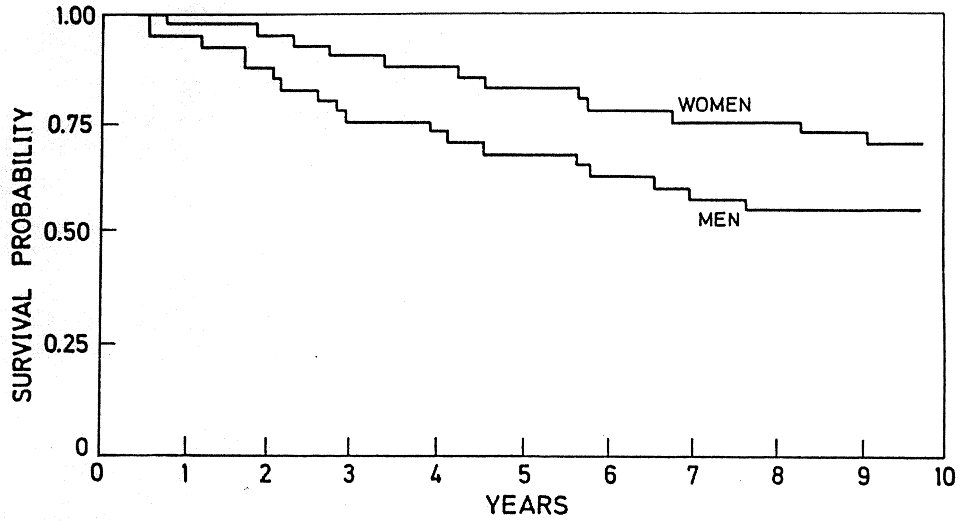
Introduction

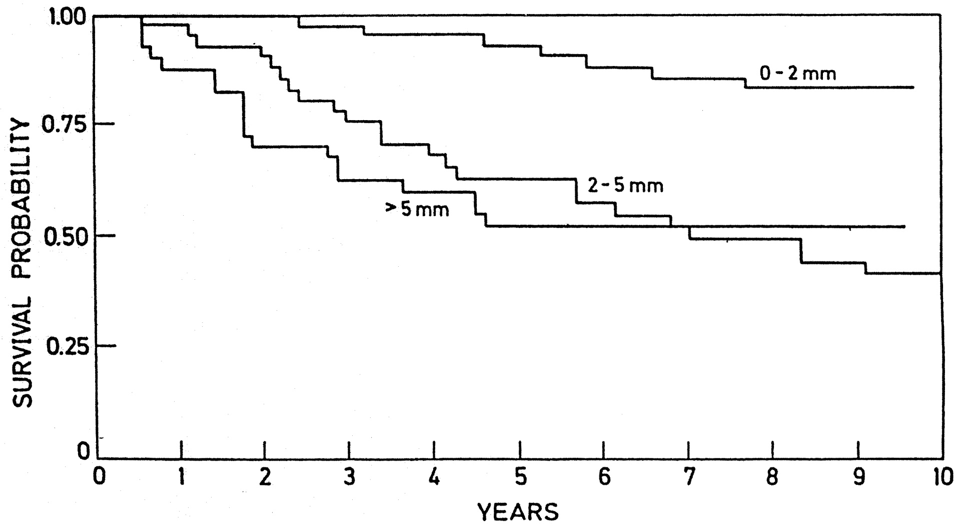
Semiparametric models have become a subject of intensive study in statistics. The idea is to combine the advantages of parametric and non-parametric modeling of a set of observations. The parametric approach is used if our knowledge of the underlying phenomenon allows us to describe it in terms of a statistical model involving a small number of numerical parameters (sample average, standard deviation, etc.). If we do not have such knowledge, nonparametric methods have to be used. In certain cases the model can be partly parameterized (semiparametric approach).
At CWI in recent years attention was paid in particular to the problems of efficient estimation for unknown parameter values in semiparametric models. Amongst others, the maximum likelihood principle and partially specified models were considered, in the presence of 'abstract' parameters.

Parametric, nonparametric, semiparametric

Quite often scientific knowledge is based on observations which are stochastic in nature: the observed values are partly determined by chance. Some examples, occurring in CWI research in the field, are: observations of the traffic flow on a freeway, water levels at the sea coast, and survival analysis (in connection with medical treatment). In such cases one wants to build *statistical models* in order to describe the phenomena so that quantitative conclusions can be drawn. Generally speaking a statistical model consists of the space of all possible events (for example, if the observation consists of counting the occurrence of a certain event, this space is the set of natural numbers 0,1,2,...), to each of which a certain probability is assigned. Such a probability measure can in certain cases be described in terms of a number of parameters; the art of the game is then to estimate the values of these parameters on the basis of the observations. It is also possible, however, to produce statistical statements without parameterization. Let us look at a few examples.
In shooting at a target one knows that the spread in the hits is due to fluctuations around some mean position, caused by various random influences. The distribution of the hits could then be very well described by a normal distribution, characterized by two parameters: the mean value and the standard deviation. This is the simplest example of a purely *parametric* model.
Suppose we want to compare certain numerical properties of two unknown populations on the basis of two independent samples, drawn from these populations. As with a control group and a treatment group in testing the effects of a certain drug, we want to establish whether there is a statistically significant effect. Here one has - at least initially - not the faintest idea how the distribution of the observations in either of the groups should be parameterized. A method often applied in this case is the old and well-known Wilcoxon two-sample rank test. It is an example of another kind of statistical analysis, *nonparametric statistics,* developed mainly since 1950.
The third example comes from the field of 'survival analysis', in which patient survival times after a certain medical treatment (e.g. a heart transplant) are studied. The statistical aspects of these observations are best modeled in a mixed way, a *semiparametric model.*







An important aspect of medical treatment of severe diseases like cancer is to observe survival times after treatment and draw statistical inferences from these observations. The curves drawn here show the survival probabilities after operation for malignant melanoma for 205 patients, stratified by (a) sex, and (b) tumour thickness. The curves are Kaplan-Meier estimates, a famous semiparametric estimation method. If we went further and assumed a Cox regression model, the curves would be powers of a fixed base-line curve. (Photo: courtesy Academisch Medisch Centrum Amsterdam.)

A famous model for this case, and a fine example of the semiparametric approach, is Cox's regression model. The survival time of patient i is modeled in terms of a 'hazard rate' $h_i(s)$, the conditional probability of dying on day s given survival past day $s-1$. If z_i represents the vector of relevant observable information about the patient, such as age and sex (coded as a number), Cox's model postulates that the hazard rate has the form $h_i(s)=g(s)\cdot\exp(\beta z_i)$. Here $g(s)$ is an overall hazard rate applying to all the patients and β is a vector of unknown coefficients, corresponding to the regression coefficients in an ordinary regression model. The expression is built up of a nonparametric part $g(s)$ and an exponential part parametrized by the finite-dimensional vector β. The parametric component is usually called finite-dimensional or Euclidean and the nonparametric part infinite-dimensional or functional. In these models the Euclidean parameters are often the parameters of interest, whereas the functional (or 'abstract') parameters represent nuisance quantities.
Another statistical method, called *bootstrap resampling*, can also be viewed in a semiparametric framework. Here one frequently uses non-parametric methods based on the empirical distribution function - which puts equal probability mass $1/n$ to each of n observations $X_1,\ldots,X_n$ - to estimate the accuracy of estimates in, e.g., parametric models. The bootstrap idea is to take a large number of artificial samples drawn (with replacement) from the empirical distribution of the observed X_i's.
Semiparametric models in general require a considerable amount of computation (they usually involve the iterative solution of large systems of equations). Nowadays however, with the present possibilities of electronic computation, this is no longer considered a serious obstacle.

Efficient estimators

A common form of statistical inference is the estimation of parameters by constructing so-called *estimators* from the set of observations. Suppose that measurements of some quantity X result in the values x_1, x_2, ..., x_n. How can we calculate the 'best' estimate for a parameter of the distribution of X (e.g. its mean value or variance) from these values? In general, an estimator is some 'suitable' function of the observations, e.g. for the mean value the ordinary average $(1/n)\Sigma_{i=1}^{n}x_i$. Now, if we know that the observations were independently generated according to some probability density function $f(x,\theta)$, with θ an unknown parameter to be estimated, one of the most frequently applied techniques is the *maximum likelihood principle*, i.e. find the value T of θ, for which the 'likelihood function' $\Pi_{i=1}^{n}f(x_i,\theta)$ is maximal. Here T is called the maximum likelihood estimator. It is easy to verify that, taking for f the normal distribution with θ as the mean value, T is the ordinary average of the x_i, and that in the case of a Laplace distribution the maximum likelihood estimator turns out to be the median. In a more complicated context such as Cox's regression model one can estimate the parametric component β by a generalized form of maximum likelihood called partial likelihood.
In general we want to estimate parameters as efficiently as possible. Efficiency can be formulated in the following way. We restrict ourselves to the class of estimators $T_n(x_1,\ldots,x_n)$ which are asymptotically normal (this is the most relevant case), in the sense that the distribution of the expression $\sqrt{n}\cdot$ (estimator — estimand) converges for $n\to\infty$ to a normal distribution (the square root is a scaling factor). The estimator for which this normal distribution has the smallest spread around the 'true' value of the parameter, is called 'efficient'. This concept of efficiency, which dates back to early this century (Fisher), was made mathematically more refined in the early seventies by Hajek and LeCam. They considered estimators which are 'regular', in the sense that small perturbations in the value of the parameter θ entail small changes in the distribution of $\sqrt{n}\cdot$ (estimator — estimand). For purely parametric models, maximizing the likelihood function as described above leads in most cases to an efficient estimator. Minimal conditions on the function f ensuring efficiency of the maximum likelihood estimator were recently presented by Dzhaparidze and Valkeila (Helsinki), not only for the case of independent observations, but also in the general framework of the theory of stochastic processes.

Application to semiparametric models

The concepts of Hajek and LeCam can, in principle, be applied to situations involving abstract parameters. In particular they can be applied to semiparametric models, as was reported by Ibragimov (joint work with Has'minskii) at a workshop 'Statistical methods for large parameter spaces', organized at CWI in December 1987. Another important contribution in this direction by Van der Vaart (Free Univ. Amsterdam) is described in CWI Tract 44. These (and preceding) investigations made it clear that the notion of 'efficiency' as mentioned above also makes sense for semiparametric models. As for the problem of major practical interest - the construction of efficient estimators - its solution is well understood in a number of practically important models. However, in many other important cases there are substantial difficulties, as was pointed out by Bickel and Wellner at the Annual Meeting 1987 of Dutch statisticians , and by Wellner at the workshop mentioned above. These difficulties are partly due to the failure of the classical maximum likelihood principle as a universal method for constructing efficient estimators for abstract parameters, unless it is essentially modified. At present a general theory is still lacking.

Some results

In order to get a feeling for the nature of the modifications required, Gill studied the efficiency of certain well-behaved nonparametric maximum likelihood estimators, using the technique of Hadamard differentiability in functional space. Other results by Gill and Johansen (Kopenhagen) concerned differentiability of the product integral, which occurs especially in survival analysis and censoring problems as a likelihood function, and via the relation between hazard and survival functions, as well as bootstrap methods for differentiable functions of the empirical distribution of the data.

Helmers completed his study of the asymptotic accuracy of the bootstrap approximation to the exact distribution of a Studentized U-statistic. As an application improved bootstrap-based confidence intervals for the mean of a U-statistic were obtained, and the relation with Edgeworth-based approximations was pointed out.

In her Ph.D. thesis Van de Geer applied powerful tools from modern empirical process theory to the study of nonparametric regression, in particular to sieved and penalized least squares estimators. Similar methods were applied to time series analysis by Sieders and Dzhaparidze.

Dzhaparidze also adapted the notions of regularity and efficiency of estimators to models which are only *partially specified.* Such models occur for example in regression analysis with stochastic regressors and in partial likelihood theory. A simple example is $X_t = S_t + N_t$, where S is some signal involving certain unknown parameters, and N is noise, about which only some characteristics are known. In partially specified models the usual likelihood theory does not apply.

Finally, theoretical as well as practical aspects of semiparametric statistics were part of a joint project with the Ministry of Public Works and the National Meteorological Institute KNMI. Dekkers and De Haan developed asymptotic theory for parameter estimators of the extreme value distributions. By combining extreme and intermediate order statistics they estimated a large quantile of the underlying distribution. This is of practical importance in connection with the verification of standards for sea dikes set by the Dutch government.

PROJECTS

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

Semiparametric statistics

The construction of statistical procedures and the derivation of their properties for semi-parametric models; i.e. models which are partly parametric and partly nonparametric in character. Furthermore, the application of techniques from parametric statistics in non-parametric models; in particular estimation theory.

- Semiparametric estimation theory (1983);

  R.D. Gill, K.O. Dzhaparidze, P. Groeneboom (advisor), C.C. Heesterman.
- Stochastic censoring (1982);

  R.D. Gill.
- Bootstrap methods (1984);

  R.D. Gill, R. Helmers.
- Order statistics (1984);

  R.D. Gill, R. Helmers.
- Statistics for sample extremes (1986).

  R. Helmers, L.F.M. de Haan (advisor), A.L.M. Dekkers.

Univ. Seattle, Univ. Kopenhagen, Harvard Univ., Univ. Oslo, Univ. Baltimore.

Stochastic processes

Fundamental research on stochastic processes with special emphasis on processes in space *and* time, and research on the statistical analysis of particular stochastic processes.

- Stationary processes and their applications in physics (1981);

  H.C.P. Berbee.
- Statistical analysis of stochastic processes (1984);

  K.O. Dzhaparidze, A.P. van der Plas.
- Statistic analysis of traffic streams (1984).

  R.D. Gill, P. Groeneboom (advisor), E.A.G. Weits (STW).

Ministry of Public Works, Moscow Univ., Razmadze Mathematical Institute Tbilisi.

Applied statistics

The aim of this project is to enrich mathematical statistics through new impulses from practical problems, and conversely to make the results of theoretical research available to (potential) users of statistics in other areas.

- Break-point methods (1984);

  R.D. Gill, S.A. van de Geer.
- Statistical consultation and cooperation;

  R.D. Gill, S.A. van de Geer, R. Helmers, C.C. Heesterman, A.W. Hoogendoorn, A.P. van der Plas, A.L.M. Dekkers, R.v.d. Horst (CWI-STO), M.J. Rottschäfer, G. van Osta, L.F.M. de Haan (advisor).

Univ. Utrecht, Univ. Amsterdam, Univ. Leiden, WAVIN BV, CBS.

Analysis and (re)construction of images

The aim of this project is to carry out research in the field of the statistical analysis of images. This means the investigation of methods for the solution of statistical problems, when the data are represented in the form of images.

- Statistical analysis of data in the form of images (1986).

  R.D. Gill, H.C.P. Berbee, M.J. Rottschäfer, L.G. Barendregt (TNO), R.A. Moyeed, W. Vervaat.

Hubrechtlab. KNAW Utrecht, Univ. Amsterdam, CSIRO Australia.

Department of Operations Research and System Theory

J.K. Lenstra (head of department)
J.M. Anthonisse
J.L. van den Berg
O.J. Boxma
J.W. Cohen
M. Desrochers
F.A. van der Duyn Schouten
W.P. Groenendijk
J.A. Hoogeveen
B.J. Lageweg
J.W. Polderman
M.W.P. Savelsbergh
A. Schrijver
J.M. Schumacher
J.H. van Schuppen
S.A. Smulders
P.J.C. Spreij
M. Stöhr
S.L. van de Velde
B. Veltman
P.R. de Waal

trainee:
J. Hendrikx

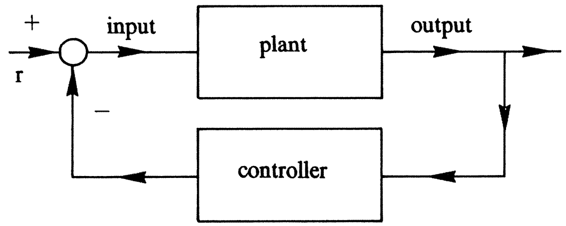
ADAPTIVE CONTROL

Introduction

Many modern industrial production processes and operations require sophisticated control mechanisms; so, for instance, the manufacture of tube glass (e.g. for television sets) in which the wall thickness and the diameter are subject to stringent conditions. Similar constraints apply in other fields, e.g. satellite or aircraft operation. Often it is enough to use a controller in the form of a computer program requiring no change during its lifetime. However, there are cases where evolution of the long term process is uncertain - as in steering a ship under varying (weather) conditions. Here, the controller must be allowed to adapt continuously in line with the changing situation.
1987 saw the conclusion of a 4-year CWI project covering several aspects of adaptive control.

Closed-loop control

Control problems usually arise in electrical or mechanical engineering, as in the motion of a robot arm. An engineer faced with the problem of designing a controller, first develops an engineering model, the 'plant'. From this he extracts a mathematical model called a 'dynamical system'. A control signal, the 'input', may influence the plant, e.g. the signal for a motor driving the robot arm. Measurements performed on the robot arm are called 'outputs'.
So, one can formulate the control problem as follows: construct a controller which, on the basis of outputs, produces an input such that the behaviour of the system satisfies given control objectives. In the example of the robot arm one function is to grasp and move an object. In this task the control objective could be smooth action with minimal energy. Several procedures have been developed to synthesize controllers. One approach is to formulate an optimization criterion (e.g. the energy used to move the robot arm to be minimal) and then to determine a controller capable of achieving it.

