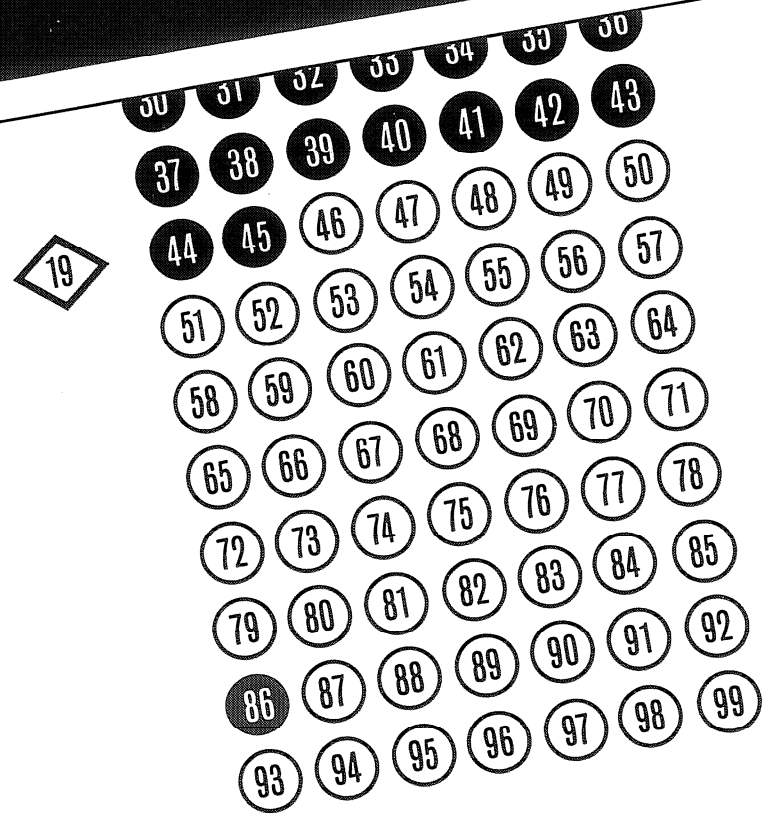
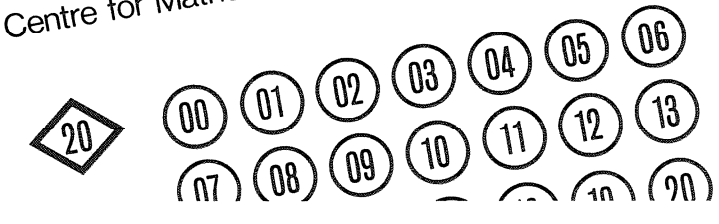
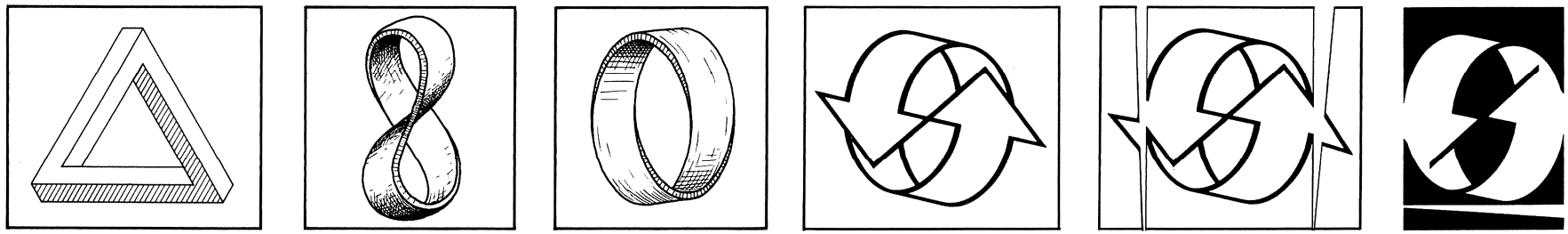
ANNUAL REPORT



Centrum voor Wiskunde en Informatica
Centre for Mathematics and Computer Science





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Centrum voor Wiskunde en Informatica
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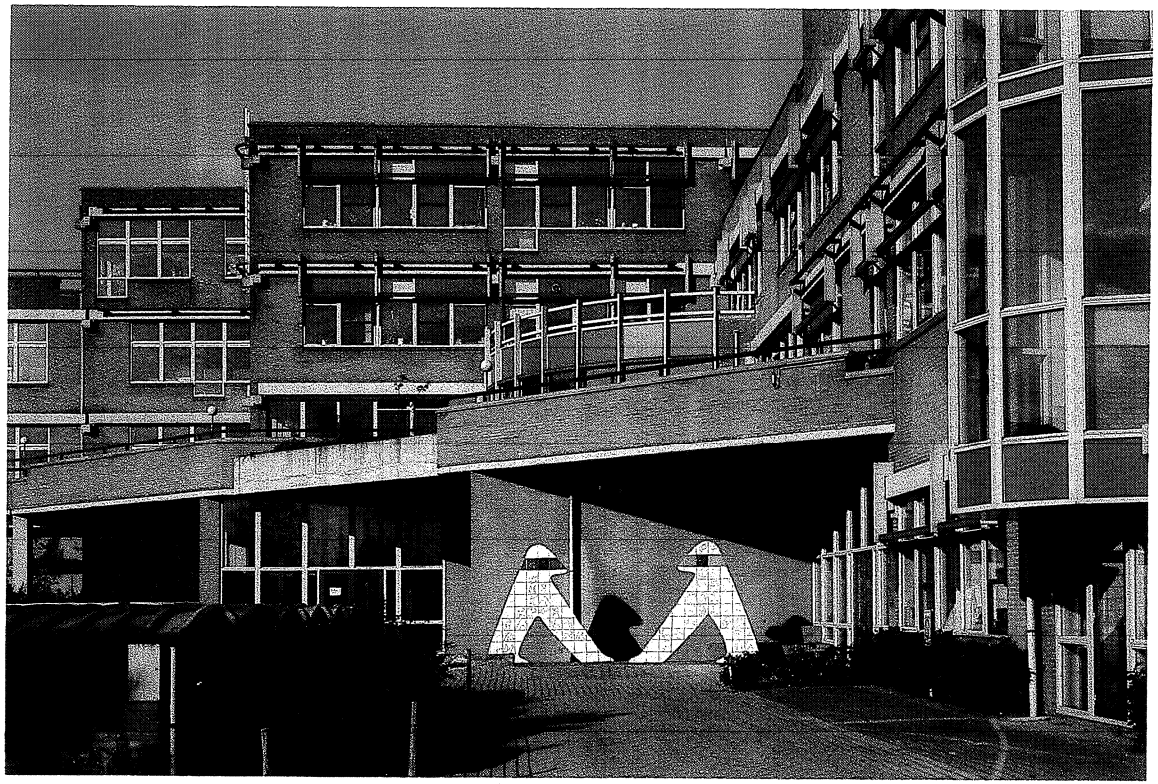

The Stichting Mathematisch Centrum was founded on february 11 1946, as non-profit institution aiming at the promotion of mathematics, computer science, and their applications. It is sponsored by the Dutch Government through the Netherlands Organization for the Advancement of Pure Research (ZWO).

Centre for Mathematics and Computer Science (CWI)

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Contents

Introduction

In 1986, the Centre for Mathematics and Computer Science (CWI) celebrated the 40th anniversary of its foundation, an event underlined by a number of special activities.
Ever since 1946, the Institute has first and foremost concentrated on basic research into mathematics and computer science - with equal emphasis on theory and application. The balanced development of the two scientific disciplines has been a priority from the very start.
A significant event during the year was the further expansion of the computer science research activities in line with CWI's 1985 development plan for this research. 1986 was also marked by the upgrading of research into mathematics and the interface between mathematics and computer science.

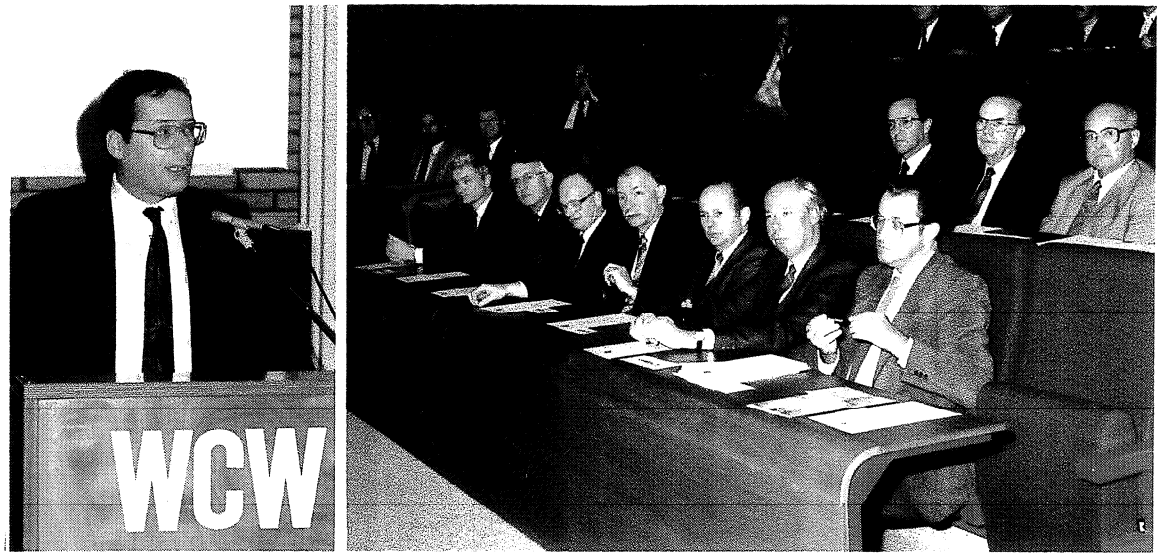
The titles of projects started or upgraded in 1986 and financed in the framework of The Netherlands Stimulation Programme for Computer Science illustrate the broad range of CWI research:

- Interactive planning methods;
- Analysis and control of information flows in networks;
- Vector algorithms;
- Interactive systems;
- Distributed operating systems;
- Distributed information systems;
- Expert systems and other aspects of artificial intelligence.