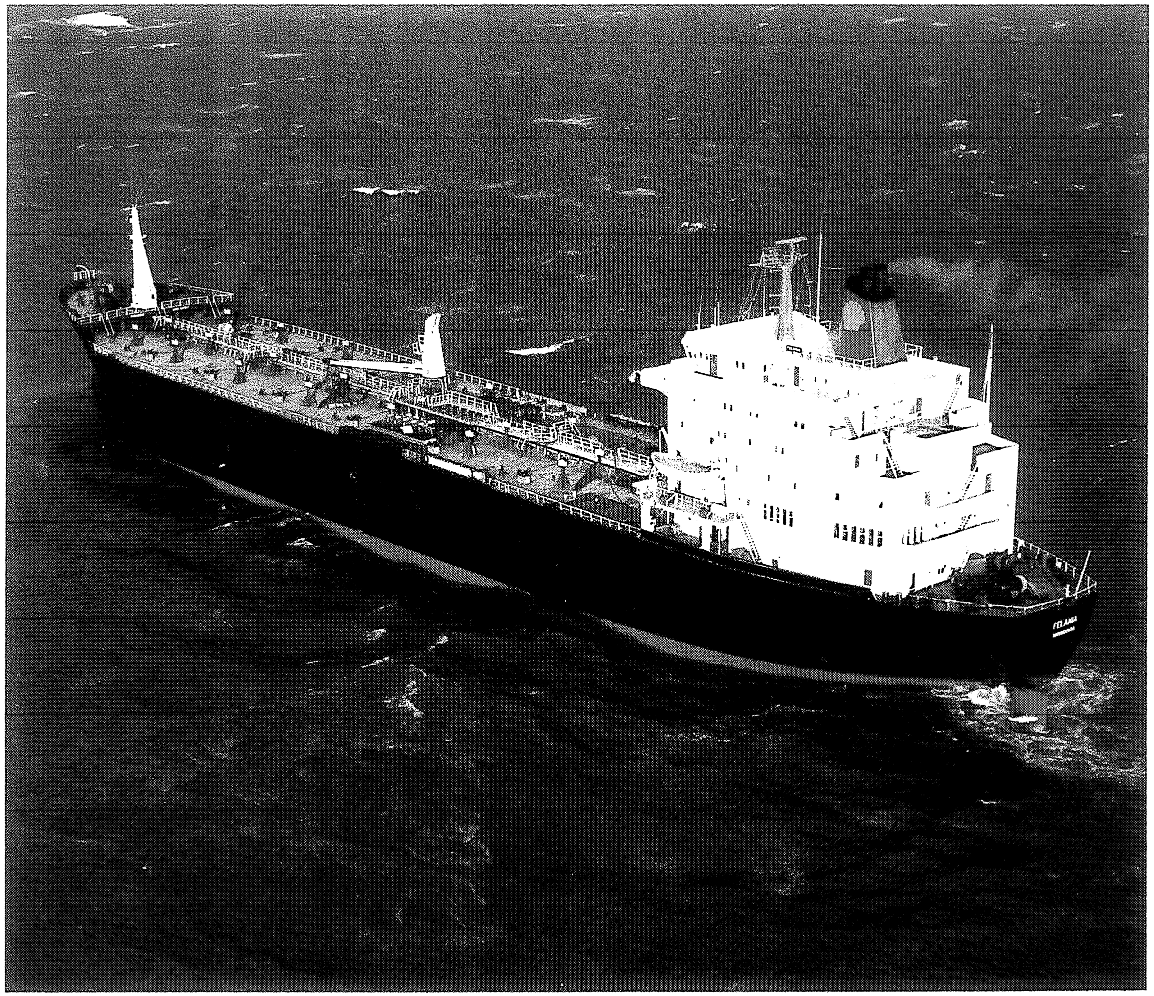


The controller may be programmed on a computer and is connected to the object to be controlled - say the robot arm. The arm is now continuously controlled and is said to operate in *closed-loop*. Controllers designed in this way work satisfactorily in widely different settings, such as windmills, steam boilers and electricity networks.

Adaptive control

However, one sees limitations to this approach when there is uncertainty about the process to be controlled, or when the process characteristics alter gradually over a period of time. Such situations occur in steering a ship in calm or rough sea, and in the control of material flows in an ore crusher requiring adjustment according to ore size. Generally, the approach outlined above will not yield a practical solution here. The controller needs the ability to adapt continuously to the

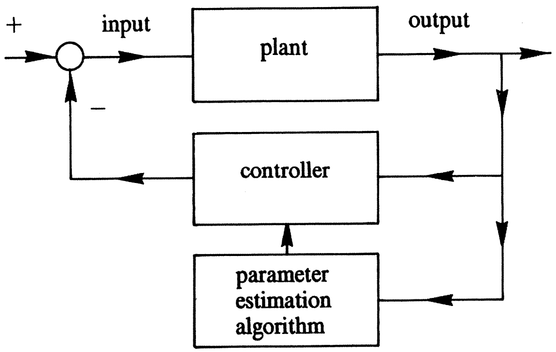
Steering a large ship, like a tanker, is a complex process. One aspect of the problem is that the steering mechanisms must react quite flexibly to varying external conditions, like the weather. In recent years the captain's job has been made easier by the successful application of adaptive control technique. (Photo: Sea Sky Martin, Rotterdam; courtesy Shell Tankers B.V.)



characteristics of the process. The ideal adaptive controller would control a dynamical system on the basis of observations only; this would enable it to be connected to any dynamical system. However, it is doubtful whether this ideal will ever be reached. Even so, research into adaptive control has gained considerable popularity over the last fifteen years with successful commercial applications reported in connection with ship-steering and ore-crushing. This popularity owes much to the feasibility of implementing adaptive controllers which has come with increased availability of relatively cheap, fast and reliable digital computers.

Self-tuning

An important and well-known example of adaptive control is the mechanism of 'self-tuning control', whose usefulness has been borne out in practice. A self-tuning controller continuously estimates the parameters of the system (in the case of ship-steering, those describing the dynamics of the sea, e.g. wave frequencies), and generates an input based on these estimates and its own structure (which now depends on the actual values of the parameters). This input is applied to the system, after which an output is observed, a new input is generated, etc.



Until a few years ago, the advantages and limitations of this approach were still unclear, hence the CWI study.

Parameter identification
Self-tuning control may not always work. The question is as follows: can one determine all parameter values if the plant is operating in closed-loop; and if not, what is the effect of self-tuning control? The answer to the first part of this question may be negative. To illustrate this, suppose the control law for the steering of an oil tanker is designed on the basis of information about the ship's behaviour in a calm sea. It is far from certain whether such a mechanism will also function in rough conditions: whilst some parameters in the ship's dynamical model may not play a significant role in calm conditions, they will dominate behaviour in rough weather. However, the control mechanism has no knowledge of these parameters: it 'missed' them. This issue is known as *closed-loop identification* in adaptive control.

Excitation
So, how does one overcome the difficulties caused by closed-loop identification? First, it has been shown that identification of the parameters is not always necessary for good self-tuning control. Consider for example the simple linear system $y_t = ay_{t-1} + bu_t + v_t$, where y is the output, u the input, v a noise signal, and a and b the system parameters. Suppose the control objective is to reduce the effect of the noise signal. To achieve minimum variance for the output one should take $u_t = -(a/b)y_{t-1}$. All we need here is the ratio of the two parameters, not the values themselves. This point was explored further in the research project described below. In other cases, however, some parameters must be identified. A possible way out is to use *excitation*: an excitation signal, e.g. a block pulse, is added to the input in order to explore the full range of all the model's parameters. There is, however, a drawback. In the case of ship-steering we want the control mechanism to prevent major deviations from the normal course. But if we are going to construct such a mechanism making use of excitation, we have to experiment with large deviations during navigation - which the control objective says we should avoid. In practice an acceptable compromise is made.

Pole assignment and linear quadratic control
In the fall of 1983, CWI started a 4-year project on adaptive control. Research in this project - carried out by J.W. Polderman for a Ph.D. thesis - concentrated on a particular class of systems (for insiders: deterministic systems, in particular linear, finite-dimensional, time-invariant, single input/single output systems of known order and described in discrete time). The self-tuning control synthesis procedure for these systems was investigated. A careful study was made of the closed-loop identification problem for two such well-known procedures: pole-assignment and linear quadratic control.
In *pole-assignment,* the closed-loop control system should possess certain stability characteristics. In a simple case the control system reads $y_{t+1} = ay_t + bu_t$, where u is the input, y the output, and a and b are the system parameters. Given a value c, the desired 'pole' of the system, the problem is to determine a feedback law $u_t = f \cdot y_t$ such that $c = a + b \cdot f$. It was shown that, true enough, the lack of excitation may lead to identification of a wrong model of the system, but that every such model nevertheless yields the desired feedback law. Similar properties have been reported in literature on the so-called

minimum-variance controller for stochastic systems.

In *linear quadratic control* the objective is to minimize a quadratic function of the input and the output of the system: $\int(a \cdot y_s^2 + b \cdot u_s^2)ds$. Here the results turned out to be in flagrant contrast with those in the pole assignment case. Self-tuning (adaptive) control almost exclusively leads to sub-optimal behaviour of the system. More generally it was shown that, unfortunately, this applies to almost all control objectives, the pole assignment problem being one of the few exceptions.

The convergence of the algorithms proposed for pole-assignment and for a modification of linear quadratic control was investigated. In the first case the estimates do not converge to the true system parameters. However, every limit point of the parameter estimates gives rise to exactly the same control signals as would have been applied in the non-adaptive case, had parameters been known and remained at some fixed value ('weak self-tuning'). The modified algorithm for linear quadratic control involves an excitation signal as part of the control loop. This signal is proportional to the output and as a result zero regulation is obtained.

Special care should be taken that parameter estimates lie inside the subset of the parameter space on which the function (which assigns a controller to every estimate) is defined. This cannot be ensured with the usual algorithms. A fairly general method was developed for this problem in order to modify a broad class of algorithms in such a way that estimates always belong to the required subset of the parameter space.

Outlook

The main contribution of this investigation is the clarification of limitations of self-tuning control due to closed-loop identification. New algorithms for self-tuning control have been proposed for certain systems. Future investigations will address the same questions for other classes of systems and the synthesis of adaptive control algorithms using external excitation. This research will be continued elsewhere.

References

1. K.J. ASTRÖM, B. WITTENMARK (1984). *Computer Controlled Systems: Theory and Design,* Prentice-Hall Inc., Englewood Cliffs, N.J.
2. P.R. KUMAR, P. VARAIYA (1986). *Stochastic Systems: Estimation, Identification and Adaptive Control,* Prentice-Hall Inc., Englewood Cliffs, N.J.

PROJECTS

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

Combinatorial optimization

Combinatorial optimization is the mathematical study of problems involving the optimal arrangement, grouping, ordering or selection of a finite number of discrete objects. The subjects are:

- Design and analysis of algorithms (1973);
- Geometric methods (1983);
- Parallel algorithms (1982);
- Interactive distribution planning (1983);
- Interactive production planning (1985).

J.K. Lenstra, J.M. Anthonisse, M. Desrochers, J.A. Hoogeveen, B.J.B.M. Lageweg, M.W.P. Savelsbergh, A. Schrijver, S.L. van de Velde (NFI).

Univ. Brabant, Univ. Augsburg, Univ. California Berkeley, Univ. Budapest, Univ. Rotterdam, Harvard Univ. Cambridge.

Analysis and control of information flows in networks

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

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

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

IBM Forschungslaboratorium Zürich, INRIA, Univ. Utrecht.

System and control theory

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

- Linear systems (1984);
- Stochastic system theory (1978);
- Adaptive control (1983);
- Point process systems (1983);
- Prediction and control problems for motorway traffic (1984);
- Overload control of communication systems (1985).

J.H. van Schuppen, M. Hazewinkel (CWI, Dept. of Pure Math.), J.W. Polderman, J.M. Schumacher, S.A. Smulders (STW), P.J.C. Spreij, P.R. de Waal (STW).

Techn. Univ. Delft, Univ. Twente, Univ. Groningen, Philips Telecomm. Hilversum, Univ. Gent, Univ. Padua.

Department of Numerical Mathematics

P.J. van der Houwen (head of department)
M. Bergman
C.T.H. Everaars
E.D. de Goede
P.W. Hemke
W.H. Hundsdorfer
J. Kok
B. Koren
G.A. Pontrelli
H.J.J. te Riele
J. Schlichting
S.P. Spekreijse
J.H.M. ten Thije Boonkkamp
J.G. Verwer
H.A. van der Vorst
P. Wesseling
F.W. Wubs
P.A. Zegeling

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

trainee:
C.B.M. Boon
H. Meckering

A NUMERICAL SHALLOW-WATER MODEL ON THE CYBER 205

Summary
A shallow-water model is a set of equations describing the flow in shallow seas, estuaries and rivers. A numerical shallow-water model is a numerical method for solving these equations. The aim of the project was to design a numerical shallow-water model exploiting the facilities offered by the special architecture of the vector computer CYBER 205.

Practical use
In recent years, numerical methods for solving problems in fluid dynamics such as the shallow-water equations have become increasingly important: firstly, numerical methods are far more flexible and are now also much cheaper than scale models; and secondly, numerical methods have become reliable for the simulation of a large variety of flow problems. Numerical shallow-water equations solvers are used to determine the influence of infrastructural works on flow (e.g. Eastern Scheldt barrier). The results obtained by such computations can then be used to calculate salt intrusion, the effect of waste discharges, water quality parameters, cooling water recirculation and sediment transports. An important Dutch application is the storm surge barrier in the mouth of the Eastern Scheldt estuary. Numerical shallow-water models developed by Delft Hydraulics and the Data Processing Division of the Ministry of Public Works have been used extensively in the development phase of the barrier. Similar numerical models provided operational guide lines after the barrier had been installed. These both protect the dikes along the banks of the Eastern Scheldt and preserve the delicate ecological balance in the estuary; site of an important fish nursery and oyster and mussel beds.

Discretization
For a number of years during the initial phase of the Delta project (the early 1960's), the Mathematical Centre was involved in providing numerical solutions for the partial differential equations describing shallow-water flow. The arrival of vector computers boosted interest in these problems at the institute, this new generation of computers being tailor-made for solving partial differential equations, provided that a suitable discretization method is chosen.
Discretization converts the partial differential equations into a system of essentially simpler equations which can be solved on a computer. We distinguish discretization in *space* and in *time*. The two basic spatial discretization methods are based on finite *differences* and finite *elements*. The first method replaces the spatial domain (e.g., the Eastern Scheldt) by a set of discrete grid points and approximates the differential operators in the original equations on these grid points by finite difference quotients. In the finite element method, the solution is replaced by a finite sum of simple basis functions which are defined on a set of elements covering the spatial domain. In both cases, the original *partial* differential equations (3 equations in the case of shallow-water flow) are converted into a huge system (10,000 or more) of *ordinary* differential equations in the time variable. This system is

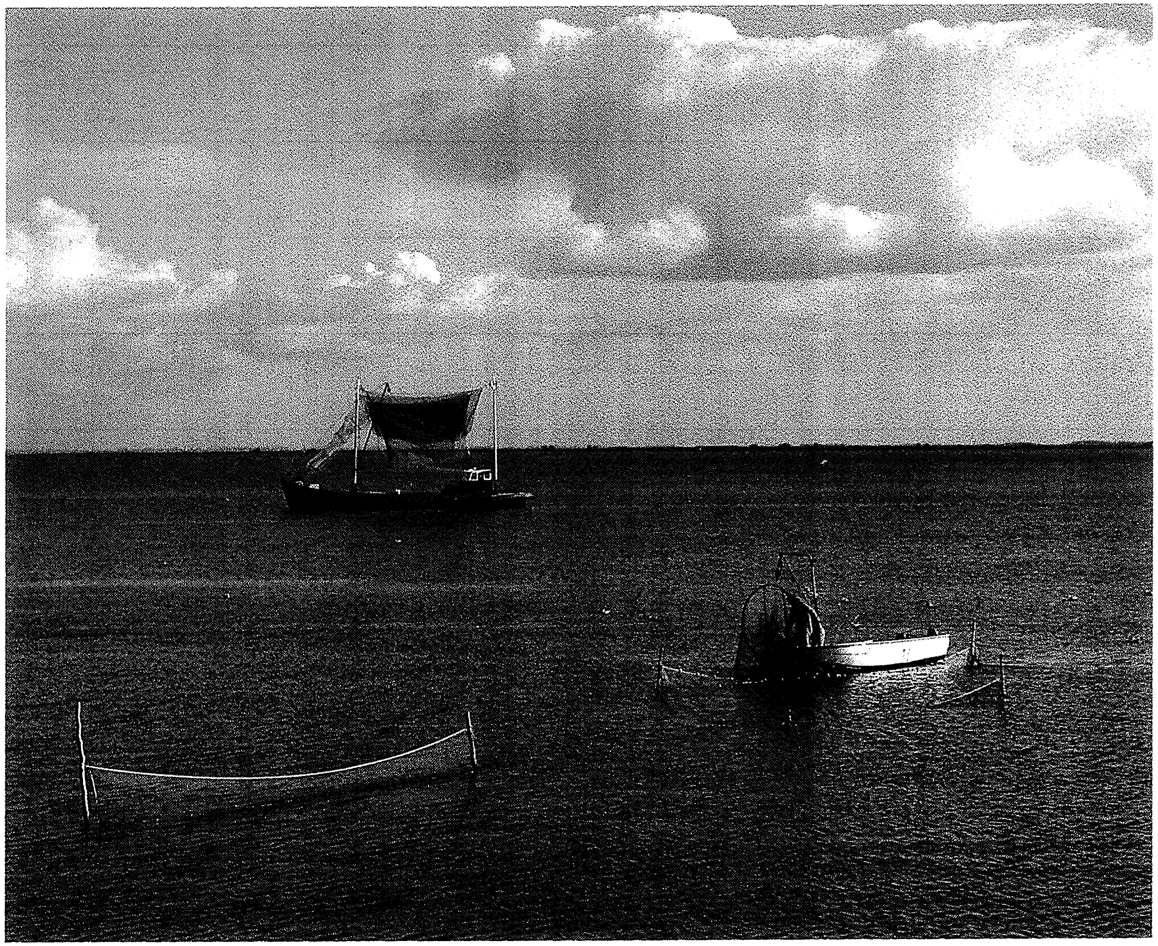
extremely ‘stiff’: its solution consists of components slowly and rapidly varying in time. So, the time-discretization is crucial: stiffness can easily render the time discretization unstable and hence completely destroy the accuracy of the numerical solution.
Among the time integration methods we distinguish *explicit* and *implicit* methods. In explicit methods, the solution (e.g., the water elevation) at time t can *directly* be computed from the solution values at time $t-\Delta t$, where Δt is the time step. In this way, one can proceed in time as soon as the initial solution at (say) $t=0$ is given. Implicit methods also compute the solution at time t from the solution values at time $t-\Delta t$, but a set of implicit relations has to be solved and this may demand excessive computer time.
Advantages and disadvantages to the various discretization methods are listed alongside.

Method	*Advantage*	*Disadvantage*
Finite differences	Regular data structures, therefore ideal on vector computers	Difficulties in irregular spatial configurations
Finite elements	Accurate approximation of irregular spatial configurations	Irregular data structures, unattractive to vectorize
Explicit time discretization	Cheap per time step, easy to vectorize	Small time steps required to preserve stability
Implicit time discretization	Large time steps allowed without instability	Expensive per time step, difficult to vectorize

A vectorized model
CWI started the STW project ‘Evaluation and stabilization of numerical methods for the shallow-water equations’ in 1983, just prior to the installation of SARA’s (Stichting Academisch Rekencentrum Amsterdam) CYBER 205 computer. Obviously, this encouraged us to concentrate on numerical methods able to exploit the full potential of the CYBER 205 architecture, and so developing shallow-water software exclusively written for this, then, state-of-the-art computer. When we started, three shallow-water models were (indeed still are) widely used in hydraulic engineering computations in The Netherlands:

- the Leendertse model developed at Rand Corporation (Santa Monica), and based on finite difference space discretization and ADI time discretization (this is a partly implicit, partly explicit discretization method);
- the Stelling model, developed at Delft Hydraulics and at the Ministry of Public Works, and providing a storage economic and stabilized version of the Leendertse model;
- the Praagman model, developed at the Technical University Delft, and based on finite element space discretization and explicit Runge-Kutta time discretization.

None of these models was designed for use on vector computers and, consequently, not all parts of the associated code vectorize well on the CYBER 205. On vector computers, one should, as a rule, employ well-structured data and avoid the solution of implicit relations. This has led us to base our CYBER 205 model on finite difference space discretization and an explicit Runge-Kutta type time discretization. We also employed smoothing techniques in order to relax the stiffness of the problem and, simultaneously, the stability conditions. The three basic elements: finite differences, explicit Runge-Kutta, and smoothing, which are characteristic for the



The Eastern Scheldt estuary is home to an important fish nursery and oyster and mussel beds. The storm surge barrier in this area - in operation since 1986 - was designed to protect the dikes as well as preserving local ecological balance. Numerical shallow-water models contribute to the project's dual priorities. (Photo: Reneé Kleingeld, Delta Institute for Hydrobiological Research, Yerseke.)

CWI model, vectorize extremely well. Moreover, increasing the number of vector pipes on the CYBER brings a substantial increase in efficiency over and above that in the case of models based on implicit time discretizations. The CWI model seems to be the most efficient code now available on the CYBER 205.

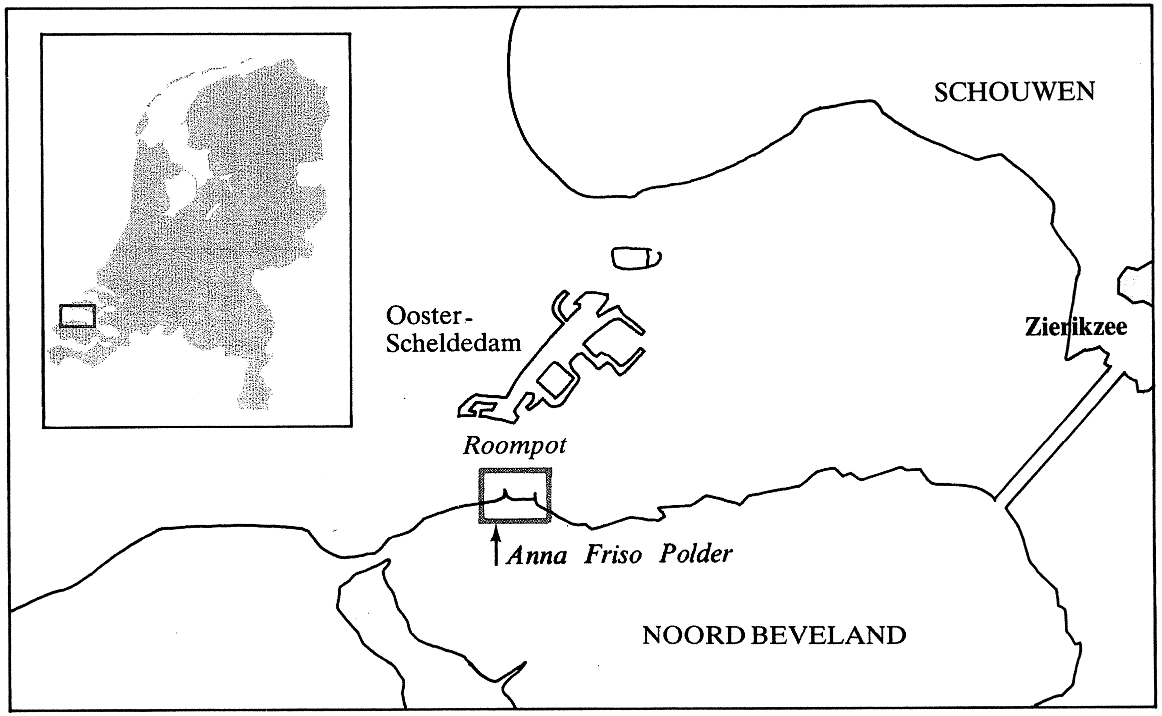
Real-life applications

1987 saw completion of the final version of documentation presenting the theoretical aspects of the CWI model as well as of the CYBER 205 code. Furthermore, a number of computations on real-life problems were performed in order to demonstrate the flexibility and reliability of the model. Here, we mention:

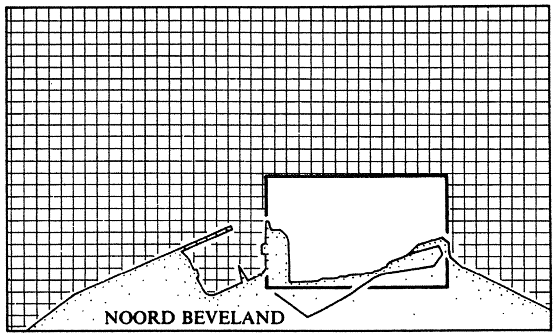
- the stationary flow in the Anna Friso Polder, a small recess at the Southern coast of the South-West entrance of the Eastern Scheldt estuary, traditionally known as the 'Roompot' (cream pot);
- draining and flooding in the Eems-Dollard estuary;
- tidal flow in the Mare Piccolo, a small bay near Taranto in Southern Italy;
- the influence of a moving ship on the water elevation.

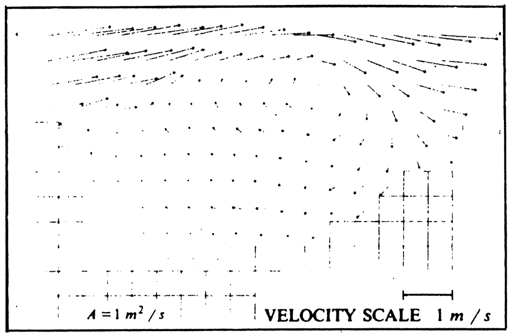
The first two experiments were carried out in close cooperation with G.K. Verboom of Delft Hydraulics who also acted as a regular consultant on the mathematical-physical aspects of the entire shallow-water project.

The third problem was provided by G. Pontrelli of IAC, Rome - a guest of the numerical mathematics department in 1987. The last experiment was an industrial commission and tested the possibility of basing a Boussinesq model on the CWI shallow-water model. The test proved satisfactory; and CWI has applied, jointly with Delft Hydraulics, Hydronamics and the University of Groningen, for a new STW project for the development of a two-dimensional Boussinesq model.



The flexibility and reliability of the CWI numerical shallow-water model was demonstrated in a number of computations on real-life problems. One concerned a stationary flow in the Anna Friso Polder, a small inlet in the Eastern Scheldt estuary. The area (approx. 2.5 × 1.5 km.) is covered by a grid, represented here in a simplified form; the equations are solved on the one-pipe CYBER 205 by a vector code which turned out to run at a rate of 100 Megaflops.





PROJECTS

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

Discretization of initial value problems
Development, analysis and documentation of algorithms for determining numerical solutions of initial value problems for differential equations. The project is divided into two groups of subjects:

- Stability and convergence (1978);
- Navier-Stokes equations (1984);
- Differential-algebraic equations (1986);
- Adaptive grid techniques (1987).

J.G. Verwer, J.G. Blom, W.H. Hundsdorfer, H. Meckering, B.P. Sommeijer, J.H.M. ten Thije Boonkkamp, F.W. Wubs, P.A. Zegeling.

- Shallow-water-equations (1985);
- Smoothing techniques (1987).

P.J. van der Houwen, J.G. Blom, E.D. de Goede, W.H. Hundsdorfer, G. Pontrelli, B.P. Sommeijer, J.H.M. ten Thije Boonkkamp, F.W. Wubs.

Univ. Bonn, Univ. Nijmegen, Univ. Manchester, Shell Research Amsterdam, Naval Postgraduate School California, Philips Eindhoven, Univ. of Valladolid, Univ. Halle, Techn. Univ. Delft.

Multigrid methods for boundary value problems
Development and analysis of modern techniques for the efficient numerical solution of boundary value problems. In particular the study of multigrid and related methods and their implementation on modern computer architectures. The subjects are:

- Defect correction and theoretical background (1978);
- Singularly perturbed boundary value problems (1978);
- Adaptive methods (1987);
- Applications in fluid dynamics (1983);
- Efficient techniques for the steady Euler and Navier-Stokes equations (1983);
- Evaluation and development of reliable and efficient numerical methods for the solution of semiconductor equations (1987).

P.W. Hemker, B. Koren (STW), S.P. Spekreijse, P. Wesseling (advisor), P.M. de Zeeuw (STW).

NLR, Univ. Marburg, ICS Colorado State Univ., AERE Harwell, Techn. Univ. Delft, Karlovy Univ. Prague, NAG Downers Grove (USA).

Computational number theory
Study of fundamental problems (which may be very old) in number theory with the help of modern (numerical) methods and fast computers (1976).

H.J.J. te Riele, J. van de Lune (CWI, Dept. of Pure Math.).

Gesamthochschule Wuppertal, Bell Laboratories/AT&T Murray Hill.

Numerical software

- Numerical software in the programming language Ada (1981).

  J. Kok, D.T. Winter.

- Numerical software for vector- and parallel processors (1984).

  H.J.J. te Riele, M. Bergman, E.D. de Goede, W.M. Lioen, M. Louter-Nool, J. Schlichting (CDC), B.P. Sommeijer, H.A. van der Vorst (advisor), D.T. Winter, P.M. de Zeeuw.

NPL Teddington, Argonne Nat. Lab., Univ. Amsterdam, NAG Oxford, Ada-Europe Numerics Working Group Brussels, ESPRIT.

Department of Software Technology

J.W. de Bakker (head of department)

K.R. Apt	H.J.M. Goeman	J.M. Rukkers
J.A. Bergstra	J. Heering	J.J.M.M. Rutten
M. Bezem	P.R.H. Hendriks	M. Teunisse
F.S. de Boer	P. Klint	F.W. Vaandrager
R.N. Bol	J.W. Klop	W.P. Weijland
N.W.P. van Diepen	J.N. Kok	
M.H.H. van Dijk	H.W. Lenferink	*trainees*:
A. Eliëns	M.H. Logger	J. van Elst
P. van Emde Boas	P.J.F. Lucas	M.A.C. Heerink
L.C. van der Gaag	J.C. Mulder	M.C.L. Kempenaar
R.J. van Glabbeek	J. Rekers	

ALGEBRAIC SPECIFICATION

Introduction

The study and application of algebraic specifications aims at providing formal techniques for the specification and prototyping of systems - software systems in particular. Formal techniques are required to maintain control of the correctness of such systems, which are becoming ever more complex. Many specialized areas of research have already emerged in this field. The research in the department of Software Technology focuses on both the design of algebraic specification formalisms (including mathematical analysis of modularization concepts and development of tools for checking and compiling algebraic specifications) and the application of these formalisms in various areas (in particular the specification of programming environments).

Semantics, languages, implementation

The work described forms part of ESPRIT project nr. 432 METEOR (jointly with Philips (PRLB, PRLE), CGE Paris, AT&T/Philips, COPS, TXT, and the University of Passau) and project nr. 348 GIPE (jointly with BSO, INRIA, and SEMA). There are connections with several distinct research areas, which we will briefly mention.

But, first of all let us elucidate some terminology. A *specification* is the description of a problem on a 'high level', concentrated on the description of the problem rather than on details such as the programming language or the computer on which it is executed. Take for example the sorting of a collection of numbers. In a specification we formulate when we consider such a collection as being sorted. A next step, *prototyping*, transforms the text of the specification into a computer program which can check whether a given collection is sorted or not, and which can even sort an unordered collection. In *algebraic specifications* the text of the specification is given in algebraic terms, using *axioms* to describe simplification rules for expressions. These axioms define the meaning of the expressions used in the specification. Similarly to the way propositions can be given a meaning *(semantics)* by assigning the value 1 ('true') or 0 ('false') to them, the constructions in an (algebraic) specification can be also given a precise meaning. It is useful to describe complex systems in terms of smaller units - *modules*. This leads to an algebraic specification language in which modules can be defined and re-used in various manners. Of course, the text of a specification should satisfy the *syntax rules* of the specification language.

In the study of the *semantics of algebraic specifications* one analyzes particular notions, such as: import of one module in another, export of names defined in a module, renaming, parameterized modules, partial functions and the specification of error cases. The results of such studies have been incorporated in several *specification languages,* e.g. ACT-ONE, ASSPEGIQUE, OBJ2, COLD, LARCH, and OBSCURE. Ordinarily, software tools are provided to support the use of these languages. Such tools range from simple checkers for both the syntax and the static semantics (i.e., typechecking) of specifications - via more sophisticated syntax-directed editors for specifications - to prototype generators which transform specifications into some executable form, thus allowing experiments with the description of the original problem. The most widely used techniques for implementing algebraic specifications are based on compiling them to (under certain conditions equivalent) *Term Rewriting Systems* (TRS) or *Prolog* programs. In a TRS one replaces the axioms in the original specification by left-to-right rewrite rules. Execution of these compiled specifications can either use existing systems for term rewriting (such as REVE and the Equation Interpreter) or use efficient implementations of Prolog (such as C-, Mu- or Nu-Prolog). Various formal specification techniques (including algebraic ones) are being used for defining programming languages and for *generating compilers,* and *programming environments* (e.g., syntax-directed editors, typecheckers and evaluators) on the basis of a given definition. Typical examples are the specification of machine-independent and machine-dependent code generation and the specification of static semantics. Continuing this line of development, (parts of) programming environments can be so generated. Among systems in this area are the Synthesizer Generator (Cornell University) and the Programming System Generator (Technical University of Darmstadt).

Three lines of research

At CWI, three lines of research are being pursued in this project:

- Design of algebraic specification formalisms and analysis of their semantics;
- Implementation of software tools to support the development of specifications in these formalisms;
- Application of the formalisms in case studies; particular attention is being paid here to the algebraic specification of the semantics of programming languages.

The long term goal of this approach is to gain insight into the mathematical properties of algebraic specification formalisms as well as in their practical applicability. Each of these lines will now be discussed in some detail.

Design and analysis of algebraic specification formalisms

There were already several algebraic specification formalisms in existence when this project started. However, we came to the conclusion that the only way to get a complete understanding of the problems involved was to design our own specification formalism. This effort led to what is now known as ASF (Algebraic Specification Formalism). This formalism is primarily based on the notion of a module consisting of a *signature* (to define the type of the arguments of functions and their result) and *(positive) conditional equations* (to define their semantics). The signature defines sorts (comparable with types in programming languages) and functions over these sorts. A definition of a function defines its name, the sorts of its arguments and the sort of its result. Equations give an axiomatic definition of the meaning of each function. In a module we distinguish *visible* (or exported) and *hidden* names. The former can be used inside as well as outside the module, the latter can only be used inside the module and are used for naming auxiliary notions. In principle, a module with hidden and visible names is sufficient for constructing arbitrary specifications. In practice, however, it is desirable to impose some structure on specifications. Therefore, ASF contains two mechanisms for constructing new modules from existing ones: *import* and *parameterization.* Import combines two modules, and parameterization allows the definition of modules in which parts of the signature are parameterized, i.e. new modules can be constructed by replacing these parameters by an (actual) module.

In order to give a meaning to an ASF specification, the notion of *normalization* has been introduced, which amounts to *removing* the modular structure from the specification and reducing it to a single, flat, module. Hence, the meaning of an ASF module is the *initial algebra* (i.e. the minimal interpretation of the axioms, which is included in all other interpretations) of the corresponding normalized module. We have developed a complete algebraic specification (and a theory of the models of this specification) of signatures and modules. This theory is called *Module Algebra.*

Software tools

Several software tools have been implemented

$$[\text{Tc1a}]\qquad \frac{[\mathrm{S}]_{[\mathrm{D}]} = \mathit{true}}{[\mathit{begin}\ \mathrm{D}\ \mathrm{S}\ \mathit{end}] = \mathit{true}}$$

$$[\text{Tc1b}]\qquad \frac{[\mathrm{S}]_{[\mathrm{D}]} \neq \mathit{true}}{[\mathit{begin}\ \mathrm{D}\ \mathrm{S}\ \mathit{end}] = \mathit{false}}$$

$$[\text{Tc2}]\qquad [\mathit{declare}\ \mathrm{Id} : \mathrm{Type},\ \text{Id-type-list}\ ;] = (\mathrm{Id} : \mathrm{Type}) \oplus [\mathit{declare}\ \text{Id-type-list}\ ;]$$

$$[\text{Tc3}]\qquad [\mathit{declare}\ ;] = \textit{empty-tenv}$$

$$[\text{Tc4}]\qquad \frac{[\mathrm{Stat}]_{\mathrm{E}} = \mathit{true},\ \ [\text{Stat-list}]_{\mathrm{E}} = \mathit{true}}{[\mathrm{Stat}\ ;\ \text{Stat-list}]_{\mathrm{E}} = \mathit{true}}$$

$$[\text{Tc5}]\qquad [\,]_{\mathrm{E}} = \mathit{true}$$

$$[\text{Tc6}]\qquad \frac{\mathit{compatible}([\mathrm{Id}]_{\mathrm{E}},\ [\mathrm{Exp}]_{\mathrm{E}}) = \mathit{true}}{[\mathrm{Id} := \mathrm{Exp}]_{\mathrm{E}} = \mathit{true}}$$

$$[\text{Tc7}]\qquad \frac{[\mathrm{Exp}]_{\mathrm{E}} = \mathit{natural},\ \ [\mathrm{S}_1]_{\mathrm{E}} = \mathit{true},\ \ [\mathrm{S}_2]_{\mathrm{E}} = \mathit{true}}{[\mathit{if}\ \mathrm{Exp}\ \mathit{then}\ \mathrm{S}_1\ \mathit{else}\ \mathrm{S}_2\ \mathit{fi}]_{\mathrm{E}} = \mathit{true}}$$

$$[\text{Tc8}]\qquad \frac{[\mathrm{Exp}]_{\mathrm{E}} = \mathit{natural},\ \ [\mathrm{S}]_{\mathrm{E}} = \mathit{true}}{[\mathit{while}\ \mathrm{Exp}\ \mathit{do}\ \mathrm{S}\ \mathit{od}]_{\mathrm{E}} = \mathit{true}}$$

$$[\text{Tc9}]\qquad \frac{[\mathrm{Exp}_1]_{\mathrm{E}} = \mathit{natural},\ \ [\mathrm{Exp}_2]_{\mathrm{E}} = \mathit{natural}}{[\mathrm{Exp}_1 + \mathrm{Exp}_2]_{\mathrm{E}} = \mathit{natural}}$$

$$[\text{Tc10}]\qquad \frac{[\mathrm{Exp}_1]_{\mathrm{E}} = \mathit{natural},\ \ [\mathrm{Exp}_2]_{\mathrm{E}} = \mathit{natural}}{[\mathrm{Exp}_1 - \mathrm{Exp}_2]_{\mathrm{E}} = \mathit{natural}}$$

$$[\text{Tc11}]\qquad \frac{[\mathrm{Exp}_1]_{\mathrm{E}} = \mathit{string},\ \ [\mathrm{Exp}_2]_{\mathrm{E}} = \mathit{string}}{[\mathrm{Exp}_1\ ||\ \mathrm{Exp}_2]_{\mathrm{E}} = \mathit{string}}$$

$$[\text{Tc12}]\qquad [\text{Nat-con}]_{\mathrm{E}} = \mathit{natural}$$

$$[\text{Tc13}]\qquad [\text{Str-con}]_{\mathrm{E}} = \mathit{string}$$

$$[\text{Tc14}]\qquad [\mathrm{Id}]_{\mathrm{E}} = \mathit{lookup}\ \mathrm{Id}\ \mathit{in}\ \mathrm{E}$$

Algebraic specification in ASF/SDF of the typechecking rules for a simple programming language.

to support the development of ASF specifications. These tools perform checking (syntax, typing), generation of structure diagrams (a graphical presentation of the modular structure of a specification), normalization and compilation to Prolog.