Unfortunately, the funds available were far from adequate for total realization of CWI's development plan. A delayed start had been foreseen for some projects. The shortfall meant a further postponement for two projects in particular: *Distributed Algorithms* and *Statistical Analysis of Images* - neither of which could be started in 1986. Other projects had to cope with a reduced budget. Regrettably these included *Expert Systems.* Perhaps most unfortunate of all was the delayed start to the strategically important *Statistical Analysis of Images.* Ironically, it is in this project that the synthesis between mathematics and computer science - a CWI speciality and at the very core of the institute's activities - comes into its own.

CWI researchers come from a multi-disciplinary background; mathematicians and computer scientists operate as a team. This combination puts the institute in a strong position offering as it does a broad approach to new developments. Increasing involvement in national and European projects, such as those sponsored by The Netherlands Foundation for the Technical Sciences (STW) and the ESPRIT and COST-11 programmes, is a logical progression.
CWI's capacity and potential are significantly reinforced by subsidies for these projects and additional grants from a variety of Dutch government programmes specifically promoting computer related research. It is regrettable that the institute's main source of finance, provided by The Netherlands Organization for the Advancement of Pure Research (ZWO), is insufficient to maintain the current rate of progress in the longer term.
Many of the externally financed projects were joint efforts with companies and (semi-)state bodies from home and abroad, including: Philips, PTT-DNL, BSO, NLR, Siemens, INRIA, Sema-Metra, Praxis, Karlsruhe University and NAG. Direct contacts with a number of companies were both renewed and strengthened. Shell showed its confidence in CWI by granting a number of basic research fellowships with particular relevance to the oil industry.
Research contracts were also signed with The Netherlands Organization for Applied Research TNO, and with IBM (in collaboration with the two Amsterdam Universities).
Among the many top level international contacts, special mention should be made of those with CWI's French and West German equivalents, INRIA and GMD.

In November 1986, the 'Frontiers in Information Technology' (FIT) organization was set up under CWI auspices to encourage international contacts in the field of information technology - in particular by organizing conferences on advanced aspects. Representatives from Dutch research, industry and government form FIT's steering body, the Permanent Board; prominent figures from the international information technology sector make up the Honorary Board. FIT's first event, a symposium on Intelligent Autonomous Systems, was held in December 1986.



In October IBM signed an agreement with the two Amsterdam universities and CWI, in the presence of the Minister for Education and Science Mr. W.J. Deetman. The agreement involves some thirty research and educational projects until 1990 using IBM material and personnel support. The alpha and gamma sectors in particular will profit from this agreement. Mr. Deetman welcomed this example of industrial participation in scientific education and research.

The output of a research body like CWI consists of more than just placing learned articles in scientific journals; the organization of conferences, colloquia and courses, book publishing, consultation and the training of researchers are also part of the job description.
Even so, 'Science and Industry' and 'Mathematics and Computer Science' were more than routine symposia marking, as they did, the Centre's 40th anniversary. As its title implies, the first targeted industry and government; the second offered fellow scientists an overview of post-1945 developments in our field and CWI's role therein.

During 1986, CWI also organized the 'International Seminar on Teletraffic Analysis and Computer Performance Evaluation' and three workshops:

- Geometries and Groups, finite and algebraic (with NATO support);
- Models for Physiologically Structured Populations (with support from ZWO, the Royal Netherlands Academy of Arts and Sciences and Leiden University);
- Making Distributed Systems Work (a SIGOPS workshop).

Among the many publications during 1986, special mention should be made of three monographs:

- *Mathematics and Computer Science,* containing the proceedings of a 1983 CWI symposium;
- *Mathematics and Computer Science II,* containing the papers presented at the symposium of the same name mentioned above;
- *The Numerical Solution of Volterra Equations* by H. Brunner and P.J. van der Houwen.

These titles put the needed momentum into the launch of a series of CWI monographs and made up for the hesitant start.

A. Schrijver's book, *Theory of Linear and Integer Programming,* was also published during the year. Another book, *The Dynamics of Physiologically Structured Populations* appeared under the joint editorship of J.A.J. Metz (Leiden University) and O. Diekmann.
A full publication list can be found at the end of this report.

The institute's function as a *Centre* for Mathematics and Computer Science was

In June the 40th anniversary of SMC was celebrated with a symposium 'Wetenschap in Bedrijf', which considered the relation between fundamental research in mathematics and computer science and its use in an industrial environment from a number of angles. Industrial speakers were Mr. F.C. Rauwenhoff, Chairman of the Senior Management Committee of Dutch Philips companies (left), and Mr. H.L. Beckers, Group Research Coordinator Royal Shell Group, Shell International Research Company (right).

reflected in a number of nation-wide colloquia organized during 1986. Such was the overwhelming response to 'Vector Software', that a follow-up colloquium is planned for autumn 1987 and CWI is to organize a course on the same subject.
Another colloquium, 'Image Processing: Theory and Practice', also attracted large numbers of researchers from the academic, technical and industrial sectors. The nature of the theme and the background of participants are both multi-disciplinary; this colloquium helped foster the essential close interdisciplinary contacts.

Using courses to share knowledge is nothing new to CWI. Vacation courses, bringing teachers up to date with the latest developments in mathematics, were among the earliest activities. Such was their success that these courses became a regular fixture. In 1986, Matrices provided the theme. CWI also organizes post-graduate courses such as 'Software Engineering', which has enjoyed a good response for a number of years. Other 1986 titles included 'Networks' and 'PROLOG'.

The following sections report in more detail on the various CWI activities in 1986. It is my sincere wish that the reader takes as much pleasure in reading this Annual Report as we had in composing it.

P.C. Baayen
Scientific Director CWI

Organization

The Centre for Mathematics and Computer Science (CWI) is the research institute of the Stichting Mathematisch Centrum (SMC), which was founded on 11th February 1946. SMC falls under The Netherlands Organization for the Advancement of Pure Research (ZWO), 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 ZWO 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:

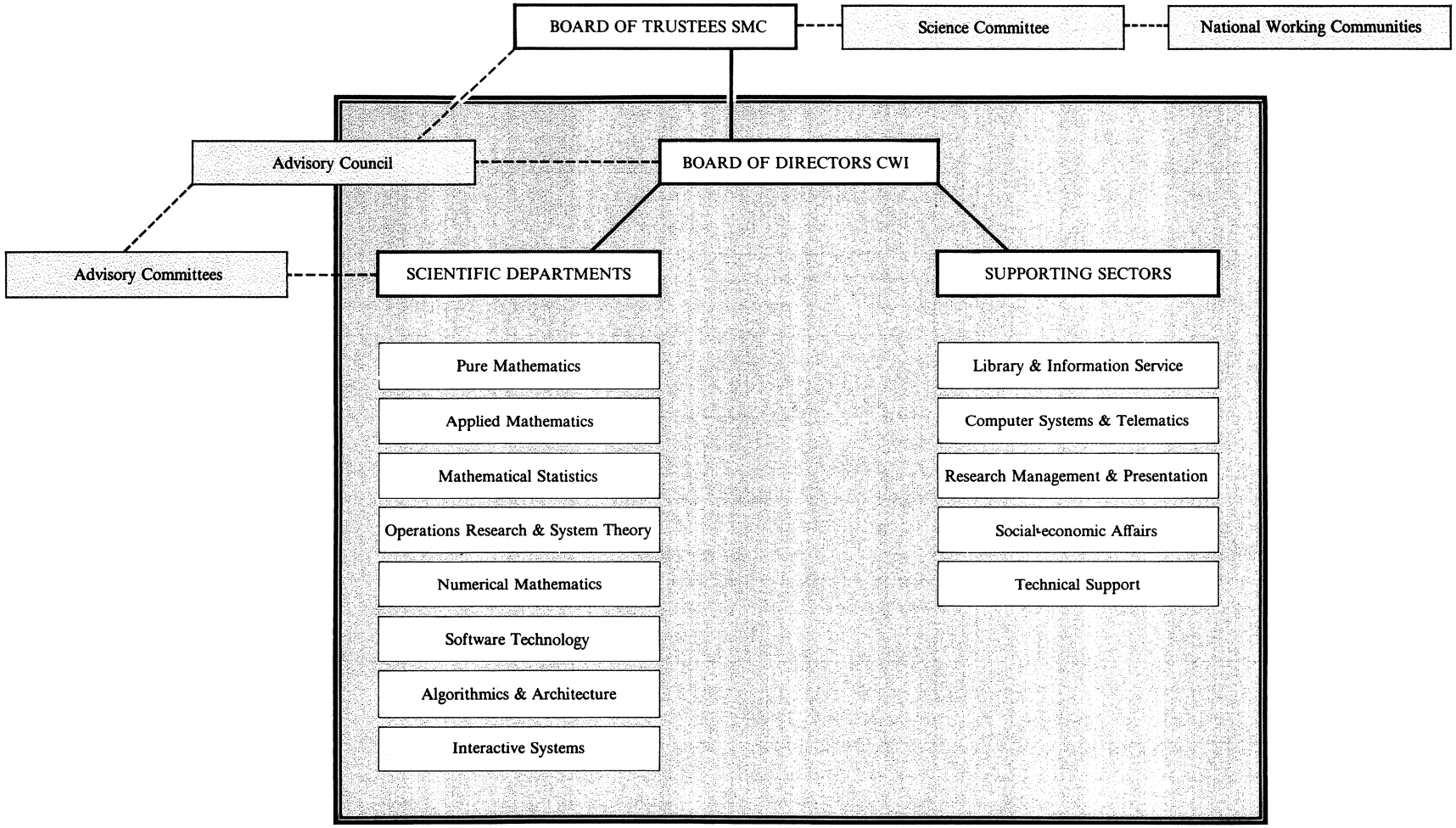
- Numerical mathematics;
- Stochastics;
- Discrete mathematics;
- Operations research and system theory;
- Analysis;
- Algebra and geometry;
- Logic and foundations of mathematics;
- Mathematical physics.