Case studies

To date a substantial number of problems has been specified using ASF: elementary data types (Booleans, Numbers, Characters, Lists, Strings, Stacks, Trees, etc.), several (toy or real) programming languages (PICO, SMALL, Mini-ML, POOL), larger systems (PDL: a system for numerical packages, CONDUCTOR: a system for statistical software, a medical expert system). These case studies have revealed a number of deficiencies in ASF and related tools - in particular: (a) the concepts of exporting and hiding names are not strong enough; (b) defining the syntax of programming languages in ASF is too cumbersome; (c) in many specifications Boolean functions are defined by giving equations for all true and all false cases, whereas only the true are 'interesting', hence the desirability of omitting specification of the false; (d) the implemented tools are too slow. Problem (b) has been solved by designing a dedicated formalism SDF (Syntax Definition Formalism) for specifying syntax. Problem (c) is currently being studied. Problems (a) and (d) will be studied in the future.

Progress

1987 saw progress made in several areas. The software tools discussed above were completed and ported to installations (Vax, Sun, Gould) at the Universities of Amsterdam, Delft and Groningen, the Software Engineering Research Centre in Utrecht, and INRIA in Sophia-Antipolis (France). Much emphasis was placed on the implementation of the syntax definition formalism SDF: a prototype editor generator was implemented which produces a complete syntax-directed editor for the defined language, on the basis of an SDF-definition. To this end, new techniques have been developed for the lazy/incremental generation of lexical scanners and parsers for arbitrary (but finitely ambiguous) context-free grammars.

References

1. J.A.Bergstra, J.Heering, P.Klint (1986). *Module Algebra*, CWI Report CS-R8617.
2. J.A.Bergstra, J.Heering, P.Klint (1987). *ASF - an Algebraic Specification Formalism*, CWI Report CS-R8705.
3. J.Heering, G. Kahn, P.Klint, B.Lang (1986). Generation of interactive programming environments. *ESPRIT'85, Status Report of Continuing Work, Part I*, North-Holland, 467-477.
4. J.Heering, P.Klint (1987). A syntax definition formalism. *ESPRIT'86: Results and Achievements,* North-Holland, 619-630.

PROJECTS

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

Concurrency

Research into the semantic aspects of parallel computation according to various programming styles (imperative, applicative-functional, dataflow, object-oriented); also proof methodology for parallel computation (1984).

J.W. de Bakker, F.S. de Boer, J.J.M.M. Rutten, J.N. Kok (SION).

Free Univ. Amsterdam, Univ. Kiel, SUNY Buffalo.

Formal specification methods

Research concerning specification languages, process algebra, executable specifications and systems development methodology (1982).

J.W. Klop, J.A. Bergstra (advisor), R.J. van Glabbeek, F.W. Vaandrager, H.J.M. Goeman.

ESPRIT, Univ. Amsterdam, Univ. Utrecht, Free Univ. Amsterdam, Philips.

Extensible programming environments

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

P. Klint, N.W.P. van Diepen, J. Heering, P.R.H. Hendriks, J. Rekers, M.H. Logger (BSO).

ESPRIT, Univ. Amsterdam.

Expert systems

Research into the applicability of methods of knowledge representation and automatic reasoning in expert systems. Distributed problem solving in expert systems. The development of prototype expert system tools (1985/1986).

P.J.F. Lucas, M. Bezem (SPIN), A. Eliëns, L.C. van der Gaag, H.W. Lenferink, J. van Elst, M.A.C. Heerink, M.C.L. Kempenaar.

Univ. Rotterdam, Philips Research Lab. Eindhoven, Univ. Leiden, Univ. Utrecht, Techn. Univ. Delft, Univ. Twente, Univ. Amsterdam.

Logical aspects of artificial intelligence

Fundamental research into topics such as: logic programming and the construction of expert system shells, non-monotonic reasoning and reasoning involving time, knowledge representation and epistemic logic, dealing with partial and inconsistent information (1987).

K.R. Apt, R.N. Bol.

Department of Algorithmics and Architecture

L.G.L.T. Meertens (head of department)
C.A. van den Berg
J.C. Ebergen
L.J.M. Geurts
M.L. Kersten
L.M. Kirousis
E. Kranakis
A.K. Lenstra
C. van der Meer
S.J. Mullender
S. Pemberton
G. van Rossum
F.H. Schippers
I. Shizgal
A.P.J.M. Siebes
P.M.B. Vitányi

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

trainees:
S.E. Advokaat
D.T. van den Bergh
H.W.K. Boenink
E.D.G. Boeve
H.L. van het Bolscher
I. Elshoff
T.A. de Goede
J.C. van der Heide
M.J. de Jong
F.J.P. Lim
H. Nijbacker
M. Roorda
P.J. van Scherpenseel
H. Tempelman
R.C.G.M. ten Teije
J.F.L. Vermeulen
K.S. Yap

ALGORITHMS AND COMPLEXITY

Introduction

The study of complexity of computations has gained special impetus from the problems posed by parallel communication processes as they occur, for example, in modern computer architectures. In what follows, we highlight recent CWI contributions to a number of research fields, specifically: a realistic theory of multicomputing, parallelism and atomicity, and Kolmogorov complexity.

Costs

A precise description of how to execute a given task, how to achieve a prescribed goal, is called an algorithm. No algorithm can be described without assumptions about the mechanism - the model of computation - which will execute it.
Focussing for the moment on a sequential computation model, where all the elementary actions constituting an execution of the algorithm happen one after the other, without concurrency, the cost of execution can be expressed in terms of the number of elementary actions required. Another cost measure is the amount of memory space. An account of the costs of execution of an algorithm, expressed in the size (number of bits) of a problem instance description, gives the computational complexity. Since this complexity all but determines the economic costs involved, it is obviously useful to determine the feasibility and limitations of the best possible algorithms for some problems. (If 1% of all computer time is spent sorting lists of items, then a 1% improvement in the running time of sorting algorithms is a multi-million dollar affair.)
Currently, we see the emergence of machines consisting of many computing nodes, interconnected by communication networks. Each such computing node consists of a sequential computer. Moreover, computing machines are linked-up in worldwide communication networks, supporting services like electronic mail and global memory. On the microscopic scale similar things happen on electronic chips which are densely packed with communicating logical devices. While the algorithms and complexity of sequential computations are moderately well understood, the possibilities and pitfalls of the new, inherently non-sequential, computations are obscure at the present time.

Realistic theory

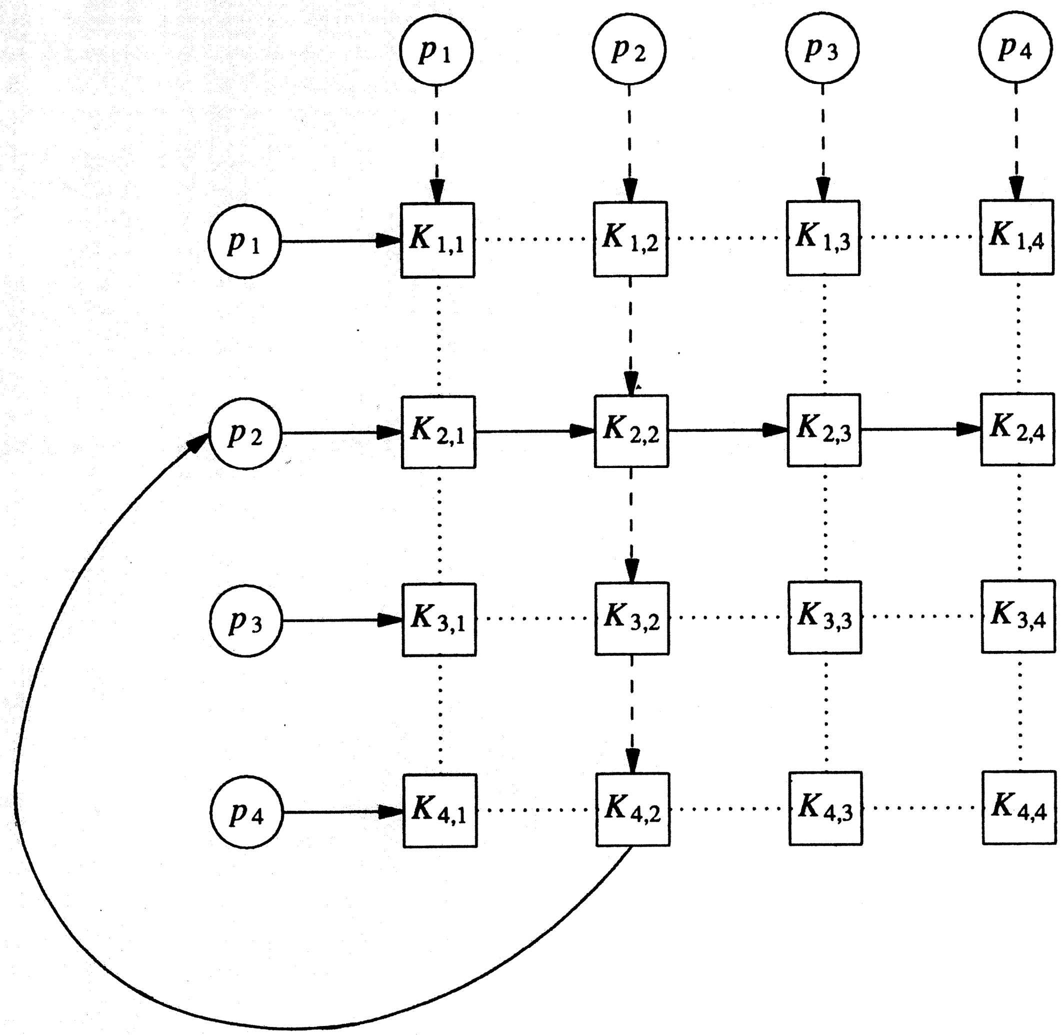
In multicomputers, where computation proceeds in parallel, the communication element increasingly dominates computing costs: far more so than in sequential computers, where the computation speed is linear dependent on the memory access time. Moreover, the laws of physics also influence communication costs to a far greater degree in parallel than in sequential computation. These laws are, for example, manifested in the impossibility of synchronizing clocks in different computers. This aspect has been largely neglected. And - whilst good theoretical progress was done in analyzing clean, but thoroughly unrealistic models - there has been no study of optimal algorithms for computational models corresponding to physically realizable parallel machines.

Work carried out at CWI has helped inject a modicum of realism into the theoretical foundations of multicomputing. So, for instance, currently popular multicomputer architectures are based on highly symmetric communication networks with small diameter allowing fast permutation of data between computing nodes. Using purely geometric arguments we have shown that, in any technology (chip, optical, biological, etc.), the 3-dimensionality of physical space requires, on average, very long interconnects. Consequently, while theoretical investigations which ignore communication costs predict incredible performance for such architectures, with an astronomical number of nodes, our analysis shows that communication time requirements will strangle performance. The bad news apart, the theory also indicates those architectures which scale well. We have also shown that, contrary to existing beliefs regarding current chip technologies, it is impossible to achieve communication speeds which are logarithmic in the interconnect length, without incurring a penalty which both wipes out the gain and dramatically increases silicon area. The basic reason for this is that (owing to technical electronic factors) such high communication speeds can only be achieved if the wires have a fixed length/breadth ratio on the whole chip, so that the area covered by wires increases quadratically with their length.

Communicating processes

Our next topic is best introduced by a simple example. A flip-flop is a Boolean variable which can be read (tested) by one processor and written (set and reset) by one other processor. Suppose, we are given flip-flops as building blocks, and are asked to implement a variable with values ranging from 1 to n, which can be written by a single processor (the writer) and read by a single other one (the reader). Of course, $\log n$ flip-flops suffice to hold such a variable. Now, suppose the two processors are asynchronous and the writer gets 'stuck' after it has set half the bits of the new value. If the reader executes a read at that time, it obtains a value consisting of half the new value and half the old one. Obviously, this is undesirable. Such problems occur if heterogeneous equipment, or unbalanced load, precludes synchrony assumptions between communicating sequential processes. Current solutions by reader-writer protocols ensure mutual exclusive access of the shared variable by synchronization devices like semaphores. Apart from eliminating concurrency, by having the processes wait for each other, this leads to a vicious circle. What happens is that the semaphores obviously presuppose interprocess communication at a lower, perhaps hardware, level. Indeed, in current practice there is always synchrony at some level. Only very recently, and partly through work carried out at CWI, research in the area has focussed on solutions which realize the maximal amount of parallelism implicit in concurrent operation executions by avoiding all waiting in the algorithms. For such a solution to be useful it must satisfy a nicety condition called *atomicity*. Atomicity of the solution means that, even though an operation execution of the solution algorithm has a duration, it seems as if it is executed in a single indivisible instant (inside the duration): i.e., if a variable is atomic, then the actions of the reader and writer may overlap each other in arbitrary ways, but the external effect of the operation executions will always be consistent with an imaginary sequential execution. In such a setting, serializability is not actively enforced, rather it is the result of a pre-established harmony in the way the executions of the algorithm by the various processors interact.

The fundamental work by L. Lamport and G. Peterson has given rise to a new way of looking at interprocessor communication. In particular, it has shown how to solve the example above. Using this work, we have shown for the first time that it is possible to implement wait-free atomic variables which are shared between any number of asynchronous readers and writers (joint work with B. Awerbuch from MIT). Subsequently, this has become a highly popular research area. However, it is extremely hard to understand the proposed implementation algorithms. In fact, apart from the Peterson-Lamport algorithm, *The $n \times n$ matrix register implements a wait-free, atomic, n writer, n reader, multivalued register via atomic, 1 writer, 1 reader, multivalued subregisters $K_{i,j}$. The processors may execute actions concurrently. The i-th processor is connected to the read-terminals of all subregisters lying on the i-th column, as well as to the write-terminals of all subregisters lying on the i-th row. Each subregister contains a value as well as a sequential number (or tag). A read execution by the processor consists of a sequence of* n *low-level (i.e. executed on the subregisters $K_{i,j}$) reads followed by* n *low-level writes; the processor reads the values of the subregisters of its column, picks the value corresponding to the highest tag, updates its own tag and writes the value to all the subregisters of its row. Similarly, in a write execution the processor reads the tags of the subregisters of its column, picks the highest tag, updates its own tag and writes the desired value to all the subregisters of its row. The illustration depicts a high-level write/read execution by the 2nd processor in the 4 × 4 matrix register. Protocols of this type accomplish the maximum degree of parallelism and make it possible to implement shared, wait-free variables for the first time. CWI helped pioneer the development of such protocols.*



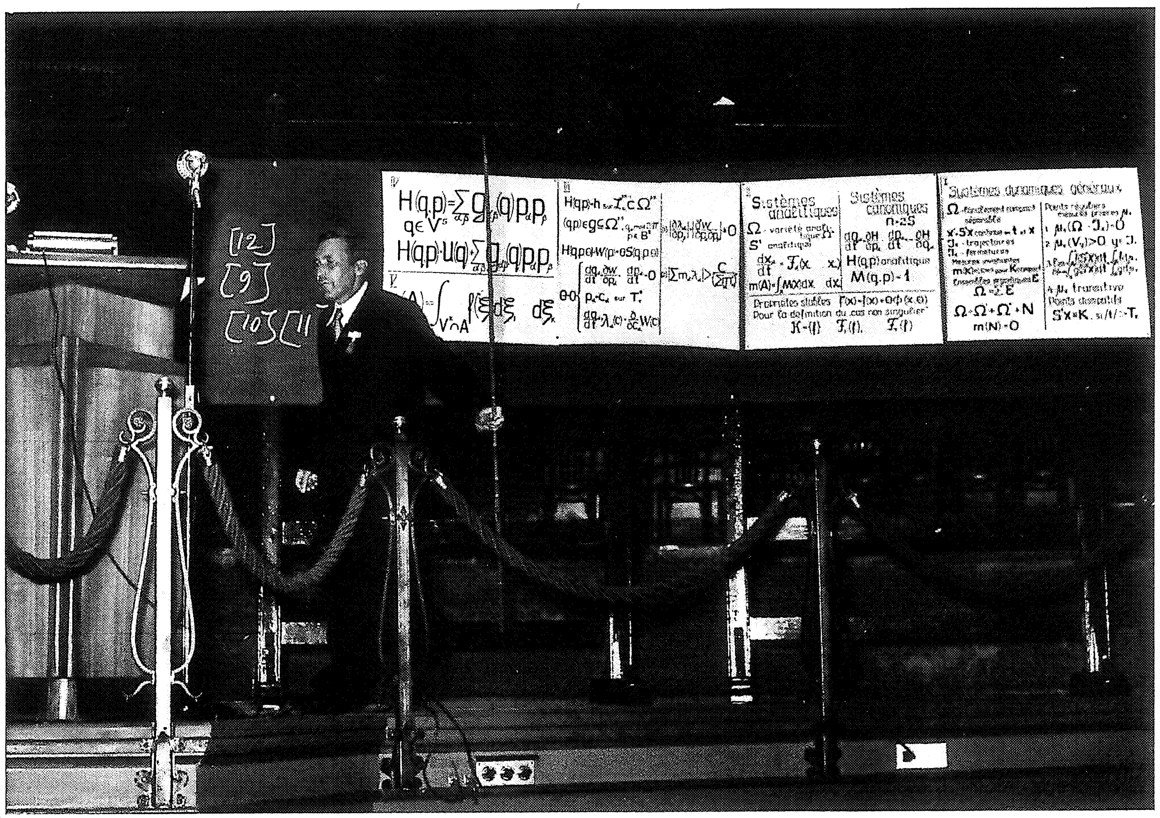
Bloom's algorithm, and the Vitányi-Awerbuch 'matrix' algorithm, the algorithms (let alone their proofs of correctness) seem to defy comprehension by everyone but the designers. We have developed a fairly simple theoretical framework in which to express correctness and proof rules for such solutions. We have also given several improved solutions for multiparty shared variables, including some which are currently optimal in complexity and simplicity. Once the feasibility of these problems had been demonstrated by obscure algorithms, simplicity and comprehensibility became the foremost concerns in this difficult area. We have begun investigating the implementations of higher constructs such as the 'test-and-set' primitive. A truly atomic solution appears impossible (M. Gouda's work at the University of Texas in Austin). However, by developing a measure theory calculus in relation to the validity of temporal logic formulae in computations, we have shown that our solution is 'correct' with measure 1, i.e., the next best thing (joint work with B. Awerbuch from MIT, L. Kirousis from the University of Patras, A. Israeli from Harvard University and Technion, and M. Li from Harvard University).

Kolmogorov complexity

A third example of the CWI-work in this field comes from the theory of computation, which is primarily concerned with the analysis and synthesis of algorithms in relation to the resources in time and space required by such algorithms. A.N. Kolmogorov and R.J. Solomonoff (and later G.J. Chaitin and D.W. Loveland) have invented an excellent theory of information content of binary strings which is most useful in this connection. Intuitively, the amount of information in a finite string is the size of the smallest program which, starting with a blank memory, computes the string and then terminates. For infinite strings, the program produces element after element forever. Thus, a string of n 1's contains little information because a program sized about $\log n$ outputs it. Likewise, the transcendental number $\pi = 3.1415...$, an infinite sequence of seemingly 'random' decimal digits, contains only constant information. (There is a short program which produces the consecutive digits of π forever; the above strings can be 'compressed' to short descriptions.) Such a definition would appear to make the amount of information in a string depend on the particular programming language used. Fortunately, it can be shown that all choices of such programming languages (which make sense) lead to quantification of the amount of information, which is invariant up to an additive constant. The resulting theory (Kolmogorov complexity) deals with the quantity of information in individual objects rather than treating objects as members of a set of objects with a given probability distribution. To say that 'randomness' is absence of 'regularity' is a truism. Even so, only now does it seem to have become possible to found precise formulations of this concept directly on the simple idea above. It turns out that most strings cannot be compressed at all. They are random in the strongest sense possible: they are their own shortest descriptions. In collaboration with M. Li from Harvard University, we have started a series of papers concerning applications of Kolmogorov complexity. These will culminate in a textbook - *Applied Kolmogorov Complexity*.

Our target comprises elegant and useful applications of Kolmogorov complexity. We distinguish three areas:

- Application of the fact that some strings are arbitrarily far compressible. This includes a strong version of Gödel's incompleteness theorem.
- Lower bound arguments which rest on application of the fact that certain strings cannot be compressed at all. Applications range from Turing machines and formal languages to electronic chips and communication complexity.
- Other issues, such as the foundations of probability theory, a priori probability, and resource-bounded Kolmogorov complexity. Applications range from NP-completeness to inductive inference in artificial intelligence.



Algorithmic information theory, or 'Kolmogorov complexity' as it is commonly called, was put forward in the early sixties independently by A.N. Kolmogorov (1903-1987) and R.J. Solomonoff, and somewhat later by G.J. Chaitin and D.W. Loveland. The theory, which has its historical roots in R. von Mises' notion of random infinite sequences (proposed as a foundation for probability theory), gives an algorithmic description of the complexity of finite objects, thus also defining the notion of 'randomness' for such objects. The photograph shows Kolmogorov during the 1954 International Mathematical Congress in Amsterdam.

PROJECTS

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

Complexity and algorithms
The design of efficient algorithms, in particular for distributed computations, and fundamental research into the concrete complexity of algorithms (1980).

P.M.B. Vitányi, E. Kranakis, L.M. Kirousis.

Univ. Amsterdam, Univ. Utrecht, Univ. Rochester, Univ. Washington, MIT.

Distributed systems
The research in this project is centred on the design and implementation of the distributed operating system Amoeba. This system consists of workstations, a processor pool, file servers and other specialized server machines, all connected through a fast local network. Research now focusses on two important fundamental problems: extensibility and error insensitivity. (1980).

S.J. Mullender, A.J. Jansen, J.G. Steiner, I. Shizgal, K.S. Yap, G. van Rossum, E.D.G. Boeve, P.J. van Scherpenseel, J.F.L. Vermeulen.

Free Univ. Amsterdam, COST-11.

ABC
The aim of this project is the design, implementation and distribution of a simple, structured, interactive programming language, built in into an integrated environment and meeting the requirements of modern personal computing (1975).

L.G.L.T. Meertens, F. van Dijk, L.J.M. Geurts, T.J.G. Krijnen, S. Pemberton, T.A. de Goede, M.J. de Jong, J.C. van der Heide, H.L. van het Bolscher, F.J.P. Lim.

NGI section SAIA, Dutch Association for Ergonomics.

Distributed adaptive information systems
The development of software techniques and theory for the realisation of flexible distributed information systems (1985).

M.L. Kersten, C. van der Meer, F.H. Schippers, A.P.J.M. Siebes, D.T. van den Bergh, R.C.G.M. ten Teije.

Free Univ. Amsterdam, Univ. Twente, Philips Nat. Lab. Eindhoven, Univ. Amsterdam, Univ. Utrecht.

Constructive algorithmics
The development of formalisms and methods to derive algorithms from a specification, with unification of the specification formalism and the algorithmic formalism proper, and the development of (pre)-algorithmic concepts and notations on a high level of abstraction. The notion of 'algorithm' as used above comprises not only traditional computer programs, but any process-defining system description built in accordance with a recursive syntax from discrete basic elements. There are two subjects:

- VLSI-design (1982);
- Abstracto (1977).

L.G.L.T. Meertens, J.C. Ebergen, S. Pemberton.

SION, IFIP Working Group 2.1, Techn. Univ. Eindhoven, Washington University St. Louis, Caltech. Pasadena, Univ. Groningen, Univ. Oxford.

Department of Interactive Systems

P.J.W. ten Hagen (head of department)
V. Akman
F. Arbab
P. Bernus
C.L. Blom
M. van Dijk
W. Eshuis
J.A. Kaandorp
A.A.M. Kuijk
J.L.H. Rogier
M.M. de Ruiter
Zs. Ruttkay
H.J. Schouten
T. Tomiyama
C.G. Trienekens
P.J. Veerkamp

programmer:
R. van Liere

trainees:
R.J. van Bavel
M.M. Megens
E.J. Weijers
R. Willemsen

DIALOGUE PROGRAMMING

Introduction

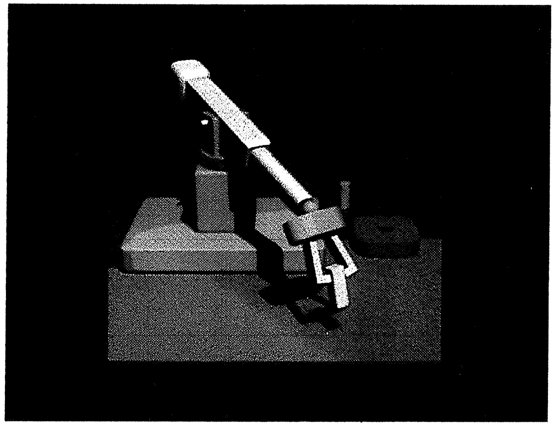
Rapid developments in hardware technology, combined with increasingly complex software systems, have necessitated the construction of high quality user interfaces. These interfaces are meant to provide the user insight into the potential of an application, e.g. by visualizing information in the form of pictures on a workstation screen. A by now familiar example is computer-aided design (CAD), which has multiple applications (e.g. throughout the manufacturing sector). Research at CWI covers various programming concepts for specifying graphical user interfaces *(dialogue programming).*

User interface management systems

In general terms, a user interface is any device placed between a user and a complicated technological application to provide practical utilization of that application. A simple example is the telephone receiver as intermediary between caller and exchange. With ever more complex software and hardware systems the need for such interfaces has become especially apparent in the area of computer applications. This is a vast field including issues related to computer graphics, data modeling, process control and, more recently, artificial intelligence. The field is also still experimental in that criteria used to evaluate user interfaces are mainly intuitive and not derived via objective, scientific channels.

It is accepted that, in order to specify its various components, the user interface designer needs high-level design tools, i.e. tools which operate as close as possible to the human level (in contrast with the 'low' machine level). One such tool is a *user interface management system* (UIMS): a software system which, on entry of a user's command, provides the user with some or all of the interface between him and the activated application routines. Input to the UIMS (not to be confused with input by the user) typically includes: screen designs, menu organization, dialogue syntax, help files, prompt messages and graphical feedback. A considerable amount of research has been done on UIMS in recent years, and several of these (experimental) systems have been implemented. Although these systems appear similar on the screen, their underlying processing mechanisms are quite different. The following list highlights a few interesting research areas concerning these mechanisms.

- Most UIMS are tightly coupled to their application; interaction is managed by low-level calls to an application-dependent servicing process. Currently only a few UIMS separate interface from application and hence permit interface reuse or modification. The key question here is - in what way can separation be achieved which will still allow the user interface to make decisions about the application (in connection with the object to be designed)?
- Only some UIMS provide explicit graphical relationships, such as composition and graphical dependency. These relationships, and their explicit representation in objects on a screen, allow important structural features of the application (e.g. connectivity) to be graphically maintained. For example, in the design of a robot one has to build-in relations between the arm sections and joints: they have to stay con-



The dialogue cell programming language DICE, developed at CWI, allows production and interactive manipulation of hierarchically structured pictures on a screen; this in turn enables a range of study including possible actions performed by a robot.

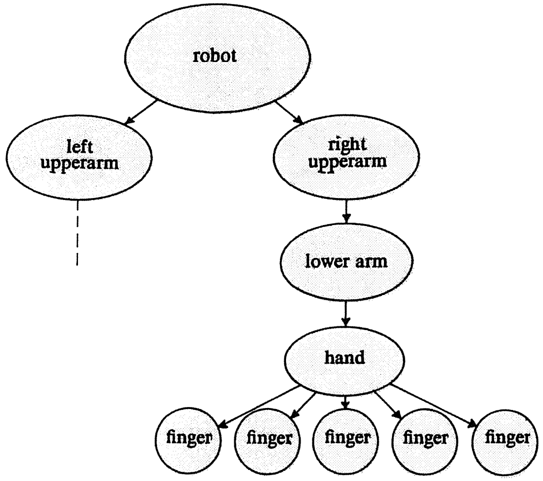
nected, the movement of an arm is restricted by the connection at the joint, etc. A graphical relationship between two segments of a robot arm ought then to assure that a movement by the one will make the other move with it in such a way that they remain properly and permanently connected. The extensive current research into the manner of defining and maintaining these relationships is resulting in new programming paradigms.

- Finally, only a few UIMS are truly device-independent. Dependency leads to considerable extra effort when attempting to port these systems on other (and newer) hardware. Results in computer graphics, obtained in solving the problems of constructing device-independent programs (e.g. the Graphical Kernel System GKS), have had considerable impact on similar research for UIMS.

Dialogue cells

CWI researchers adopted a fundamental approach to the problem of defining the interactive part (user interface) of a complete computer program (application + user interface). First, an abstract model for interaction was defined, based on the concept of *dialogue cells.* Informally, a dialogue cell implements an independent process which is responsible for an interaction. In the previous robot example each component of the robot (arms, joints, etc.) can be mapped onto one dialogue cell. Complex interactions are defined by combining dialogue cells in a hierarchical fashion. Very strict rules are defined for the mutual communication between cells as well as the communication between an individual cell and the application program. Specifically, a dialogue cell is a construction which performs the following four functions:

- Activation of all sibling dialogue cells in the hierarchy. Every cell is responsible for activating its sibling dialogue cells. This includes providing information about the mode in which a sibling will be activated, the parameter values and the resources needed by each sibling.
- Reception of input values from its siblings. Defining dialogue cells in terms of other cells allows a hierarchical approach to



Logically, the robot is described in terms of dialogue cells, corresponding to its various components (arms, joints, etc.). Dialogue cells are connected in a tree-like hierarchical structure under very strict communication rules, e.g. the robot's right lower arm has no direct connection with its left hand.

specifying input values. Input to the lowest parts of the hierarchy is received from so-called basic dialogue cells which simulate physical input devices (e.g. mouse, keyboard, etc.).

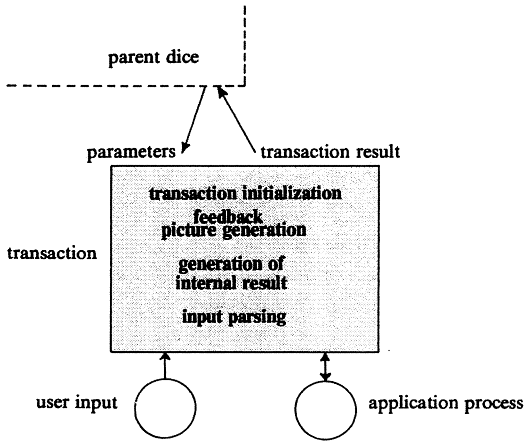
- Production of a result value. Received inputs are mapped onto values and are passed in turn to the application or other dialogue cells.
- Production of visual feedback. This occurs in episodes as the dialogue cell proceeds through its execution phase and is ultimately passed as a result to another dialogue cell. Hence, dialogue cells can also return pictures or parts of a picture.

The dialogue cell model contains features which are rarely considered in other models, such as parallel input/output and the maintenance of the integrity between the data structures within the application and the visual representation of these on the display. Here integrity means that the user receives - on screen - a correct representation of the situation inside the computer.

DICE

The DICE specification language was developed using the model for interaction as basis. DICE supports various advanced features such as: automatic error recovery, mixed mode application control, general resource management, goal directed scheduling and a history mechanism.

In 1987 work concentrated in the following areas:



Overview of the functionality and interfaces of a dialogue cell. A dialogue cell gives a complete description of a (compound) user-computer transaction, possibly involving communication with the application. Results of sibling dialogue cells are parsed according to the specification.

Fundamental research on general input models
A general logical input model was devised using the results obtained from the dialogue cell system. The model - based on the GKS logical input device model - contains extra features to maintain the integrity between input and output data. The basic ideas behind this new model have provided valuable input for the international working group which is reviewing the ISO standard graphical package GKS.

Case studies using DICE within large scale applications
Two case studies were initiated:
The first, for Dutch Railways, involved development of an interactive graphical editor which carries out changes in a database containing information on marshalling yard management. Among other things, the editor makes it possible to shift tracks and change semaphore image cards. In both cases various consistency controls, as defined within the application, have to be maintained. For example, the database could be queried if the distance between two semaphores is sufficient for all possible signal colours. The problems introduced in this case study are typical of the situation when separation of the application from the user interface is required.
The second case study will result in the implementation of a *'sketching system'*. This system will aid the user who is sketching an object by giving information on the object under construction. To achieve this the system must possess knowledge on representation of the object. Artificial intelligence techniques will be used to retrieve the information needed to complete the sketch. The sketch system is a typical example of the design of general purpose dialogues which are in turn to be used in application-dependent domains.

PROJECTS

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

Computer graphics

The design of functionally complete basic graphics systems, with special support for interactive use. Results to be made available, on the one hand as (contribution to) international standards, on the other hand as implementations, again with special attention to efficiency required for high quality interaction (1980).

A.A.M. Kuijk, M. Bakker (CWI-STO), F.J. Burger (CWI-STO), J. Kaandorp, B.P. Rouwhorst (CWI-STO), D. Soede (CWI-STO), C.G. Trienekens (STW).

Techn. Univ. Eindhoven, Techn. Univ. Delft, Univ. Twente, TNO-IBBC, ECN, MARIN, ACCU, ISO-working group TC97/SC21/WG5-2, Philips, Systeem Experts, Hoogovens, Techn. Hochschule Darmstadt, INRIA Paris, Rutherford Labs Abingdon, George Washington University.

User interfaces

Information systems should be addressed in high level, natural user languages. The user interface is then to provide the mappings between the user language and the abstract system concepts. Attempts are being made to enrich user languages by supporting speech-recognition and -generation, natural language instructs and picture elements (e.g. sketches). This project focusses on picture interpretation. This is a new area. The major difference with computer vision is that with picture interpretation the computer is actively involved in the picture construction process. The emphasis therefore is on correlating pictures with other information. (1984).

M.M. de Ruiter, C.L. Blom, P.J.W. ten Hagen, A.A.M. Kuijk, H.J. Schouten, R.J. van Bavel, R. Willemsen.

TNO-IBBC, Univ. Twente, Techn. Hochschule Darmstadt, Rutherford Labs Abingdon.

Dialogue programming

The project is aimed at the development of a complete programming method for interactive dialogues. According to this method dialogue programs will be written which specify the syntax of a dialogue language for a given application. In addition the dialogue program also determines all external effects associated with this syntax, such as the specification of all input-output procedures and the associations with application processes. (1983).

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

TNO/IBBC, NLR, Océ, Philips, Univ. Amsterdam, Techn. Hochschule Darmstadt, Univ. Tokyo.

Intelligent CAD systems

The project will, through the use of AI-based methods and techniques, attempt to produce CAD-systems which will be more complete, integrated and have a high quality user interface (1985).

V. Akman (NFI), P. Bernus, P.J.W. ten Hagen, J.L.H. Rogier, T. Tomiyama, P.J. Veerkamp (NFI), M.M. Megens, E.J. Weijers, Zs. Ruttkay, F. Arbab.

TNO-IBBC, Univ. Tokyo, Helsinki Univ. of Technology, Computer and Automations Institute Budapest.

User controlled systems

User controlled systems are information systems in which databases and program libraries are integrated. This type of systems is needed for making the various autonomous components of a complex computer system cooperate (for instance, a complete design and manufacturing system). With this technology it is hoped to realize CIM (computer integrated manufacturing). (1987).

W. Eshuis, P.J.W. ten Hagen.
NLR, Fokker, Stork, Demtec, CIAD, TNO, Univ. Twente, Univ. Karlsruhe.

Knowledge Transfer, Expert Training, Central Role

Introduction

The Policy Document 1988-1993 produced by CWI in 1987 goes into some detail on three significant aspects of SMC's statutory aims vis-à-vis CWI: conducting excellent research, the promotion of knowledge transfer and expert training, and the function as international meeting point. The first aspect remains by far the most important. However, attention devoted to the others in recent years has grown apace: in part this is due to CWI's increased emphasis on strategic and application-oriented research, and on applied research and development. A grant from the Dutch government's Information Technology Promotion Plan provided the basis for this broader approach. The additional funds helped put CWI in a position to take part in programmes such as ESPRIT, SPIN, IOP, etc.; these in turn produced income approximately equal to the original grant. (For CWI income development during recent years see the diagrams in the chapter Financial and other Data.)

There was, however, a less rosy side to the picture. Particularly in CWI's computer science departments there was a serious loss of equilibrium with contract research booming at the cost of pure scientific activities.

Another development giving cause for some concern during 1987 was the establishment of the Software Engineering Research Centre (SERC) - part of the SPIN programme - in Utrecht. Now that the software sector has created its own access to fundamental research - any future relationship with CWI will be less direct.

Research contracts

The report year saw the introduction of Company fellowships at CWI, a highly effective 'packaging' of research, expert training and knowledge transfer. The sponsor company funds a CWI research position in a jointly selected area of fundamental research for a given number of years. All parties benefit: the fellowships contribute to the CWI research programme; the research fellow is supervised by a CWI project leader; and, in principle, the resulting know-how is available to industry at the end of the contract period. Two such fellowships, established by Shell in 1986, were filled in 1987. The subjects involve Inverse scattering and image processing of seismic signals, and Combinatorial algorithms for planning and scheduling.

A range of new research contracts was finalized. A research project into numerical solutions of the Euler equations was extended as part of the European Space Agency's Hermes space shuttle programme. The project examines the applicability of a geometrical multigrid method for the solution of two-dimensional stationary Euler equations, with special attention to flows around airfoils at high Mach numbers and high angle of attack.

Another research contract involves the solution of semiconductor equations (partial differential equations which describe the behaviour of a semiconductor). We are researching both two- and three-dimensional numerical solutions for these equations jointly with Philips' Corporate CAD-Centre mathematical software group, as part of the IOP IC-Technology programme.