SMC is administered by a Board of Trustees, in which the Minister of Education and Science is represented. 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. An Advisory Council is being set up to advise the Boards of Trustees and Directors on general research policy and strategic decisions involving CWI. Members of this Council come from government, industry and university circles. 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.



Organization of the Centre for Mathematics and Computer Science.

Each Annual Report spotlights one particular CWI research topic. This year's contribution deals with concurrency.

CONCURRENCY

J.W. de Bakker (Department of Software Technology)

The study of distributed processing has become a central theme in computer science. The field is vast containing, amongst others, questions of complexity, parallelism and concurrency. The Department of Software Technology deals in particular with programming concepts for concurrency.

Whereas a *sequential* computation runs on one processor, a *parallel* computation assumes a number of processors which interact in a variety of ways depending upon the particular situation. At the macroscopic level, one often speaks of *distributed systems,* e.g. networks of computers or distributed databases. At the microscopic level, *parallel architectures* are the prime example, where sometimes thousands of - mostly identical - processors within one computer system cooperate in computations the organization of which is a major focus of current algorithmic research.

Mathematical modelling is substantially more difficult for concurrent programming concepts than for sequential ones. In a sequential programme the output depends only on the input, whereas in parallel programmes it also depends on the history of the processing, for which a structured representation of the intermediate actions and states is necessary. The following small case study illustrates the difficulties in defining meaningful semantics for parallel computations.

A sequential program S may, semantically, be seen as a function ϕ which transforms a given input state σ to an output state σ'. For example, the assignment $x:=x+1$ will change a state where x equals zero to a state where x equals one. Expressed in symbols this reads $[\![S]\!]=\phi\in\Sigma\rightarrow\Sigma$, or: the *meaning* $[\![S]\!]$ of S is a function ϕ from domain Σ to codomain Σ. Sequential composition $S_1; S_2$ (first perform S_1, then S_2) is modelled in a straightforward manner by the composition of functions. Inclusion of non-deterministic constructions in sequential programmes does not pose serious semantic problems. We simply enlarge the codomain Σ to the power set $\mathcal{P}(\Sigma)$, i.e. the collection of all subsets of Σ. Suppose that, for example, at a certain stage of the execution there is a choice between two programmes S_1 and S_2 to follow, expressed by the symbol $S_1 \square S_2$, then we can model its meaning $[\![S_1 \square S_2]\!]$ by the function $\lambda\sigma.([\![S_1]\!](\sigma)\cup[\![S_2]\!](\sigma))$, where the two operands of the set union '$\cup$' in this function are elements of the power set $\mathcal{P}(\Sigma)$.

We encounter an essential difficulty when extending this approach to the language construct $S_1 \| S_2$, standing for the parallel execution of S_1 and S_2 - here and often elsewhere taken in the sense of the arbitrary interleaving of the elementary ('atomic') actions making up S_1 and S_2. There is no immediate mathematical operator modelling the programming notion of parallel execution, and in the semantic research one takes various ways out.

One method (only a partial solution) is not to view programmes as state transformations, but to describe them on a higher level of abstraction in terms of 'atomic' or uninterpreted actions only. In this description the assignment $x:=x+1$ is viewed as an 'atom', without any inner structure. Models of this kind consist of sets of sequences or tree-like structures composed of atomic building blocks. They have a strong flavour of formal language theory and sequences of atomic actions are eminently suited to undergo the 'merge' operation, contrary to the case for (state transforming) functions.

A second method, which we have advocated for some time, is to introduce a domain P of so-called processes p as solution of the equation

$$P = \{p_0\} \cup (\Sigma \rightarrow \mathcal{P}_{\text{closed}}(\Sigma \times P))$$

We can read this equation as follows: any process p belonging to P is either the 'nil process' p_0, which cannot take any action, or is a function, and it makes good sense to write $<\sigma',p'>\in p(\sigma)$: process p, for input state σ, yields output state σ' *together with* the so-called *resumption* p' (a concept put forward

Logo of the Dutch National Concurrency Project

by Plotkin). From the equation it can be seen that the processes belonging to its solution have a structure which combines features of sequences ($\Sigma \times \mathcal{P}$), sets ($\mathcal{P}_{\text{closed}}(...)$) and functions ($\Sigma \rightarrow \cdots$). It now turns out that the semantic operators . (composition), $\cup$ (union) and $\|$ (parallel) can all be defined satisfactorily. This allows us to write down equations such as $[\![S_1 \| S_2]\!] = [\![S_1]\!] \| [\![S_2]\!]$. Many more details of this style of semantic definitions can be found in [2].

The CWI concurrency project emphasizes *languages* for parallelism and, more specifically, formal models for parallel programming concepts. The project participates in two collaborative efforts: ESPRIT project 415 and the Dutch National Concurrency Project.

ESPRIT is the European Strategic Programme for Research and Development in Information Technology. In project 415, six major European industries, with Philips as prime contractor, work together on 'Parallel Architectures and Languages for Advanced Information Processing: a VLSI Directed Approach'. Six sub-projects investigate parallel architectures based on a variety of parallel programming styles, e.g. object oriented, functional and dataflow, and logic programming. Their activities in the areas of Semantics and Proof Techniques, and of Architecture and Applications are integrated in two working groups. CWI participates in the mathematical modelling of the Parallel Object Oriented Language (POOL), developed by Philips as conceptual starting point for the architectural design of its Distributed Object Oriented Machine (DOOM). So far, we have jointly designed an operational and denotational semantics for POOL [1], [2], and made initial steps towards the design of a proof theory. CWI is also active in the Working Group on Semantics and Proof Techniques.

The Dutch National Concurrency Project (LPC) has been operative since the beginning of 1984, and is primarily sponsored by the Research Foundation for Computer Science (SION). The project concentrates on syntactic, semantic and proof theoretic aspects of concurrency. CWI researches the semantics of non-deterministic dataflow, a computational model which underlies an important branch of contemporary research in parallel architectures. A recent achievement was the design of a 'fully abstract' mathematical model, in which an observer of the behaviour of a dataflow net sees the right level of detail. LPC is also involved in a variety of organizational activities. One of these is a formalized contact with two other national programmes: the French C^3 programme (Cooperation, Concurrency and Communication) and the British Alvey programme (chapter Formal Aspects of Computer Science).

Alongside work in these projects CWI also researches the foundations of concurrency semantics in cooperation with a number of universities (VU Amsterdam, Kiel and SUNY at Buffalo, see [3] for an overview). The *metric process theory* developed jointly with J.I. Zucker (SUNY) proved to be a very useful tool for our denotational semantics for POOL, and is now also being applied to the assessment of various models for the new programming notion of *process creation.* Attempts are also being made to unify and interrelate semantic models for *logic programming.*

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2. Idem (1986). *A denotational semantics for a parallel object-oriented language,* Report CS-R8626, CWI Amsterdam.
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Department of Pure Mathematics

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J.T.M. van Bon
A.E. Brouwer
D. Chaum
A.M. Cohen
J.H. Evertse
J.A.M. van de Graaf
T.H. Koornwinder
J. van de Lune
J.C. van der Meer
S.N.M. Ruijsenaars
G.C.M. Ruitenburg
J.K. Scholma
J. de Vries

The last decennia have shown an integration of various branches of science, which hardly touched each other in the past. The same is true of mathematics where a strong interaction between specialisms also got under way - with occasionally surprising results. An example is the interaction between stochastics and computer science. Purely mathematical problem areas frequently emerged from concrete questions. This mathematics often turns out to be relevant for the original - or another - application area. A fine example is found in gauge theories (arising in connection with particle physics) and its related differential topology and algebraic geometry (research in this area won a Fields Medal in 1986). Another striking development is the increasing interest in purely mathematical research by physicists, chemists and engineers.
Departmental subjects are chosen for their interesting connections with other areas in mathematics. In particular the notion of symmetry - its exploration and description in all kinds of situations - plays a central role in this choice. The importance of contacts with computer science - e.g. in cryptography - goes without saying.