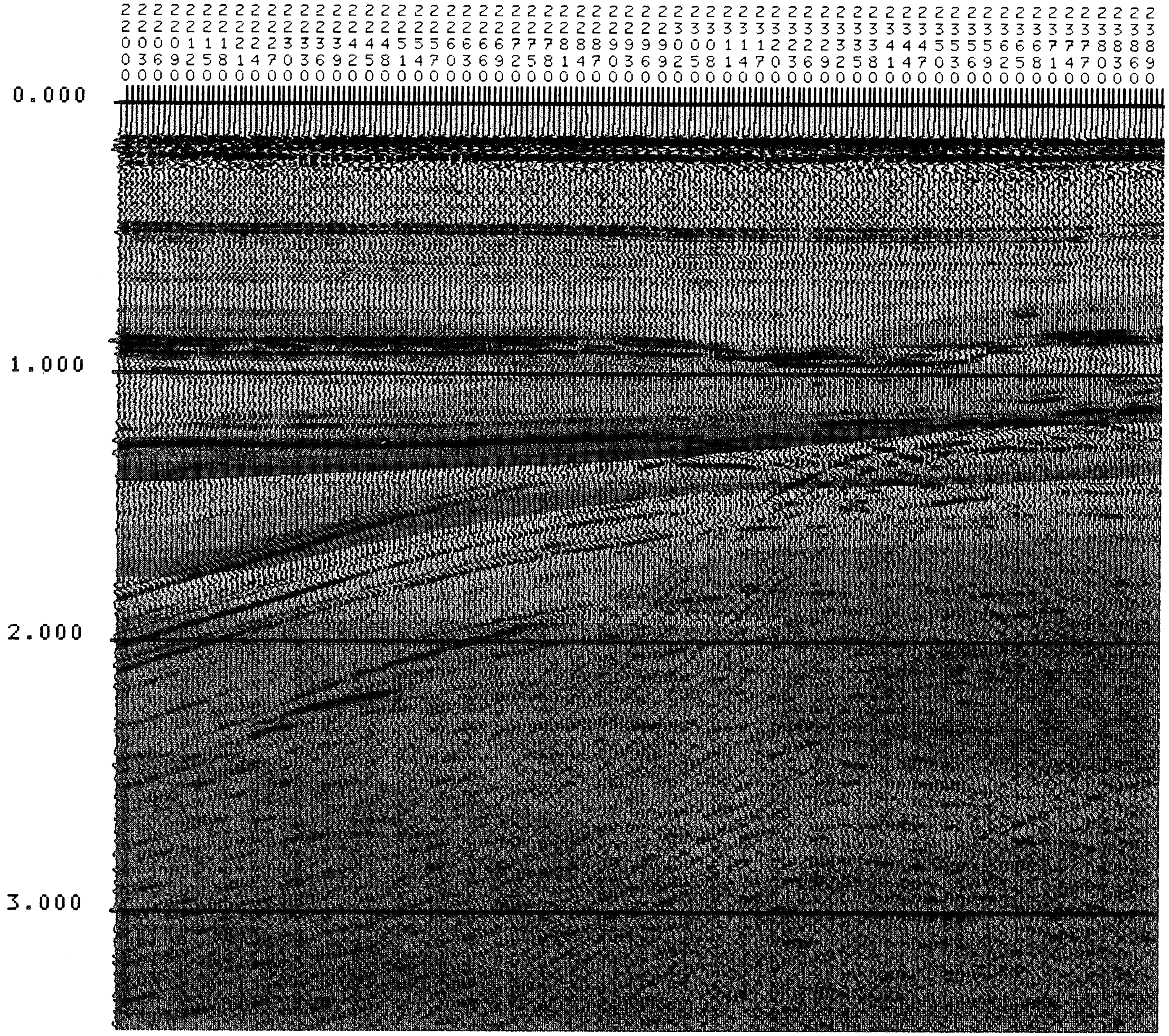
An agreement was signed with the Public Works Department for joint research into efficient numerical algorithms on vector computers. An existing Public Works contract involving numerical and statistical calculations to determine extreme water levels on the North Sea coast was extended.

Other research contracts concerned development of a graphic system for improved management of Dutch Railways' marshalling yards, and a system to direct aircraft to loading/unloading areas at Schiphol Airport.

Joint projects

Compilation of the 'Information Technology Atlas - Europe' was another example of pooled effort. North-Holland Publishing Company, with support from the European Commission, produced the first edition in 1987. Joint editing was in the hands of Wedgwood & Co. Ltd (London), International Organisations Services B.V. (Amsterdam) and J.C.P. Bus of CWI. The atlas gives a national and Europe-wide overview of research policies and programmes, research institutes, trade associations, companies, standards bodies, telecommunication agencies and professional bodies involved in information technology. CWI contributed to the chapter on research institutes.

Discussions within the Coordinating Group Computer Science Professional Training (which includes CWI, the University of Utrecht and both Amsterdam Universities) resulted in a decision to start post-graduate courses, to which CWI will contribute.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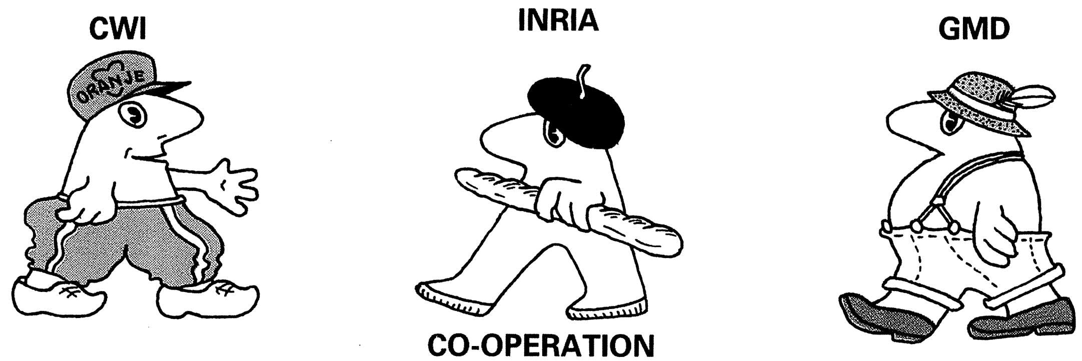
The NFI approved two projects: 'Transformational Programming' (jointly with Nijmegen and Utrecht Universities) and 'REX: Research and Education in Concurrent Systems' (jointly with Eindhoven and Leiden Universities).
Closer connections with the West German GMD (Gesellschaft für Mathematik und Datenverarbeitung) and the French INRIA (Institut National de Récherche en Informatique et Automatique) during 1987 yielded significant agreements on intensified collaboration in 1988 (including some joint workshops).



Scientific meetings
CWI as central meeting point came into its own with a series of workshops, conferences etc.

◄
Processed seismic data for a vertical cross-section of the earth, indicating reflector positions of geologically interesting layers. Colour is used to distinguish interval velocities of the seismic signal in the various layers. This velocity increases with depth and with rock density. Horizontally the position of the signals along the earth's surface, vertically the running time of the signals is indicated. Fundamental aspects of inverse scattering and image processing of seismic signals are studied at CWI in a research project sponsored by Shell (Picture: Shell Research B.V.)

The 5th annual Eurocrypt Conference (European forum on all aspects of cryptography), sponsored by the International Association of Cryptologic Research, aided by CWI, was held in Amsterdam in April 1987. The approx. 200 expert delegates, from Europe and further afield, were chaired by D. Chaum.
In the same month, April, CWI organized a conference on IIICAD (Intelligent, Integrated, Interactive Computer-Aided Design) in Noordwijkerhout.
We also contributed to content and organization of the PARLE-Conference (Parallel Architectures and Languages Europe) in Eindhoven in June. PARLE was based in ESPRIT project Nr. 415; organization was in joint hands of Philips Research Laboratories and the National Concurrency Project. J.W. de Bakker co-chaired the programme committee.
A number of Interactive Systems department staff contributed to Eurographics '87, the annual congress of the European Association for Computer Graphics, organized by CWI in Amsterdam in August. Significant subjects covered were: geometric modeling, parallelism in graphics, object-oriented graphics, computational geometry and computer graphics standards. The congress was preceded by special workshops on User Interface Management Systems, VLSI for graphics hardware and intelligent CAD-systems.
In September there was a workshop on Image analysis with input from Dutch and Danish experts (Univ. Aarhus). In November, J.P. Serra (Paris) was among those who presented papers at a national colloquium on Mathematical Morphology. Approximately 100 delegates attended.
The Frontiers of Technology organization, formed under CWI auspices, got off to a good start in late 1986 with its Intelligent Auto-

nomous Systems symposium. This was followed up in December 1987 with the Frontiers in Computing symposium, held in Amsterdam. Prominent international researchers discussed highly topical issues including: non-conventional architectures, architectures for neuro- and supercomputing ((bio)molecular and optical components), new architectures for large systems and networks, and computing needs in society and the impact on software development. CWI's scientific director, P.C. Baayen, took part in a panel discussion on comparison of various IT-programmes.
The roots of the conference went back to a similar event held in Rotterdam some years ago in reaction to the Japanese Fifth Generation Computer Project. Appropriately, the opening session was dedicated to the memory of Professor Moto-oka, one of the project's most active initiators.
In November CWI organized an extremely successful course under the title Vector- and Parallel Computing, designed specially for industry: there were 20 participants. The course concentrated on special techniques for the solution of large-scale numerical and combinatorial problems on vector- and parallel computers. CWI enjoys considerable in-house expertise in this area. Subjects covered included: hardware and software, systems of equations, special equations (e.g. Navier-Stokes) and parallel combinatorial optimization.

Finally, we summarize the various large-scale national and international joint projects.

CWI Participation in (Inter)National Programmes

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

European Programmes

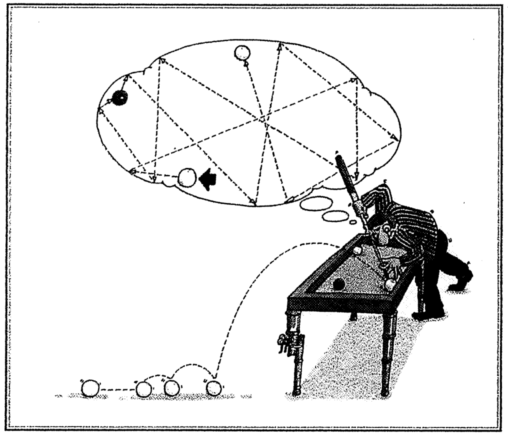
ESPRIT

METEOR (432): An integrated formal approach to industrial software development
October 1984 - October 1989
Philips (PRLB, PRLE), CGE Paris, AT&T/Philips, COPS, TXT, Univ. Passau
J.A. Bergstra

GIPE (348): Generation of Interactive Programming Environments
November 1984 - November 1989
INRIA, SEMA, BSO
P. Klint

415: Parallel architectures and language for AIP - a VLSI directed approach
November 1984 - November 1989
Subcontractor of Philips
J.W. de Bakker

DIAMOND (1072): Development and Integration of Accurate Mathematical Operations in Numerical Data processing
January 1986 - January 1989
NAG, Siemens, Univ. Karlsruhe
J. Kok



Computers don't calculate accurately... that's why we work on
DIAMOND
Development and Integration of Accurate Mathematical Operations in Numerical Dataprocessing
Project n° 1072
Siemens AG (Prime Contractor)
Centrum voor Wiskunde en Informatica
Numerical Algorithms Group Ltd.
Universität Karlsruhe
University of Bath (Subcontr. to NAG)

VIP (1229(1283)): VDM Interfaces for PCTE
November 1986 - November 1988
Praxis, Dr. Neherlab. PTT, Océ, Univ. Leicester
J.A. Bergstra

Other programmes

European Commission Project: Pilot implementation of basic modules for large portable numerical libraries in Ada
April 1985 - April 1987
NAG, NPL, Trinity College
J. Kok

COST-11: Distributed systems management
1983-1987
15 institutes in 8 countries
S.J. Mullender

ESA project HERMES: Convergence acceleration of a finite volume Euler solution with a geometric and algebraic adapted multigrid method in finite volume Euler solutions
July 1987 - July 1988
P.W. Hemker

National Programmes

SPIN (Stimulation Project Team Computer Science)

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

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

NFI (National Facility Computer Science)

Decision support systems for operational planning
July 1986 - July 1990
Technical Univ. Eindhoven, Erasmus University Rotterdam
J.K. Lenstra

REX: Research and Education in Concurrent Systems
January 1988 - January 1992
Technical Univ. Eindhoven, Univ. Leiden
J.W. de Bakker

Transformational programming
September 1987 - September 1992
Univ. Nijmegen, Univ. Utrecht
L.G.L.T. Meertens

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

Intelligent CAD systems
October 1986 - October 1990
TNO/IBBC
P.J.W. ten Hagen

STW (Foundation for the Technical Sciences)

Facilities for raster graphics in programming languages
September 1982 - April 1987
Univ. Leiden
P.J.W. ten Hagen

Shallow-water equations: evaluation and stabilization of numerical methods
June 1983 - June 1987
P.J. van der Houwen

Mathematical methods for the analysis of spectral atmospheric models
October 1983 - December 1987
KNMI
J. Grasman

Development of efficient numerical methods for flows described by the stationary Euler equations
July 1984 - July 1988
P.W. Hemker

Statistical analysis of traffic flows
April 1986 - April 1990
Univ. Amsterdam, Technical Univ. Delft
P. Groeneboom/R.D. Gill

Prediction and control problems for the Dutch freeway control and signalling system
January 1986 - January 1990
Univ. Twente
J.H. van Schuppen

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

Adaptive grid techniques for evolutionary partial differential equations
September 1987 - September 1990
Shell
J.G. Verwer

New architecture for interactive raster graphics on the basis of VLSI
April 1987 - April 1990
Univ. Twente
P.J.W. ten Hagen

IOP (Innovative Research Programmes)

IC-Technology: numerical methods for semiconductor device modelling
October 1987 - October 1989
FOM, Technical Univ. Delft
P.W. Hemker

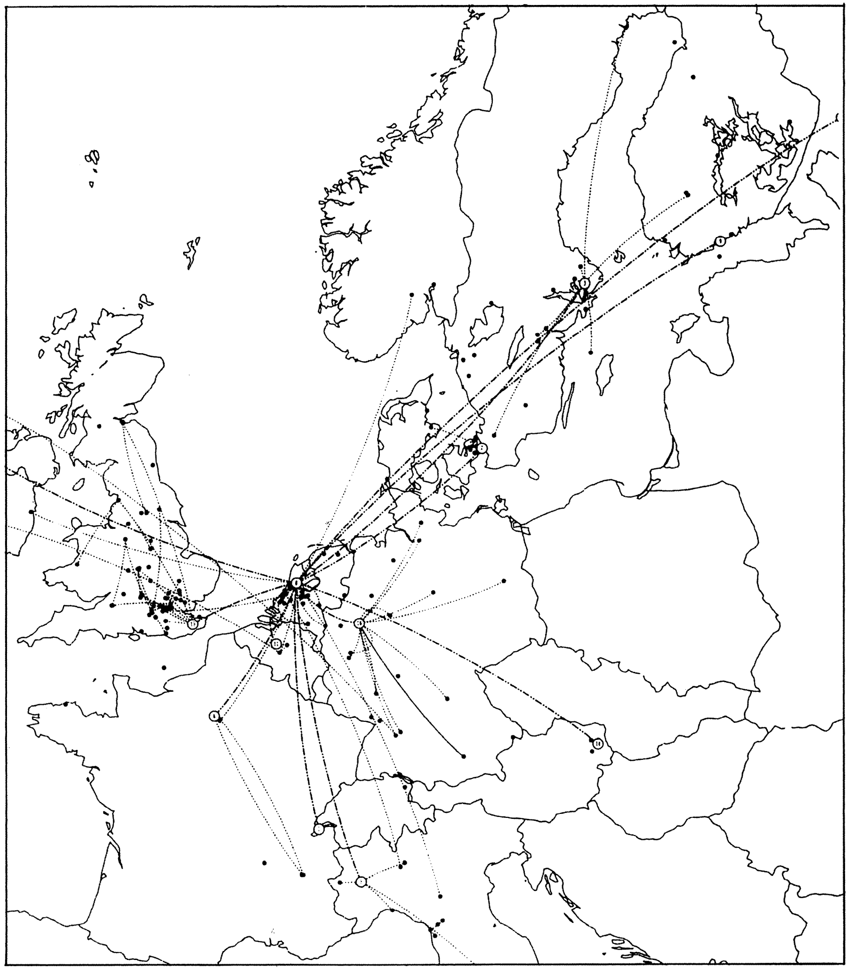
ISNAS: an information system for simulation of flows with the Navier-Stokes equation
April 1987 -
NLR, ECN, MARIN, WL, Univ. Twente, Technical Univ. Delft
P.J.W. ten Hagen

Computer Infrastructure and Support

The CWI Policy Document 1988-1993 (mainly composed in 1987) stressed the importance of an up-to-date computer infrastructure and service to a research institute like CWI. A separate Policy Plan Computer Equipment, presented in November '87, considers the consequences on computing facilities of the rapidly increasing requirements of researchers and supporting staff, particularly with an eye to recent expansion of CWI computer science research resulting from the Dutch Information Technology Promotion Plan (INSP). An important observation was that growth in research potential has not been matched by adequate computing support. As noted by Prof. R.B.K. Dewar of the New York Courant Institute of Mathematical Sciences in his analysis of the computer equipment situation at CWI in August '87: 'In some areas, most strikingly in the support for computer science research, the level of equipment has fallen far below what is adequate.' First rate equipment is necessary, e.g. to maintain the present level of participation in international projects such as ESPRIT and to fulfill CWI's traditional central role in network services (EUnet).

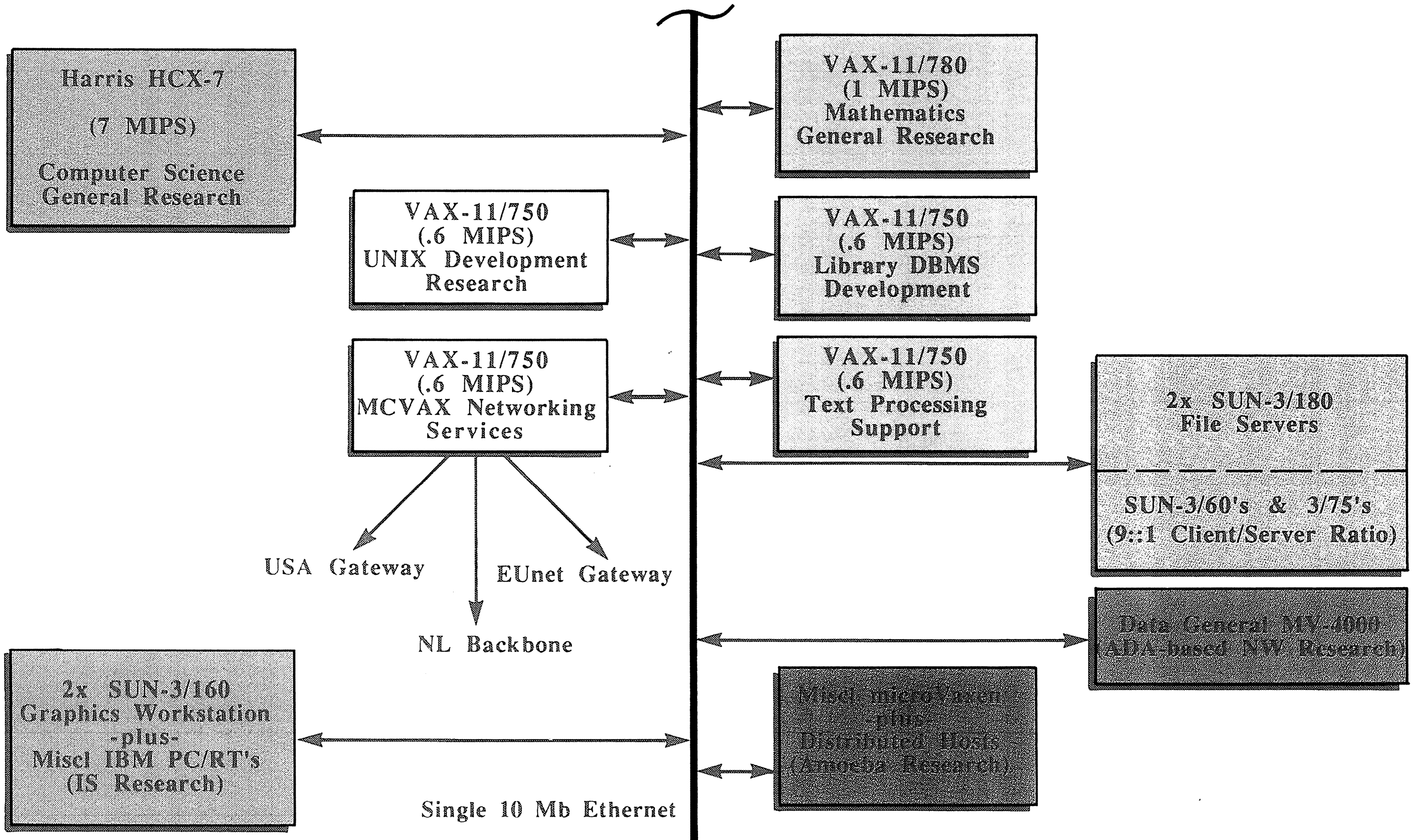
Meanwhile, ongoing computing support activities were concentrated in CWI's Technical Support (STO) and Computer Systems and Telematics (CST) sections; activities included the following.