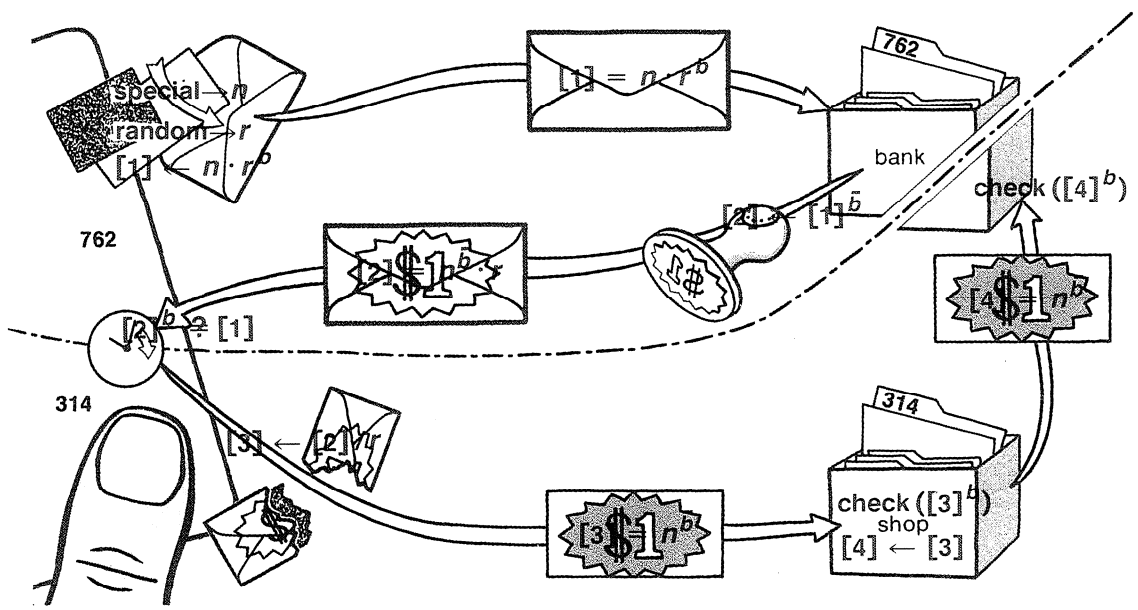
The current research projects are:

- Discrete mathematics (Van Bon, Brouwer, Cohen);
- Cryptography (Den Boer, Chaum, Evertse, Van de Graaf);
- Analysis (Koornwinder, Van de Lune, Ruitenburg);
- Algebraic mathematical physics (Hazewinkel, Van der Meer, Ruijsenaars, Scholma);
- Dynamical systems (De Vries).

Discrete mathematics
During recent years CWI research into discrete mathematics has focused on graph theory and finite groups. Brouwer, Cohen and Neumaier's book *Distance Regular Graphs* nears completion. The far reaching expertise developed by the department in the field of Lie-type and diagram-type geometries was applied to determination of maximal subgroups of certain Lie-type groups and of finite subgroups of Lie groups. Particular attention was given to finite quasi-simple subgroups of E_8, the 27-dimensional module of $E_6(q)$, groups of exceptional Lie-type and the covariant algebra of $SL(2,C)$.

Cryptography
In cryptography, mathematical techniques are developed to protect the transmission of confidential data against tapping or falsification. The need for such a protection will greatly increase (e.g. in electronic payment systems) with the advent of distributed computer systems. CWI research concentrated on the development of certain protocols. The 'credential mechanism' protocol is based on the well-known RSA-system, which uses the practical impossibility to factorize very large numbers. Its goal is to protect personal data as well as an organization's security interest, where there is exchange of data on individuals. A generally applicable credential mechanism was developed, which comes very close to this goal. Other research dealt with 'zero information' protocols, where one party proves to the other that it possesses a secret, without revealing information about it. Finally, an implementation in the programming language C was made of an electronic payment system developed at CWI.

Analysis, in particular on Lie groups
The main goal of this project is harmonic



Untraceable electronic cash is illustrated by an analogy to envelopes and carbon paper. The individual seals a blank slip of paper and a facing piece of carbon paper in an envelope, and supplies it to the bank. The bank deducts one dollar from the individual's account, applies a 'worth one dollar' signature (stamp) to the outside of the envelope, and returns the unopened envelope to the individual. The individual verifies the signature and removes the envelope and carbon, leaving only the signed slip of paper. When the shop receives the slip as payment, it verifies the carbon image of the validating signature on the slip, and supplies it to the bank for deposit. When it too has verified the slip's validating signature, the bank honours the deposit knowing the slip must have been in an envelope it (the bank) signed. The bank does not, however, know which of the many envelopes it signed contained the slip, and thus the bank cannot trace it to the individual's account, unless the individual wishes it to be traced. The mathematical notation superimposed above shows how the system could be realized using personal card computers and the RSA public key crypto-system. It is a rather special case of a credential mechanism, the first practical examples of which were put forward in 1986 by CWI. These are quite flexible, highly secure, and, like the payment system, can be proven to protect privacy optimally - even against infinite computing resources.

analysis on symmetric spaces connected with semisimple Lie groups, in particular in relation to special functions; the various problems of a number theoretic nature are also covered.

Work has been done on the group theoretical interpretation of Askey's tableau of hypergeometric orthogonal polynomials. This involved replacement of the independent variable by a differential operator or by an element from the universal enveloping algebra of a special semisimple Lie algebra. Furthermore, Askey's tableau was extended to orthogonal systems of hypergeometric functions. The study of orthogonal systems associated with root systems continued in close collaboration with Leiden University. Product formulas for generalized Jacobi polynomials were also developed. Attention was also paid to various smaller subjects, such as: irreducibility of polynomials in connection with polylogarithms; k-modal polynomials; convex polygons on lattices; and the zeros of 'arbitrary' sections of the series $\Sigma_n n^{-s}$ (the Riemann zeta function). Lastly, a syllabus on Tauber theorems was completed.

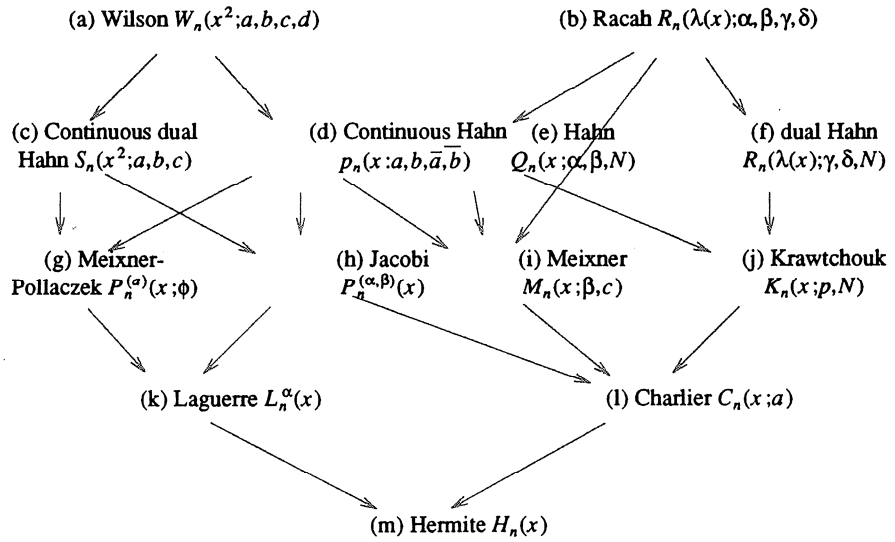
Algebraic mathematical physics

The research in this field involves completely integrable Hamiltonian systems (quantum as well as classical), exactly solvable lattice models in statistical mechanics and related problems in gauge and representation theories. Some examples of completely integrable systems are: Toda lattices (chains of springs with nonlinear interactions), Korte-

weg-De Vries equations for shallow water waves, the self-dual Yang-Mills equation used in particle physics, and some twenty other equations, many of which have important applications. Among exactly solvable lattice models are the hard hexagon and the Ising models.
Normal forms for Hamiltonian systems (a normal form is an approximation of a system with some degree of symmetry which is possibly integrable) were studied as were a new class of integrable N-particle systems (quantum and classical) which form the relativistic generalization of the Calogero-Moser systems. A literature study was made of the still unsolved problems in the quantum context. These problems are related to the theory of spherical Fourier transforms on symmetric spaces. Finally, research was initiated to find a method of constructing lattice invariants of classical integrable continuum models. This work is connected with the so-called classical and quantum inverse scattering method of the Leningrad school.

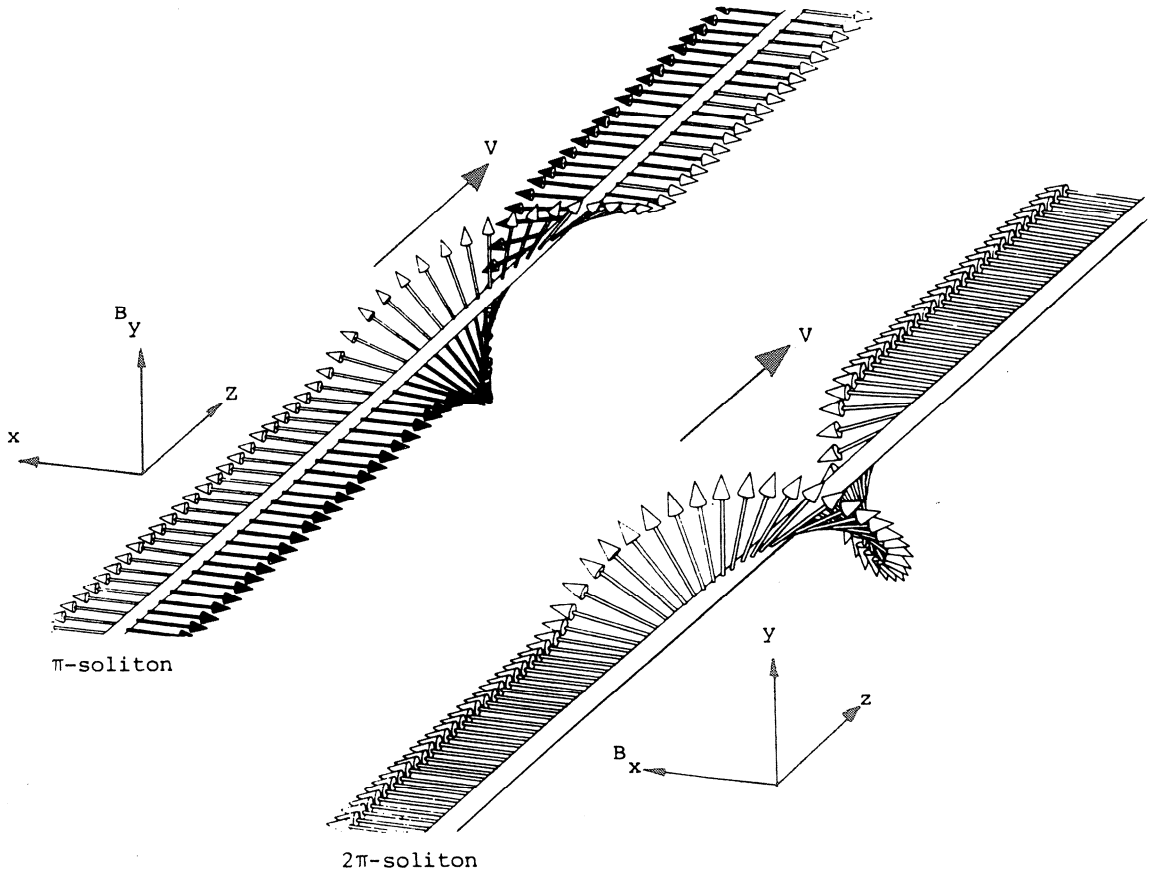
Dynamical systems
At CWI, the emphasis lies on topological dynamics and ergodic theory. The theory of dynamical systems concerns groups or semigroups of mappings of a space into itself. This space can represent a physical system and the mappings its transitions from one state to another. Topological dynamics involves the study of topological transformation groups, whereas ergodic theory deals with measure conserving transformations in measure spaces. These subjects are of considerable importance for all phenomena where nonlinear aspects of differential equations become manifest, e.g. bifurcation and strange attractors.

Considerable attention was given to the construction of - preferably simple - examples and counter examples in connection with the composition of the book *Elements of Topologi-*



The Askey scheme of classical hypergeometric orthogonal polynomials.

Originally, only the Jacobi, Laguerre and Hermite polynomials were considered as classical. A slight relaxation of the properties required in order to be classical, has increased the number of families deserving this name considerably. The arrows in the scheme denote limit transitions. The families at the left hand side are orthogonal with respect to a continuous weight function, those on the right hand side are discrete orthogonal polynomials. The polynomials on top have the most complicated hypergeometric type: ${}_4F_3$. CWI's department of Pure Mathematics has given group theoretic interpretations of the Askey scheme and its extensions to generalized orthogonal systems of hypergeometric functions (not necessarily polynomials).



The research on completely integrable Hamiltonian systems gained considerable impetus by the phenomenon of 'solitons': travelling waves which retain their shape while travelling and with remarkable stability properties. The study of solitons led to exact solutions of various physically important nonlinear equations, e.g. the Korteweg-De Vries, cubic Schrödinger and sine-Gordon equations. The soliton phenomenon plays an important role in the hitherto unsolved problem of determining whether a given system is (completely) integrable. The illustration (J.F. Kaashoek, Erasmus University Rotterdam 1983) shows two soliton solutions to the sine-Gordon equation $\phi_{zz} - \phi_{tt} = \omega_0^2 \sin\phi$, *in an application to magnetic systems.*

cal Dynamics (they appear almost nonexistent in the literature). Research into certain product conserving functors (resembling reflections) was completed. Application of the results to compactifications of semigroups will be published in 1987. Preliminary literature study was carried out in anticipation of a possible future research in ergodic theory.

Last, but not least, several departmental researchers provided expert advice for the translation of the Russian Encyclopaedia of Mathematics.

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Broadly speaking, applied mathematics has the task of winning more insight into natural processes by mathematical analysis. Until recently this was mainly linear analysis, but nowadays attention is focused on nonlinear problems. For example, recent theoretical developments in bifurcation theory and chaotic phenomena, in combination with the strongly increased possibilities of performing computer experiments, have led to a new appreciation of fluid mechanics. The Department emphasizes the development of new analytic methods, with an increasing input from statistics and computer science. The application areas lie in biology, medicine and meteorology, in fields where classical methods are loosing their usefulness.

The current research projects are:

- Dynamical systems with stochastic perturbations (Grasman, De Kerf, Roerdink, Roozen, De Swart);
- Asymptotics and applied analysis (Dijkhuis, Grasman, Temme);
- Nonlinear analysis and biomathematics (Diekmann, Heijmans, Heesterbeek, De Kerf, Lauwerier, Metz);
- Processing and reconstruction of images (Heijmans, Van Herwijnen, Roerdink, Temme).

Dynamical systems with stochastic perturbations

Many models of natural phenomena are deterministic, finite-dimensional and dissipative in character. Their long-time behaviour is of particular interest. These models ignore external influences, which cannot be described deterministically. Inclusion of such influences as stochastic perturbations in the model leads to essential changes in the behaviour of the solutions. CWI studies two such systems in the field of meteorology and biology.
Two 'spectral' models of the large-scale atmospheric circulation have been investigated. The most elaborate of them, a ten component barotropic model, exhibits a number of preferential states in phase space, between which the system can make transitions. The finite predictability of such chaotic systems was analyzed. It turned out that the stochastic structure cannot be parametrized in a simple way.
In the field of population dynamics a density dependent birth-death process was studied by means of a two-dimensional stochastic system which forms the diffusion approximation of the process. Expressions were derived for the stochastic stability of the ecosystem using asymptotic methods. Finally, a joint project was initiated with Prof. K.E. Shuler (USCD La Jolla, USA); research involves the difficult task of calculating numerically large time parameters such as diffusion constants and is based on a previously developed theory of stochastic walks on inhomogeneous random lattices.

Asymptotics and applied analysis

For many physical or biological problems, asymptotic methods are an important means to gain qualitative information on solutions of equations or to find approximations for solutions. In recent years the Department has acquired considerable expertise in dealing with asymptotic problems; this has given rise to internal (CWI) and external demand for problem solving in the fields of complex analysis, integrals, and differential equations.
The asymptotics of Laguerre polynomials $L_n^{(\alpha)}(x)$ were studied for large values of the degree. New developments were given where the parameter α can also be arbitrarily large,

Participants in the international workshop 'Models for physiologically structured populations' enjoy a stroll along the beach of Texel island.

in which case a Hermite polynomial is a good asymptotic representation. A chapter on chaotic and stochastic relaxation oscillations was completed for a monograph on asymptotics of integrals, and a monograph on relaxation oscillations in general was submitted to a publisher.

The structure of residual currents in a rectangular tidal basin was investigated as a two-parameter model, in collaboration with Prof. J.T.F. Zimmerman (Netherlands Institute for Sea Research (NIOZ) and Utrecht University). There turned out to be two distinct regimes. An approximate technique was developed for calculating the residual current for strong self-interaction.

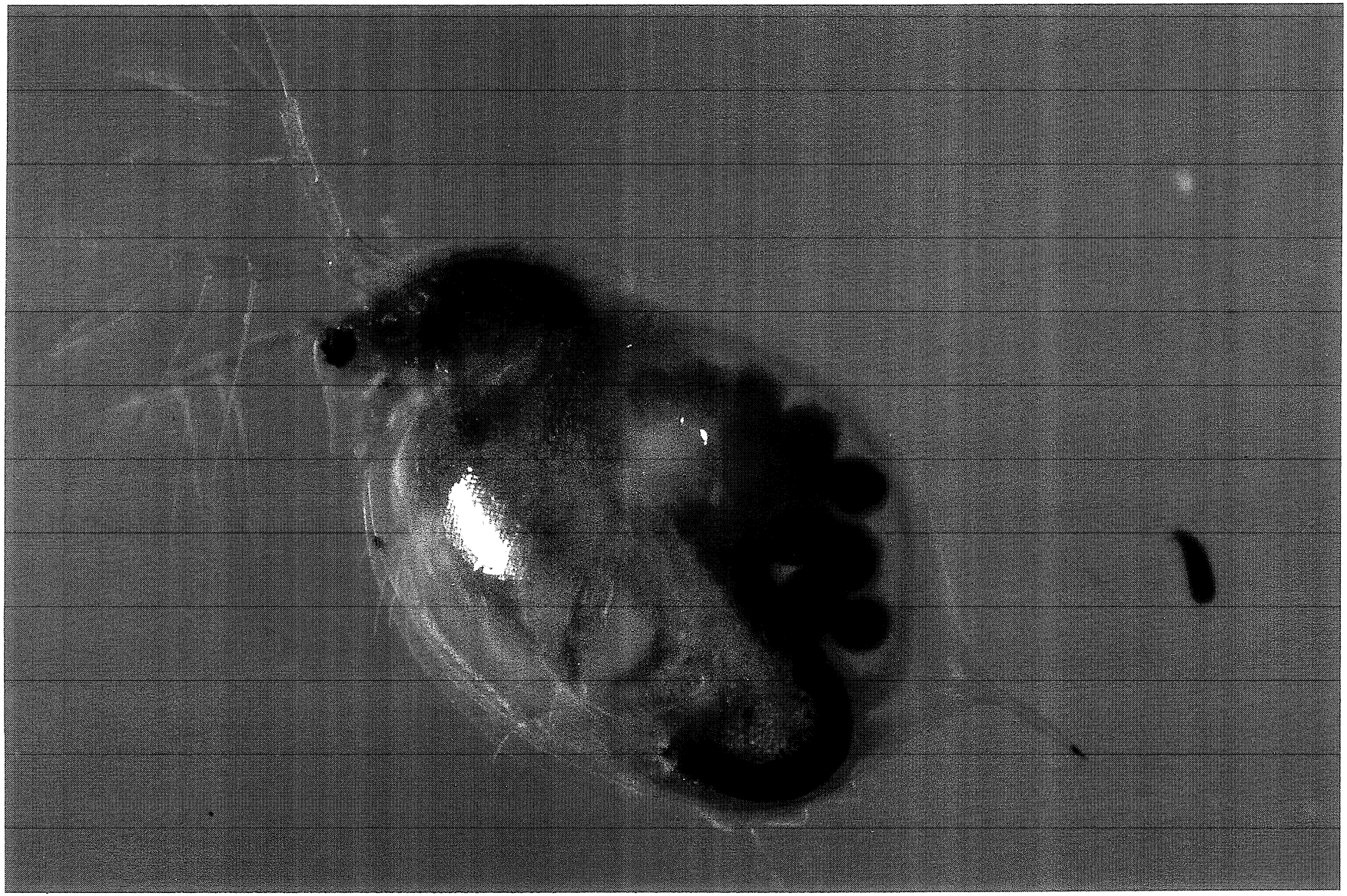
If soluble material is injected into a streaming fluid (e.g. drainage into a river), there is considerable difference between initial and eventual diffusion patterns. Analytic approximations for intermediate time scales are being studied in a simple model of Poiseuille flow in an infinitely long cylinder. The model is described by a Schrödinger equation for the harmonic oscillator on a circular disk. The dependence of eigenvalues and eigenfunctions on the oscillator strength is investigated.