STO's external programming commissions amounted to some fifteen larger projects for banks, government institutions, universities



CWI manages the EUNET / USENET gateway between the USA and Europe. These two major networks provide researchers with the means for fast exchange of long-distance information. The map shows European USENET news connections (September 1986).

CWI Computing Equipment Resources
(as of December 31, 1987)



Not shown:
- ~90 Apple Macintosh +
- 6 Apple LaserWriters and miscl. output devices
- Harris phototypesetter
- Miscl. terminals and terminal concentrators

and industry, e.g. research into the capacity of motorways; complete automation of scientific linguistic data; and the development, documentation and transfer of a package for calculation with absorption simulation models.

As in previous years considerable programming support was given to a number of CWI research projects: participation in the development of a numerical program library in Ada (ESPRIT's DIAMOND-project); implementation of an electronic payment system (Cryptography-project); and various projects in the departments of Interactive Systems (GKS, PHIGS, etc.) and Mathematical Statistics (citation analysis, special software packages such as S, etc.).

Attention in the field of office and library automation focussed on the use and support of the database management system INGRES (acquired in 1986), on the basis of which an advanced address system was designed and almost implemented. A journal administration system (with automated check-in) was developed for the library.

Finally, STO's computer services and support mainly concerned the development of user introductions and supporting tools, e.g. for CWI's Macintoshes and MS-DOS machines.

CST's task is to provide fundamental technical support and direction for the operation, acquisition, installation and development of computer systems to service CWI's research and support requirements. As such, CST has both a service/support and a research role, concentrated on the following activities:

- Operating systems development and analysis;
- Wide-area network support services;
- Text processing facilities (for internal and external use);
- Microcomputer support and networking.

CST staff were engaged in several tasks during 1987:

- Porting UNIX 4.3BSD to the Harris HCX-7 pipelined processor, including development of special-purpose support for several of CWI's ongoing research projects;
- Development of local enhancements to UNIX text processing facilities, and evaluation of a layered implementation of UNIX on a large mainframe host at SARA;
- Networking support on behalf of the EUUG and NLUUG which maintained CWI's position as the central network node for inter- and intra-European network traffic;
- Research on Euromath, the principal goal being the development of text processing facilities for the network-based searching and acquisition of previously published, and to-be-published, mathematical material.

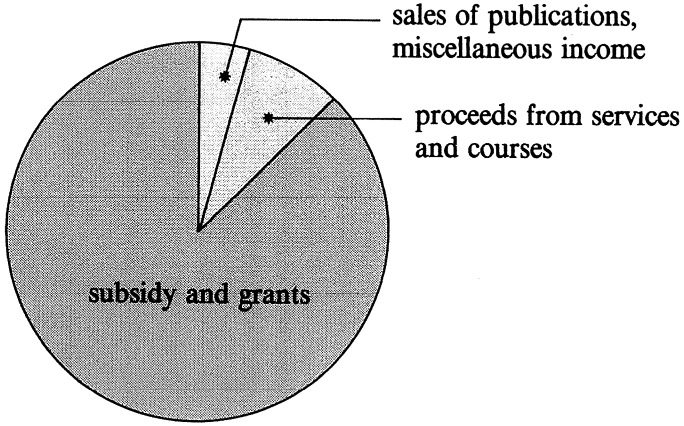
Financial and other Data

FINANCES 1987

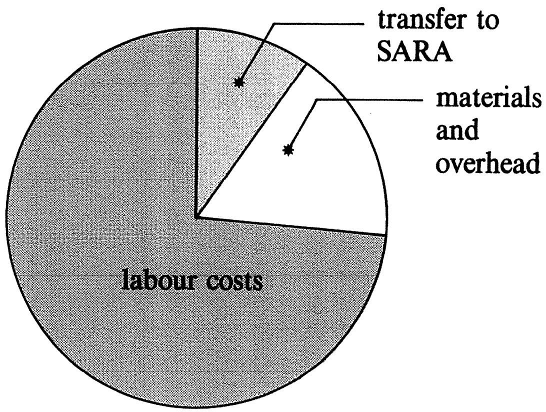
In 1987, SMC spent over Dfl. 19 million, of which about Dfl. 1.74 million was allocated to research by the national working communities and over Dfl. 17.3 million to CWI.
The expenses were covered by a subsidy from ZWO (Dfl. 12.92 million), from SION (Dfl. 0.1 million), from INSP (Dfl. 2 million), from the Free University of Amsterdam (Dfl. 0.07 million), from NFI (Dfl. 0.13 million), from Shell (Dfl. 0.02 million) and from a grant of Dfl. 1.65 million from the European Community for its ESPRIT and Ada projects. Finally, an amount of about Dfl. 2.16 million was obtained as revenues out of third-party-services and other sources.
During 1987 CWI also employed 17 researchers in positions financed by STW and industry. These are not included in the adjacent financial summary.

	national working communities	*CWI*	*SMC*
	× *Dfl.* 1000		
income			
subsidy and grants	1743	15149	16892
proceeds from services and courses	-	1436	1436
sales of publications	-	163	163
miscellaneous income	-	558	558
total income	1743	17306	19049
expenses			
labour costs	1674	12723	14397
materials and overhead	15	2882	2897
transfer to SARA	-	1700	1700
total expenses	1689	17305	18994
origin of subsidy and grants			
ZWO	1743	11182	12925
SION	-	97	97
INSP	-	2002	2002
VU	-	75	75
NFI	-	126	126
ESPRIT	-	1650	1650
Shell		17	17
total	1743	15149	16892

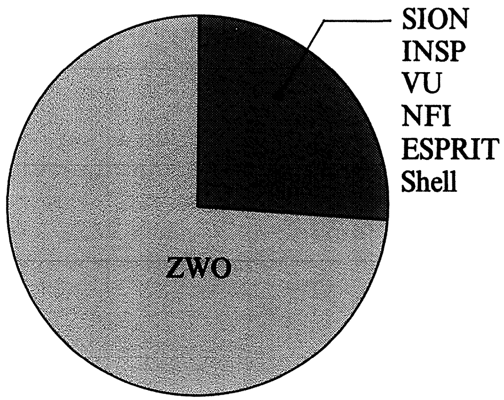
income CWI



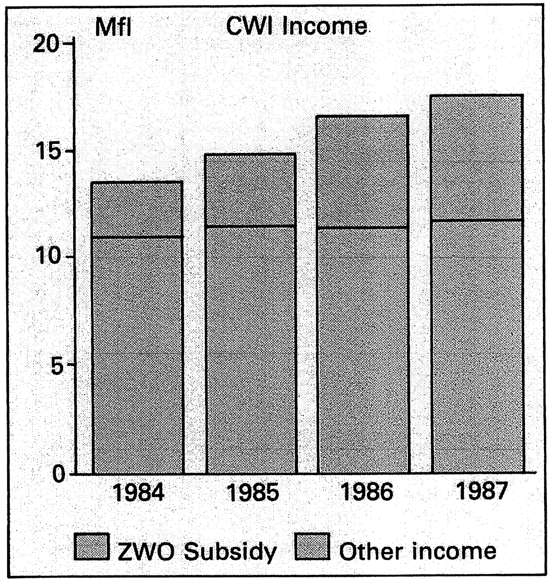
expenses CWI

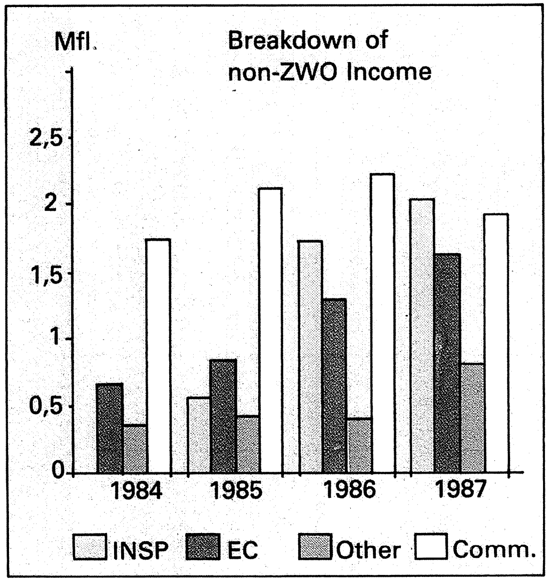


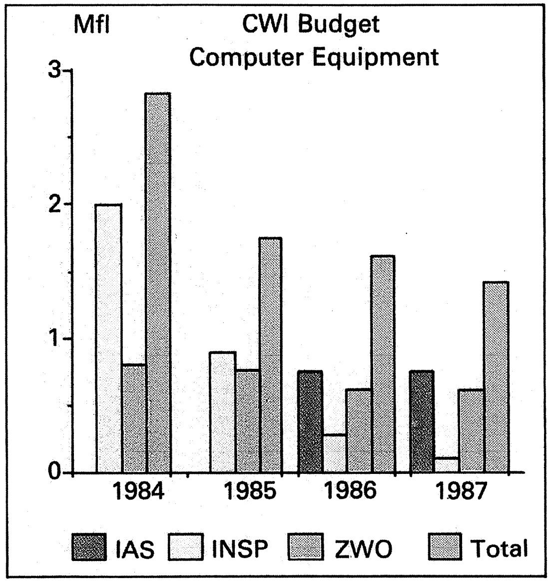
origin of subsidy and grants CWI



FINANCES 1984-1987





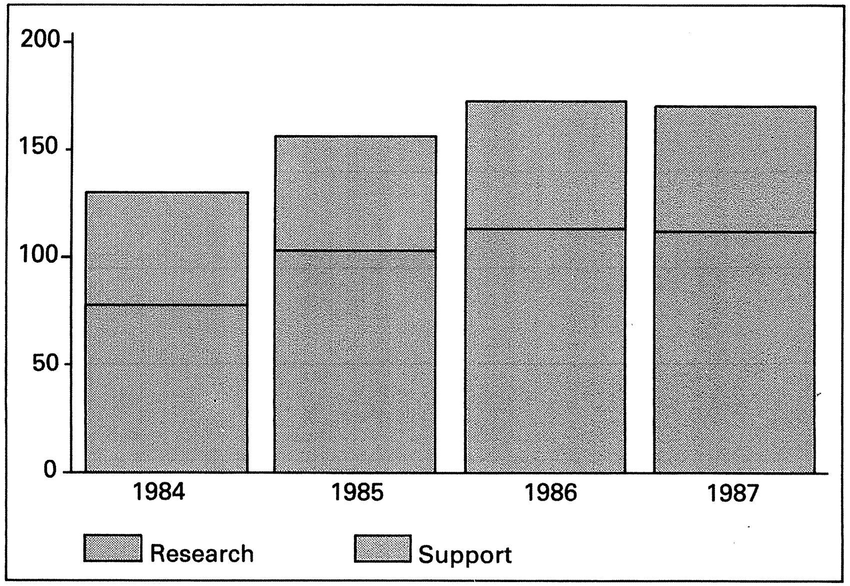


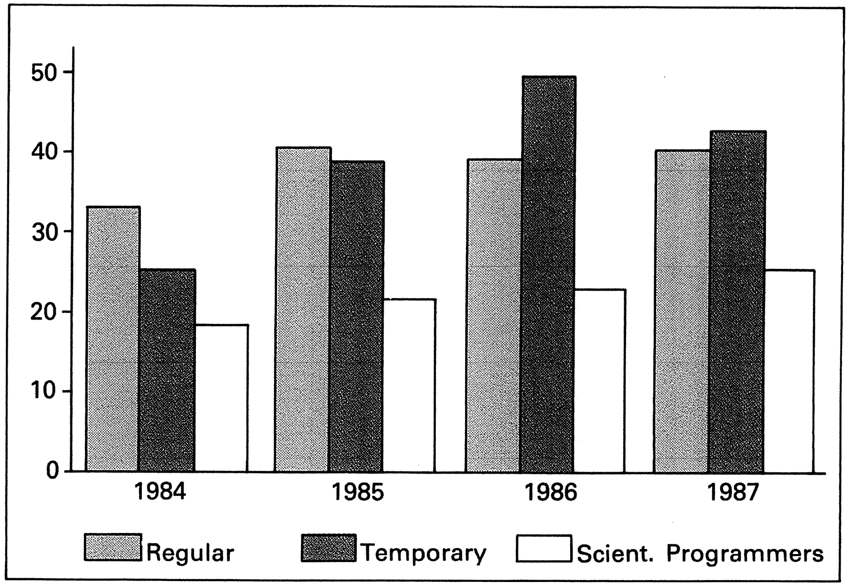
Proportion of total operating costs for the years 1984-1987 covered by the ZWO grant. An increasing proportion of finance comes from sources other than ZWO.

In addition to the INSP grant, other forms of research subsidy and commission fees account for a growing contribution. This source of growing income is particularly related to involvement in national and international application-oriented computer science research programmes (ESPRIT, SPIN, etc.).

To maintain parity with the financial injection from the INSP programme, an increasing contribution from IAS - a governmental equipment support scheme - is required in addition to the regular ZWO subsidy for computer equipment.

PERSONNEL 1984-1987





The size of the personnel force is expressed in full-time equivalents, averaged over the year in question. Not included are externally financed positions (from STW and industry). For the years 1984-1987 these amounted to 5, 7, 10 and 17 respectively. To the right the breakdown of the research personnel is shown.

LIBRARY AND PUBLICATIONS

Library: accretion

	1984	1985	1986	1987
books	1130	1120	1072	1215
subscriptions on journals	50	67	82	61
reports	4985	5455	5891	6566

Library: collection ultimo 1987

books	33,650
subscriptions on journals	1,237
reports	61,906

Publications

	1984	1985	1986	1987
syllabi	5	4	3	3
tracts	9	6	12	14
reports	100	94	108	142
publications in journals, proceedings, etc.	123	129	146	125
Ph.D. Theses	3	5	0	6

CWI Monographs

nr.	*Title*	*Authors/editors*
1	Mathematics and Computer Science Proceedings of the CWI Symposium, November 1983	J.W. de Bakker, M. Hazewinkel and J.K. Lenstra, editors (1986)
2	Stability of Runge-Kutta Methods for Stiff Nonlinear Differential Equations	K. Dekker and J.G. Verwer (1984)
3	The Numerical Solution of Volterra Equations	H. Brunner and P.J. van der Houwen (1986)
4	Mathematics and Computer Science II Fundamental Contributions in the Netherlands since 1945	M. Hazewinkel, J.K. Lenstra and L.G.L.T. Meertens, editors (1986)
5	One-Parameter Semigroups	Ph. Clément, H.J.A.M. Heijmans, S. Angenent, C.J. van Duijn and B. de Pagter (1987)
6	Program Correctness over Abstract Data Types with Error State Semantics	J.V. Tucker and J.I. Zucker (1988)

Foreign Visitors

Pure Mathematics

W. van Assche (Belgium)
E. Brickel (USA)
A. Camina (UK)
C. Crépeau (Canada)
B. Fuchssteiner (BRD)
S. Helgason (USA)
W.M. Kantor (USA)
M. Mizony (France)
A. Neumaier (BRD)
F. Rouvière (France)
F. Sommen (Belgium)
D. Venable (USA)
W. Wiwianka (BRD)
A.I. Zayed (USA)

Applied Mathematics

S. Burys (Poland)
D. Dee (USA)
L. Gatteschi (Italy)
M.L. Glasser (USA)
M. Mimura (Japan)
R. Nisbet (Scotland)
J. Prüss (BRD)
C. Ronse (Belgium)
J. Serra (France)
K.E. Shuler (USA)
K. Soni & R.P. Soni (USA)
Binggen Zhang (China)

Mathematical Statistics

A. Baddeley (Australia)
B.R. Clarke (Australia)
M. Hušková (Czechoslovakia)
C. Jennison (UK)
E.V. Khamaladze (USSR)
V.K. Klonias (Greece)
J. Mau (BRD)
R.A. Moyeed (Bangladesh/UK)
J.A. Wellner (USA)
W. Woyczynski (USA)

Operations Research and System Theory

M. Arato (Hungary)
M.L. Balinski (France/USA)
W. Cook (BRD)
H.R. Gail (USA)
M. Gevers (Belgium)
A. Gombani (Italy)
J. Grabowski (Poland)
C.V. Jones (USA)
A.G. Konheim (USA)
G. Latouche (Belgium)
E.L. Lawler (USA)
A. Lindquist (Sweden)
A. Lucena (Brazil)
F. Maffioli (Italy)
J. Matsuda (Japan/BRD)
S. Morse (USA)
T.J. Ott (USA)
J. Paixao (Portugal)
L. Praly (France)
H.N. Psaraftis (USA)
W.R. Pulleyblank (Canada/BRD)
D. Scott (Canada)
D.B. Shmoys (USA)
R.L. Smith (USA)
G. Steiner (Canada)
H. Takagi (Japan)
M.J. Todd (USA)
P. Toth (Italy)
J. Walrand (USA)

Numerical Mathematics

C.A. Addison (Norway)
A. Bellen (Italy)
Guo Ben-Yu (China)
I. Boglaev (USSR)
B. Braams (USA)
J. Carroll (Ireland)
R. Charron (Canada)
J.H. Davenport (UK)
L.M. Delves (UK)
M. Erl (UK)
B. Ford (UK)
R. Haggenmüller (BRD)
C. Hirsch (Belgium)
G.S. Hodgson (UK)
W. Klein (BRD)
T. Krückeberg (BRD)
M.-H. Lallemand (France)
J.J. Lauture (Belgium)
R. Maerz (DDR)
D. Moody (UK)
A.M. Odlyzko (USA)
G. Pontrelli (Italy)
Lin Qun (China)
G.T. Symm (UK)
C. Ullrich (BRD)
T.C. Winkler (USA)
J. Wolff von Gudenberg (BRD)
A. Zöllner (BRD)