Nonlinear analysis and biomathematics

Central theme in this project is the dynamics of populations with an internal, physiological structure. Its description via equations relates the course of life of individuals to the development of the population. In this way biological knowledge can generate a detailed description of the interaction between the population and its environment. Concrete applications are found in epidemiology and toxicology. There is no satisfactory mathematical theory for dealing with such models. This project aims at developing such a theory, by studying infinite-dimensional dynamical systems.

A review of the existing theory, along with a number of applications, was given in *The Dynamics of Physiologically Structured Populations* (Springer Lecture Notes in Biomathematics 68, J.A.J. Metz & O. Diekmann editors), which appeared in August. In September, an international workshop 'Models for physiologically structured populations' was held at NIOZ. Participant's background varied from pure mathematics to experimental biology. Other research topics in this field were: justification of model approximations by the Trotter-Kato theorem, and mathematical aspects of the Daphnia model.

The mathematical research focussed on per-



turbation theory of dual semigroups. The sun-reflexive case was studied and applied to functional differential equations, and turned out to be useful in control problems as well. A survey was also given of results relating to the structure of the resolvent operator of linear functional differential equations. Finally, work was done on certain degenerate first-order partial differential equations, on extending a singular perturbation theorem by Tykhonov to certain infinite-dimensional systems, and on a coupled system of differential and difference equations in connection with the dynamics of an epidemic model.

< *Female waterflea (Daphnia magna) with eggs. This Daphnia species is used as an experimental animal to study effects of toxic chemicals on individuals. The theory of dynamics of physiologically structured populations, as described in Metz & Diekmann's book, can be used to deduce the population consequences of these effects, under environmental conditions differing from those in the experiment. In the case of linear models, the key concept is that of a stable distribution. The spectral theory of positive semigroups is very useful in deriving results about these stable distributions. The mathematical machinery necessary to deal with nonlinear models is still in its early stages, and its creation requires the solution of many interesting mathematical problems.*

Photo S.A.L.M. Kooijman, VU Amsterdam

Research on iterative maps, Julia sets and fractals continued. A joint study with J.A.J. Metz (Leiden University) considered a host-parasitoid model. Another paper discussed the structure of the strange attractor in a model described in terms of elementary functions.

Processing and reconstruction of images

This is a joint project with the Department of Mathematical Statistics. Image processing consists of manipulation with data available in image form. In digitalized form, they can be processed by a computer. Various actions can be performed on the images: transformation, coding, restauration, correction, segmentation, and analysis. In many cases statistical techniques are applied, in particular in segmentation and in the reconstruction of images distorted by noise. Another important technique is computer tomography, the reconstruction of images from a finite number of projections. Applications of the research in this project are mainly found in medical diagnostics, biomedical research, remote sensing and inverse scattering.

In the first phase of this new project a broad orientation was carried out with emphasis on mathematical morphology. During the autumn, a national colloquium 'Image analysis: Theory and Practice', was organized at CWI. Both mathematical aspects and applications were treated by various CWI and outside speakers in this series of meetings. The colloquium offered excellent opportunities for establishing the closer contacts between various researchers from scientific, technical and industrial circles - considered essential in such a multi-disciplinary research field. At the end of 1986 a research plan was formulated, at present the main subjects to be:

- reconstruction of NMR-images (collaboration with Philips Medical Systems);
- mathematical morphology;
- inverse scattering and image processing of seismic data (collaboration with Shell).

Department of Mathematical Statistics

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The effects of two major current developments in mathematical statistics are clearly discernable: firstly an ongoing spread of application in a broad range of scientific disciplines including psychometrics, econometry, demography and epidemiology; and secondly use of such new computer science tools as image processing techniques. The ever more complex data available across the board of scientific, industrial and social enquiry were matched by an explosive growth in potential for computer application making it possible to analyse far more realistic models. CWI's mathematical research centres on statistics in cases where parameters or data are not in a finite-dimensional Euclidean space, but in sets with a far more complicated structure. The abstract spaces occurring in it prompted Grenander to term this field 'abstract inference'. The department's research is, however, far from abstract. It is directed at the most urgent practical problems of applied statistics. At the same time it continues recent developments in theoretical, statistics - in particular the convergence of parametric and non-parametric statistics. Attention is paid both to the process of hypothesis forming and model building and to those activities occurring within an already precisely formulated model. This is reflected in research and consultation in such areas as bootstrap methods and semiparametric models.

The current research projects are:

- Semiparametric statistics (Ter Burg, Dekkers, Dzhaparidze, Gill, Heesterman, Helmers);
- Stochastic processes (Berbee, Corstjens, Dzhaparidze, Gill, Groeneboom, Van der Plas, Weits);
- Applied statistics (Berbee, Van de Geer, Gill, De Haan, Rottschäfer, Verbeek, Voors).

Semiparametric statistics

Semiparametric models have become highly popular in several application fields, e.g. biostatistics. The idea is to combine the advantages of parametric estimation theory and non-parametric test theory, by using parametric modeling only for those parts of a phenomenon which are of special interest. A theory has gradually emerged which characterizes the optimal asymptotic behaviour of estimators in semiparametric models. The aims of this project are to construct statistical procedures and to derive their properties for semiparametric models, as well in general to apply techniques from parametric statistics in non-parametric models, in particular estimation theory.

Local Asymptotic Normality (LAN) results were used in the current study on properties of the Cox estimator for the intensity parameter of a multivariate counting process. A report on the study was made to the First World Congress of the Bernoulli Society (Tashkent, USSR). It was shown that some non-parametric maximum likelihood estimators are differentiable functionals of the empirical distribution function so that their asymptotic distribution can be derived by Von Mises calculus. These results were reported at the Statistische Tagen (Heidelberg, West Germany) and the Von Mises & NPMLE seminar (Leiden, The Netherlands). Random samples - from an unknown distribution, weighed in a known way - are combined in the model of 'selection bias' in collaboration with J.A. Wellner (Seattle, USA); and a joint study of non-parametric mixture models was started with T.A. Louis of Harvard.

An article and report were written jointly with The Netherlands Interuniversity Demographic Institute on the statistical analysis of observations on a Markov process aggregated over time and individuals. Up until now such data were studied via ad hoc interpolation methods, occasionally leading to probabilities outside the interval [0,1]. Work continued with P.K. Andersen and N. Keiding (Copenhagen) and O. Ø. Borgan (Oslo) on the book *Statistical Models for Counting Processes.* The department is preparing a joint review article concerning product integrals frequently applied in survival analysis and the statistical analysis of Markov and counting processes. A joint study was started with N. Keiding on the model of left truncated data which showed up recently in connection with star brightness measurements. There are similarities, but also differences, with the analysis of censured data. It transpired that a simple analysis with counting process methods is possible, if the model is equivalent to a certain Markov process. The application of new methods for the analysis of survival times in Dutch epidemiologic research was studied during meetings with epidemiologists from the Netherlands Institute for Public Health and Environmental Hygiene. These methods combine prospective and retrospective data.

Reports on research concerning the asymptotic properties of bootstrap estimators of the distribution function of 'studentized' statistical quantities were given at the Sixth Pannonian Symposium on Mathematical Statistics (Bad Tatzmannsdorf, Austria) and a workshop on Capitalization on Chance and Sample Reuse Methods (Groningen, The Netherlands). Differences between three estimation methods (jackknife, bootstrap and delta) in terms of the bias and variance of the estimators were analyzed by second order expansions.

A report appeared in collaboration with A.J. Van Es (University of Amsterdam) on the asymptotic behaviour of elementary symmetric polynomials. The joint study with F.H. Ruymgaart (University of Nijmegen) on asymptotic normality of generalized *L*-statistics with unbounded weight functions was completed. The results will appear in the *Journal of Statistical Planning and Inference,* as will earlier research on Edgeworth expansions for functions of uniform spacings.

New research was started on the asymptotic properties of the Picklands estimator for the main parameter of the generalized extreme value distribution. Weak and strong consistency could be shown for this estimator. The problem of estimating the extremal index θ of a stationary series of stochastic quantities was studied and possible applications of bootstrap methods in the theory of extremal values explored.

Stochastic processes

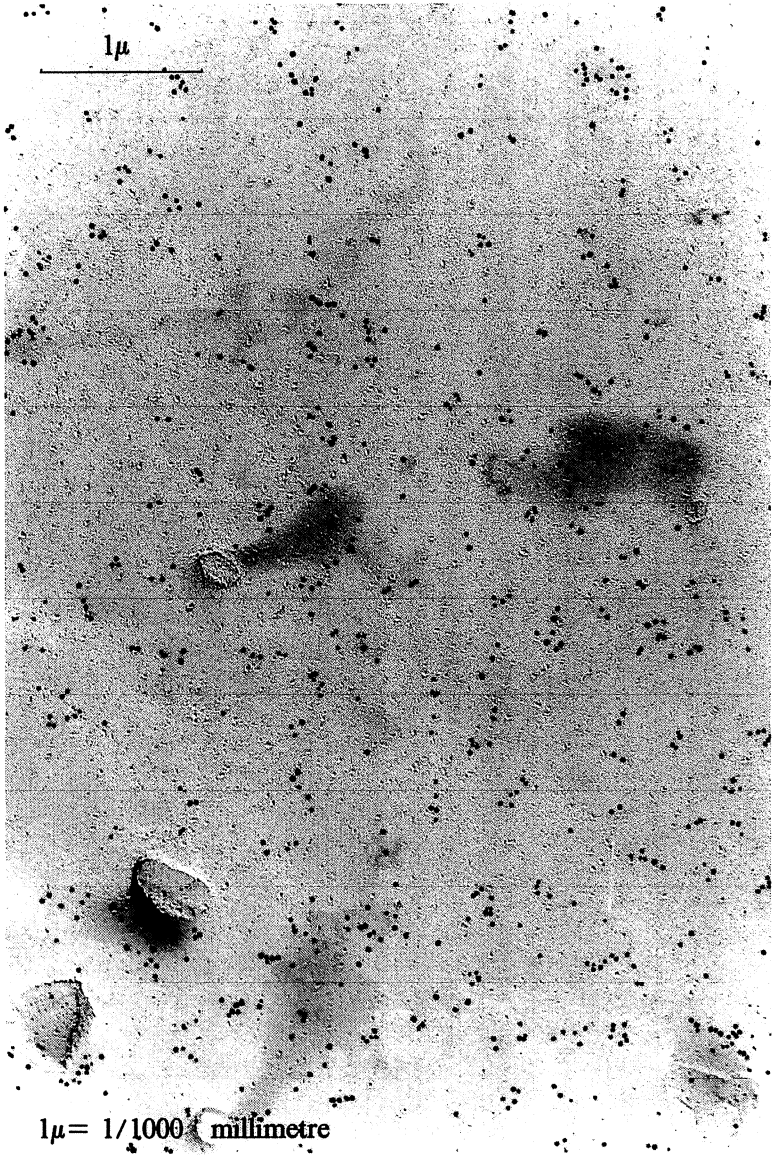
This project emphasizes processes in space and time, in particular the class of functionals on a Markov-dependent process. The study employs the physical description of processes by 'interaction'. A second aspect is the statistical analysis of stochastic processes, in particular the extension of classical methods to counting processes, time series, etc., the study of Markov processes by projection of estimator functions, and modelling by stochastic processes of traffic streams.

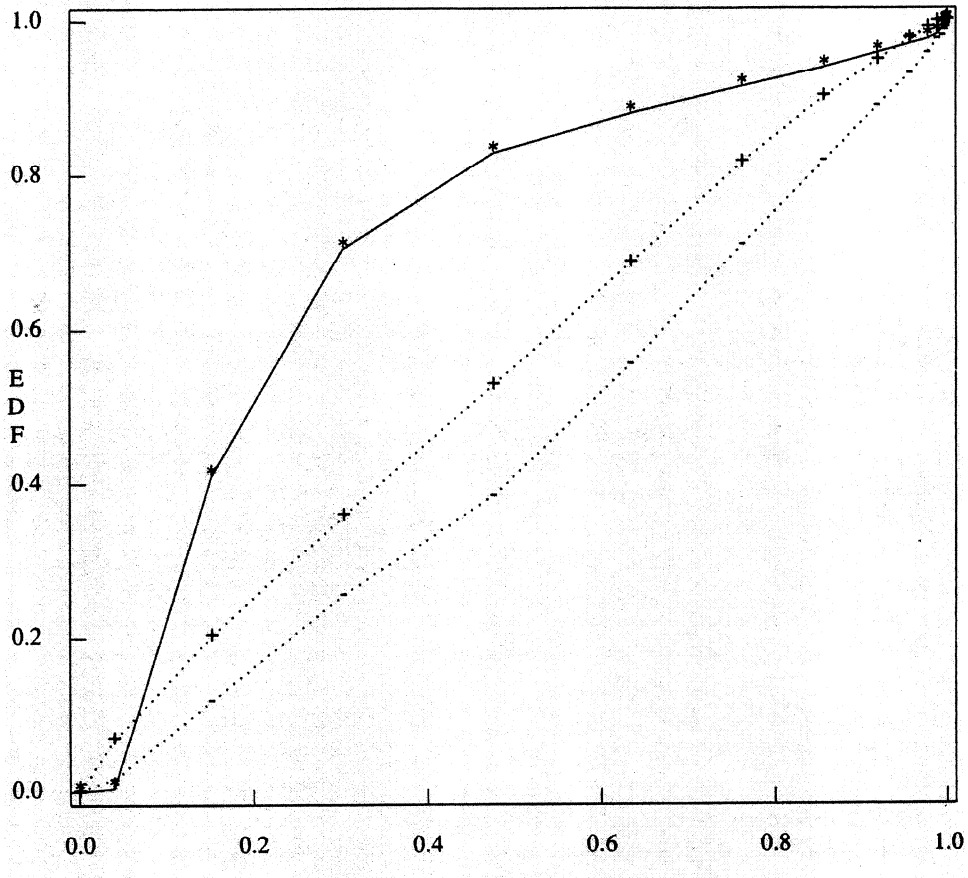
The uniqueness of Gibbs measures in statistical mechanics was related to absorption probabilities of a series of Markov operators associated with this measure. Applied to one-dimensional systems it improves one of Ruelle's results (1968). Attention was paid to computer networks in connection with a study of Markov representations for stationary processes.

The work on evaluating probabilities of general *M*-estimators in the case of large deviations was applied to nonlinear regression analysis and will be published in *Annals of Statistics.* Identification has been established in the area of estimating the intensity between two aggregate transient states of a multivariate counting process. However, finding a good estimation method remains problematic. The emergence of a stationary state is studied in macroscopic models of traffic flow, based on wave equations with 'white noise'. Technically the problem is formulated as a stochastic differential equation in an infinite-dimensional space. Studies were made of recurrent patterns in Markov-dependent chains starting from research on the behaviour of rats.

Applied statistics

The aim of this project is to enrich mathemat-





Simulation average

ical statistics through new impulses from practical problems and, conversely, to make the results of theoretical research available to users of statistics in other areas. The current topics are: breakpoint methods, stochastic models in biology, image analysis (joint project with the Department of Applied Mathematics), and statistical software.

Polypeptide growth factors play an important role in the regulation of cellular proliferation and differentiation. One of the most intensively studied among them, the Epidermal Growth Factor (EGF), binds to specific receptor proteins on the cell surface. The lateral distribution of EGF receptors, in particular their clustering, is related to the cellular response to EGF. This distribution can be studied by the so-called label fracture method, in combination with immunogold labeling of the EGF-receptors. In the picture - an electron micrograph taken at the Hubrecht Laboratory for Developmental Biology in Utrecht - the black dots correspond to gold particles attached to A431 cells.

At CWI a statistical analysis of such pictures is being made, in order to model and quantify such clustering effects. The first results indicate clear clustering, as can be seen in an EDF-plot (EDF = Empirical Distribution Function) of nearest neighbour distances, where the deviation of the solid line from the region between the two dotted lines (the reliability band of the simulation) measures the deviation from Complete Spatial Randomness.

Two reports appeared giving the results of research on breakpoint methods, concerning the extension of the two-phase model to the multi-dimensional model. Sections will appear in *Annals of Statistics*. A program was written for the estimation of parameters in a two-phase regression model.

A compartment model for the behaviour of algae was developed in collaboration with A. Tip (AMOLF, Amsterdam) and R. Dernats (University of Amsterdam).

The project on statistical analysis of images (see also the report of the Department of Applied Mathematics) started with a working group; outside participation came from computer scientists from University of Amsterdam and statisticians from TNO, the Free University of Amsterdam and the University of Nijmegen. A thorough literature study concentrated on *Image Analysis and Mathematical Morphology* by J. Serra, and the recent exciting contributions made by D. Geman and S. Geman (Brown University, USA) and J. Besag (Durham, UK) on the application of Markov field models to image reconstruction.

A statistical analysis was started of electron microscopy images of the spatial distribution of protein molecules in a cell membrane (data from the KNAW Hubrecht Laboratory, Utrecht). Diagnostic plots showed clear clustering and stochastic models for such point processes will be constructed and estimated.

Considerable progress was made with the preparations of the STATAL-manual. Demonstrations were given of the interactive data-analysis package S (Bell Labs), which is powerful but easy to use and has excellent graphics facilities.

Consultation

As in preceding years, the department was involved in a number of consultation projects. Some of these, e.g. segmentation of speech, estimation of motorway capacity, citation analysis, and extreme water levels on the North Sea coast, are ongoing. A short description of two new projects follows.

The first involved statistical advice relating to accountant control, on the application of modern methods in time series analysis to 'cipher analysis', and of multi-step sampling techniques.