Software Technology

D. Andrews (UK)
S. Bayerl (BRD)
M. Bellia (Italy)
H.A. Blair (USA)
P. Borras (France)
P.G. Bosco (Italy)
M. Bruynooghe (Belgium)
G.L. Burn (UK)
R. Caferra (France)
M. Chabrier (France)
A.K. Chandra (USA)
D. Clément (France)
S. Colwill (UK)
G. Cousineau (France)
W. Damm (BRD)
P. Degano (Italy)
M. O'Donnell (USA)
T. Flannagan (UK)
H.J. Genrich (BRD)
E. Glück-Hiltrop (BRD)
S. Grumbach (France)
I. Guessarian (France)
O. Hanseth (Norway)
B. Hauksson (Norway)
M. Hennessy (UK)
M. Jackson (UK)
S. Jubb (UK)
G. Kahn (France)
Ms. Kanchana Kanchanasut (Thailand)
D. Kozen (USA)
B. Lang (France)
D. Leivant (USA)
M. Martelli (Italy)
J. Metthey (Belgium)

R. Nossum (Norway)
H. Oliver (UK)
C. Palamidessi (Italy)
V. Pascual (France)
J.M. Pereira (France)
L. Rideau (France)
N. Sabadini (Italy)
P. Schäfer (BRD)
G. Schäffler (BRD)
Ph. Schnoebelen (France)
J. Sidi (France)
M. Sievers (BRD)
Y. Toyama (Japan)
J.I. Zucker (USA)

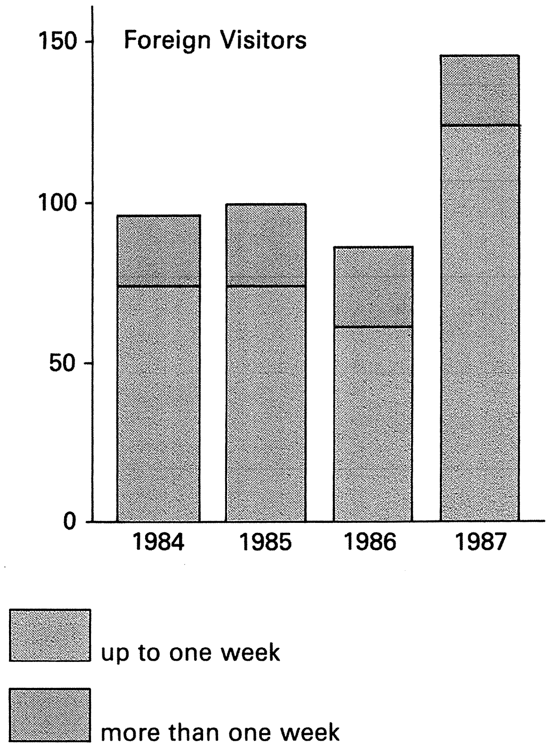
Algorithmics and Architecture

A. Aggarwal (USA)
B. Awerbuch (USA)
M. Beynon (UK)
I. Elshoff (USA)
L. Guibas (USA)
J. Halpern (USA)
L.M. Kirousis (Greece)
A.K. Lenstra (USA)
L. Shrira (USA)
A.J. Smith (USA)
J. Vitter (USA/France)
K.S. Yap (USA)

Interactive Systems

F. Arbab (USA)
M.R. Gomez (Portugal)
Z. Létray (Hungary)
Zs. Ruttkay (Hungary)

FOREIGN VISITORS 1984-1987



List of Publications

Department of Pure Mathematics

Report series

PM-R8701 M. HUŠEK, J. DE VRIES. *A note on compactifications of products of semigroups.*
PM-R8702 S.N.M. RUIJSENAARS. *Relativistic Calogero-Moser systems and solitons.*
PM-R8703 T.H. KOORNWINDER. *Group theoretic interpretations of Askey's scheme of hypergeometric orthogonal polynomials.*
PM-R8704 S.N.M. RUIJSENAARS. *Action-angle maps and scattering theory for some finite-dimensional integrable systems; The pure solution case.*
PM-R8705 D.J. SMIT. *String theory and algebraic geometry of moduli spaces.*
PM-R8706 A.I. ZAYED. *Jacobi polynomials as generalized Faber polynomials.*
PM-R8707 J. VAN BON, A.M. COHEN, H. CUYPERS. *Graphs related to Held's simple group.*
PM-R8708 D.J. SMIT. *Algebraic and arithmetic geometry in string theory.*
PM-R8709 M. HAZEWINKEL. *Introduction to nilpotent approximation filtering.*
PM-R8710 G. BRASSARD, D. CHAUM, C. CRÉPEAU. *Minimum disclosure proofs of knowledge (revised version).*
PM-N8701 J.T.M. VAN BON. *Distance regular antipodal covers of Johnson and Hamming graphs.*

Publications in Journals, proceedings, etc.

Z1 A.E. BROUWER, E.W. LAMBECK (1987). An inequality on the parameters of distance-regular graphs and the uniqueness of a graph associated to M_{23}. *Ann. Discr. Math. 34,* 101-106.
Z2 A.M. COHEN, G.M. SEITZ (1987). The *r*-rank of the groups of exceptional Lie type. *Proc. KNAW Series A 90,* 251-259.
Z3 D. CHAUM, J.-H. EVERTSE (1987). A secure and privacy-protecting protocol for transmitting personal information between organizations. A.M. ODLYZKO (ed.). *Proc. Crypto '86,* LNCS 263, Springer-Verlag, Berlijn, 118-167.
Z4 D. CHAUM, J.-H. EVERTSE, J.A.M. VAN DE GRAAF, R. PERALTA (1987). Demonstrating possession of a discrete logarithm without revealing it. A.M. ODLYZKO (ed.). *Proc. Crypto '86,* LNCS 263, Springer-Verlag, Berlijn, 200-212.
Z5 M. HAZEWINKEL (1987). Technical wordprocessing and Euromath. *Wheels of the Mind,* September, 15-20.
Z6 M. HAZEWINKEL (1987). Introduction to nilpotent approximation filtering. A.H.P. VAN DER BURGH, R.M.M. MATTHEIJ (eds.). *Proceedings of the First International Conference on Industrial and Applied Mathematics (ICIAM 87),* CWI Tract 36, CWI, Amsterdam, 197-202.
Z7 M. HAZEWINKEL (1987). Lie algebraic methods in filtering and identification. M. MEBKHOUT et.al. (eds.). *Proc. 8th International Congress on Mathematical Physics,* Luminy, 1986, World Scientific, 120-137.
Z8 T.H. KOORNWINDER (1987). A group theoretic interpretation of Wilson polynomials. *Complex Analysis and Applications '85,* Sofia, 335-355.
Z9 S.N.M. RUIJSENAARS (1987). Complete integrability of relativistic Calogero-Moser systems and elliptic function identities. *Comm. Math. Phys. 110,* 191-213.
Z10 S.N.M. RUIJSENAARS (met A. CAREY) (1987). On fermion groups, current algebras and Kac-Moody algebras. *Acta Appl. Math. 10,* 1-86.
Z11 S.N.M. RUIJSENAARS (with S. FULLING) (1987). Temperature, periodicity and horizons. *Phys. Reps. 152,* 135-176.
Z12 S.N.M. RUIJSENAARS (1987). Relativistic Calogero-Moser systems and solitons. M. ABLOWITZ, B. FUCHSSTEINER, M. KRUSKAL (eds.). *Topics in Soliton Theory and Exactly Soluble Nonlinear Equations (Proc. Conf. Oberwolfach, 1986),* World Scientific, Singapore, 182-190.
Z13 J. DE VRIES (with S.A. ANTONYAN) (1987). Tychonov's theorem for *G*-spaces. *Acta Math. Hung. 50,* 253-256.
Z14 J. DE VRIES (with M. HUŠEK) (1987). Preservation of products by functors close to reflectors. *Topology Appl. 27,* 171-189.

Other publications

Z15 A.M. COHEN (with W.H. HESSELINK, W.L.J. VAN DER KALLEN, J.R. STROOKER) (eds.) (1987). *Algebraic Groups,* LNM 1271, Springer-Verlag, Berlijn.
Z16 M. HAZEWINKEL (1987). English translation of: Yu.I. Manin, Book review of J. Lepovsky e.o. Vertex operators in mathematics and physics. *Acta Appl. Math. 8,* 322-324.
Z17 M. HAZEWINKEL, J.F. KAASHOEK, B. LEIJNSE (1987). Liesegang Rings, Pattern Formation at Phase Transition: Experiment and Mathematical Modelling. Report 8729/A, Econometric Institute, EU Rotterdam.
Z18 J. VAN DE LUNE (1987). Getaltheorie en de PC. *Vacantiecursus 1987: De Personal Computer en de Wiskunde op School,* CWI Syllabus 14, CWI, Amsterdam, 25-57.

Department of Applied Mathematics

Report series

AM-R8701 JIANG FURU. *Boundary value problems for ordinary differential equations with multiple turning points.*
AM-R8702 H. ROOZEN. *An asymptotic solution to a two-dimensional exit problem arising in population dynamics.*
AM-R8703 J.B.T.M. ROERDINK. *The biennial life strategy in a random environment.*
AM-R8704 J. GRASMAN, J.B.T.M. ROERDINK. *Stochastic and chaotic relaxation oscillations.*
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tion: a survey.

AM-R8706 PH. CLÉMENT, O. DIEKMANN, M. GYLLENBERG, H.J.A.M. HEIJMANS, H.R. THIEME. *Perturbation theory for dual semigroups III. Nonlinear Lipschitz continuous perturbations in the sun-reflexive case.*

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AM-R8710 H.E. DE SWART. *Analysis of a six-component barotropic spectral model: chaotic motion, predictability and vacillation.*

AM-N8701 M. VAN HERWIJNEN. BEELDEN: *Een studie naar de mathematische morfologie van Serra.*

Publications in Journals, proceedings, etc.

T1 PH. CLÉMENT, O. DIEKMANN, M. GYLLENBERG, H.J.A.M. HEIJMANS, H.R. THIEME (1987). Perturbation theory for dual semigroups I. The sun-reflexive case. *Math. Ann. 277,* 709-725.

T2 O. DIEKMANN (1987). Perturbed dual semigroups and delay equations. S-N. CHOW, J. K. HALE (eds.). *Dynamics of Infinite Dimensional Systems,* NATO ASI-Series, Springer, 67-73.

T3 O. DIEKMANN (1987). On the mathematical synthesis of physiological and behavioural mechanisms and population dynamics. E. TERAMOTO, M. YAMAGUTI, (eds.). *Mathematical Topics in Population Biology, Morphogenesis and Neurosciences,* Springer Lect. Notes in Biomath. 71, 48-52.

T4 J. GRASMAN, H.E. DE SWART (1987). Low-order spectral models of the atmospheric circulation. A.H.P. VAN DER BURGH, R.M.M. MATTHEIJ (eds.). *Proceedings of the First International Conference on Industrial and Applied Mathmatics (ICIAM 87),* CWI Tract 36, CWI, Amsterdam, 351-360.

T5 M. GYLLENBERG, H.J.A.M. HEIJMANS (1987). An abstract delay-differential equation modelling size dependent cell growth and division. *Siam J. Math. Anal. 18,* 74-88.

T6 J.A.P. HEESTERBEEK, J.C. ZADOKS (1987). Modelling pandemics of quarantine pests and diseases: problems and perspectives. *Crop Protection 6,* 211-221.

T7 H.J.A.M. HEIJMANS (1987). Semigroup theory for control on sun-reflexive Banach spaces. *IMA Journal of Mathematical Control & Information 4,* 111-129.

T8 L.R.M. MAAS, J.T.F. ZIMMERMAN, N.M. TEMME (1987). On the exact shape of the horizontal profile of a topographically rectified tidal flow. *Geophysical and Astrophysical Fluid Dynamics 38,* 105-129.

T9 H. ROOZEN, A. VAN OOSTEROM (1987). Computing the activation sequence at the ventricular heart surface from body surface potentials. *IEEE Medical & Biological Engineering and Computing 25,* 250-260.

T10 H.E. DE SWART, J. GRASMAN (1987). Effect of stochastic perturbations on a low-order spectral model of the atmospheric circulation. *Tellus 39A,* 10-24.

T11 H.E. DE SWART, J.T.F. ZIMMERMAN (1987). Tidal rectification in lateral viscous boundary layers of a semi-enclosed basin. *J. Fluid Mech. 184,* 381-389.

T12 N.M. TEMME (1987). On the computation of the incomplete gamma functions for large values of the parameters. J.C. MASON, M.G. COX (eds.). *Algorithms for Approximation, Proceedings of the IMA-Conference,* Shrivenham, July 15-19, 1985, Oxford, Clarendon, 479-489.

T13 N.M. TEMME (1987). Recent problems in uniform asymptotic expansions of integrals. A.H.P. VAN DER BURGH, R.M.M. MATTHEIJ (eds.). *Proceedings of the First International Conference on Industrial and Applied Mathematics (ICIAM 87),* CWI Tract 36, CWI, Amsterdam, 117-128.

T14 N.M. TEMME (1987). Incomplete Laplace integrals: uniform asymptotic expansions with application to the incomplete beta function. *SIAM J. Math. Anal. 18,* 1638-1663.

Other publications

T15 PH. CLÉMENT, O. DIEKMANN, M. GYLLENBERG, H.J.A.M. HEIJMANS, H.R. THIEME (1987). *Perturbation Theory for Dual Semigroups II. Time-Dependent Perturbation in the Sun-Reflexive Case.* Helsinki University of Technology.

T16 PH. CLÉMENT, H.J.A.M. HEIJMANS (1987). *One-Parameter Semigroups.* CWI Monograph 5, North-Holland, Amsterdam.

T17 O. DIEKMANN, J.A.J. METZ (1986). *Een Dialoog over een Krachtige Bastaard.* Inaugural speech, RU Leiden.

T18 H.A. LAUWERIER (1987). Fractals; Meetkundige Figuren in Eindeloze Herhaling. Aramith Uitgevers, Amsterdam.

T19 H.A. LAUWERIER (1987). Analyse met de Microcomputer. Epsilon Uitgaven, No. 7, Utrecht.

T20 H.A. LAUWERIER (1987). Meetkunde met de Microcomputer. Epsilon Uitgaven, No. 8, Utrecht.

Department of Mathematical Statistics

Report series

MS-R8701 E. VALKEILA. *A Prohorov bound for a Poisson process and a Bernoulli process.*

MS-R8702 N. KEIDING, R.D. GILL. *Random truncation models and Markov processes.*

MS-R8703 M.L. EATON. *Admissibility in fair Bayes prediction problem, I. General theory.*

MS-R8704 T.A. LOUIS, J.K. BAILEY. *Controlling error rates using prior information and marginal totals to select tumor sites.*
MS-R8705 T.A. LOUIS. *Efficient monotone sequential design.*
MS-R8706 M.L. EATON. *Concentration inequalities for Gauss Markov estimators.*
MS-R8707 R.D. GILL, S. JOHANSEN. *Product-integrals and counting processes.*
MS-R8708 R. HELMERS. *On the Edgeworth expansion and the bootstrap approximation for a studentized U-statistic.*
MS-R8709 R.D. GILL. *Non- and semiparametric maximum likelihood estimators and the von Mises method (part I).*
MS-R7810 A.L.M. DEKKERS, L. DE HAAN. *On a consistent estimate of the index of an extreme value distribution.*
MS-R8711 A.L.M. DEKKERS, L. DE HAAN. *Large quantile estimation under extreme-value conditions.*
MS-R8712 E.V. KHMALADZE. *An innovation approach to goodness of fit tests in R^m.*
MS-R8713 C.C. HEESTERMAN. *A central limit theorem for M-estimators by the von Mises method.*
MS-R8714 A.J. KONING. *On single lane roads.*

Publications in Journals, proceedings, etc.

S1 H. BERBEE (1986). Periodicity and absolute regularity. *Israel J. Math. 55,* 289-304.
S2 H. BERBEE, C.G.E. BOENDER, A.H.G. RINNOOY KAN, C.L. SCHEFFER, R.L. SMITH, J. TELGEN (1987). The identification of nonredundant constraints of a system of linear inequalities from asymptotically uniform interior points. *Mathematical Programming 37,* 184-207.
S3 H. BERBEE (1987). Convergence rates in the strong law for bounded mixing sequences. *Probab. Th. Rel. Fields 74,* 255-270.
S4 H. BERBEE (1987). Chains with infinite connections: uniqueness and Markov representation. *Probab. Th. Rel. Fields 76,* 243-253.
S5 R.J.M.M. DOES, R. HELMERS, C.A.J. KLAASSEN (1987). On the Edgeworth expansion for the sum of a function of uniform spacings. *Journal of Statistical Planning and Inference 17,* 149-157.
S6 S. VAN DE GEER (1987). A new approach to least squares estimation, with applications. *Ann. Statist. 15,* 587-602.
S7 R.D. GILL, M. SCHUMACHER (1987). On a simple test of the proportional hazards model. *Biometrika 74,* 289-300.
S8 A. SIEDERS, K. DZHAPARIDZE (1987). A large deviation result for parameter estimators and its application to nonlinear regression analysis. *Annals of Statistics 15,* 1031-1049.

Other publications
From or with the cooperation of members of the department.

S9 R.J.M.M. DOES, R. HELMERS, C.A.J. KLAASSEN (1987). *Higher Order Asymptotics for the Sum of Functions of Uniform Spacings with an Application to Greenwood's Statistic.* Report 16, Capaciteitsgroep Medische Informatica en Statistiek, RU Limburg.
S10 S.A. VAN DE GEER (1987). *Regression Analysis and Empirical Processes.* Thesis, CWI, Amsterdam.
S11 R.D. GILL, W. METTROP (1987). De profeet, de missionaris en de handelsreiziger (interview with J. Hemelrijk). G. ALBERTS, F. VAN DER BLIJ, J. NUIS (eds.). *Zij Mogen Uiteraard Daarbij de Zuivere Wiskunde Niet Verwaarloozen,* CWI, Amsterdam, 187-197.
S12 R.D. GILL (1987). *Gemiste Kansen.* Inaugural speech, RU Leiden.
S13 R.D. GILL, Y. VARDI, J.A. WELLNER (1987). *Large Sample Theory of Empirical Distributions in Biased Sampling Models.* Report 104, Department of Statistics, University of Washington, Seattle, USA (cf. report MS-R8603).
S14 K.A. LAWSON, R.A. PEDERSON (with appendix by S. VAN DE GEER). Cell fate, morphogenetic movement and population genetics of embryonic endoderm at the time of germ layer formation of the mouse (to appear in *Development* (1988)).

Department of Operations Research and System Theory

Report series

OS-R8701 A. SCHRIJVER. *Polyhedral combinatorics.*
OS-R8702 J.L. VAN DEN BERG, O.J. BOXMA. *Throughput analysis of a flow-controlled communication network with buffer space limitations.*
OS-R8703 M. DESROCHERS. *A note on the partitioning shortest path algorithm.*
OS-R8704 J.W. POLDERMAN. *A state space approach to the problem of adaptive pole assignment.*
OS-R8705 J.W. POLDERMAN. *Adaptive exponential stabilization of a first order continuous-time system.*
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