In the second project, AKZO (a Dutch chemical multinational) posed the following problem: a population of three-dimensional spheres is observed in two-dimensional cross sections. What statistical conclusions can be drawn about the distribution of sphere diameters from the empirical distribution of circle diameters? This is a form of the classical Wichsell problem. It seems possible to use modern techniques of density estimation (penalized maximum likelihood) for its solution.

Department of Operations Research and System Theory

J.K. Lenstra (head of department)

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J.L. van den Berg	J.W. Polderman	M. Stöhr
O.J. Boxma	M.W.P. Savelsbergh	L. Stougie
J.W. Cohen	A. Schrijver	S.L. van de Velde
M. Desrochers	J.M. Schumacher	P.R. de Waal
W.P. Groenendijk	J.H. van Schuppen	*trainee*:
G.A.P. Kindervater	S.A. Smulders	I.L. Braam

As its name implies the department covers a variety of subjects, ranging from complexity theory and combinatorics to probability theory and differential geometry. The unifying element is found outside mathematics, in the applicability of the research in decision situations. Problems were originally supplied by economics and industrial engineering, where the need for optimal action in decision situations was first felt. Nowadays they also come from communications and control, and even from political and social sciences. Although the very nature of its subject would seem to put the emphasis on applications, the department has always retained an interest in the development of the underlying mathematical theory. It proved possible to find a balance between pure scientific research and an involvement in practical projects.

The current research projects are:

- Combinatorial optimization (Anthonisse, Braam, Desrochers, Kindervater, Lageweg, Lenstra, Savelsbergh, Schrijver, Stougie, Van de Velde);
- Analysis and control of information flows in networks (Van den Berg, Boxma, Cohen, Groenendijk);
- System and control theory (Polderman, Schumacher, Van Schuppen, Smulders, Spreij, Stöhr, De Waal).

Combinatorial Optimization

Combinatorial optimization is concerned with the investigation of problems that require the determination of an optimal ordering, choice, or assignment of a finite number of objects, such as the determination of distribution systems, depot locations, timetables and production plans. Results employed come from discrete mathematics, probability theory and computer science. In 1986 departmental research concentrated on design and analysis of algorithms, polyhedral and polynomial methods, parallel algorithms and interactive planning methods.

Problems of scheduling fixed jobs, pipelines, unrelated parallel machines, and machines with load-dependent speeds were investigated in collaboration with researchers from abroad. Twelve open questions relating to the traveling salesman problem were collected, and work continued on a book on scheduling. Finally, a verification was given of the proof by Carlier and Pinson of the optimality of Lageweg's solution for the notorious 10×10-job-shop scheduling problem.

Research continued on matrices with the Edmonds property which solve integer linear programming problems after one round of Gomory cuts. The decomposition of graphs without certain 'forbidden' substructures was studied. Research on multicommodity flows - relevant for integrated circuit design - was marked by three-fold progress: in the relations between fractional and integral flows, and between distances and cuts, and in the existence of paths of prescribed homotopy. In addition, a polyhedral characterization was found for the existence of edge-disjoint paths between three given pairs of points in a graph. Randomized algorithms for quick determination of graph connectedness were developed using orthogonal representations. A fully-polynomial approximation scheme was given for the problem of assigning resources to a partially ordered set of tasks in such a way that the required time to complete all tasks in the proper order is minimized. All work on polyhedral and polynomial methods was carried out in collaboration with researchers from non-Dutch organizations

including Bell Communications Research and other US institutes, and from Budapest (Hungary). Four review articles were written on Polyhedral Combinatorics, and the book *Theory of Linear and Integer Programming* by A. Schrijver (Wiley) appeared during 1986. Progress was made with another book *Geometric Algorithms and Combinatorial Optimization* under the joint authorship of Schrijver, M. Grötschel (Augsburg) and L. Lovász (Budapest), which should appear in late 1987.

Parallel enumerative methods for combinatorial optimization problems were experimentally implemented on the IBM-LCAP in Rome, and a queueing model describing congestion phenomena in such processes was analyzed. The research on the parallel computational complexity of approximation algorithms for the traveling salesman problem was completed. A review article on parallel combinatorial computing was presented in Cornell University's *Distinguished Lecturer Series in Discrete Optimization.*

In the field of interactive planning methods, the clustering, routing and scheduling modules of CAR (an interactive system for computer aided routing) were improved; CAR was installed on the IBM PC/AT with a Professional Graphics Display and on the IBM 6150 (PC/RT) with a 5081 Graphics Display. An implementation of CAR at Fashion Transport Holland is expected to take place mid-1987. Functional and technical descriptions of CAR will appear in 1987. The Department is developing a system for interactive production planning in the clothing industry in close cooperation with the TNO-Fibre Institute; the programme receives a partial subsidy via the INSP. The research also focuses on algorithms for a generalization of the job shop scheduling problem; this has a relevance for planning of assembly processes. A detailed problem classification was designed within the context of an expert system for classification and manipulation of problem types within a coherent subfield of mathematical programming. Finally, a start was made on the description of the functional and structural properties of decision support systems - an NFI supported joint project with the Universities of Eindhoven, Rotterdam and Delft.

Computer applications are playing a role in revitalizing the Dutch clothing industry. As part of a NFI supported project also involving the TNO Fibre Institute, CWI is developing a decision support system for the planning and scheduling of a sewing department. Primarily, this will support the control of the assembly shop in order to meet due dates, reduce in-process inventory work and improve overall efficiency.

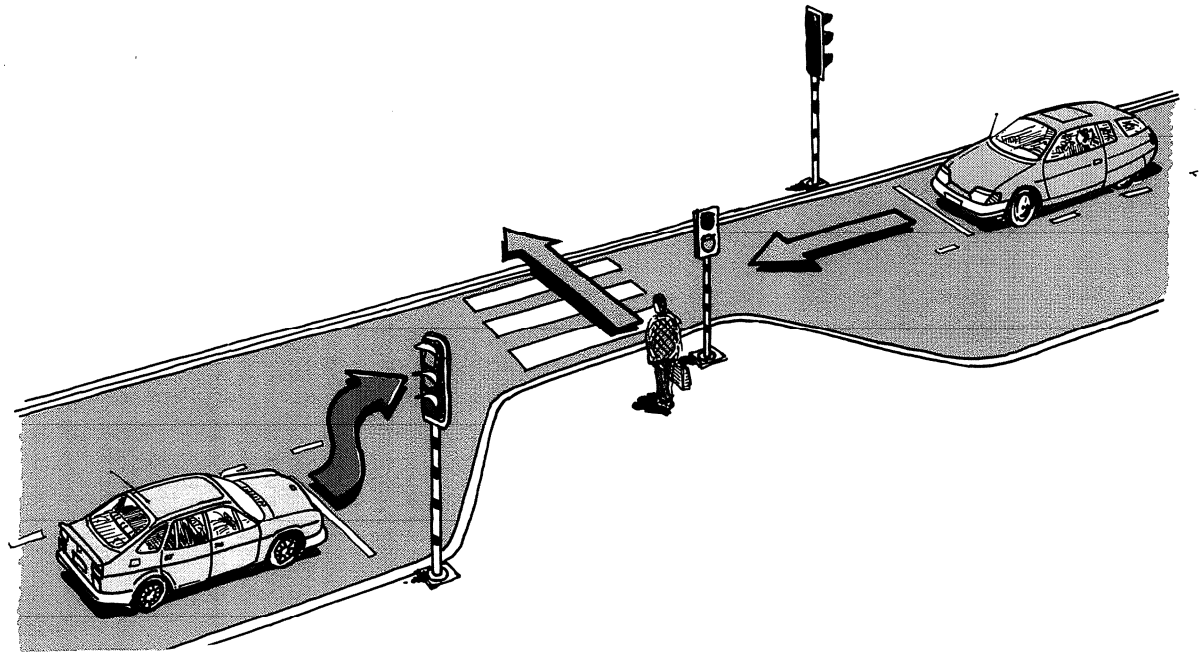
(Photo KOALA Tricotagefabrieken BV, Aalten)

Analysis and control of information flows in networks

This project concerns the mathematical modeling, analysis and control of information flows in computer systems (computer performance analysis) and telecommunication networks (teletraffic analysis). Given the stochastic nature of traffic flows, performance analysis is based on probability theory. Applications range from traditional fields like telephony and telegraphy to computer intercommunication, as well as communication via satellites and mobile communication systems. The rapidly increasing influence of computer- and communication networks in everyday life makes the research element of this project of considerable social interest. The problems are usually formulated in terms of a network with servers and customers queueing for service. Queueing theory studies performance measures such as customer waiting and sojourn times, and queue lengths.

One of the queueing models studied describes congestion phenomena in the dispatch of branch-and-bound algorithms on parallel processors. Another simple model gives insight into the interaction of terminal and batch traffic in a computer system. A review article

on two-queue models was completed, and progress made on the Russian translation of *Boundary Value Problems in Queueing System Analysis* by J.W. Cohen and O.J. Boxma. A study was made of flow control protocols for computer communication networks where messages can get lost because of restricted buffer space. A conservation law was derived for waiting times in multi-queue models with cyclic service. Such models are important in the study of Local Area Networks with a bus or ring structure. The conservation law has far-reaching implications: it unifies and generalizes many existing queueing formulas and has already been used in colloboration with B. Meister (IBM Zürich) to derive waiting times in the IBM Token Ring. Considerable attention was paid to recent important developments in software for queueing analysis. The general-purpose package QNAP2 is now operational at CWI, and the special-purpose package QLIB is also available. In June, the International Seminar on Teletraffic Analysis and Computer Performance Evaluation at CWI was attended by some eighty experts, more than half from abroad.



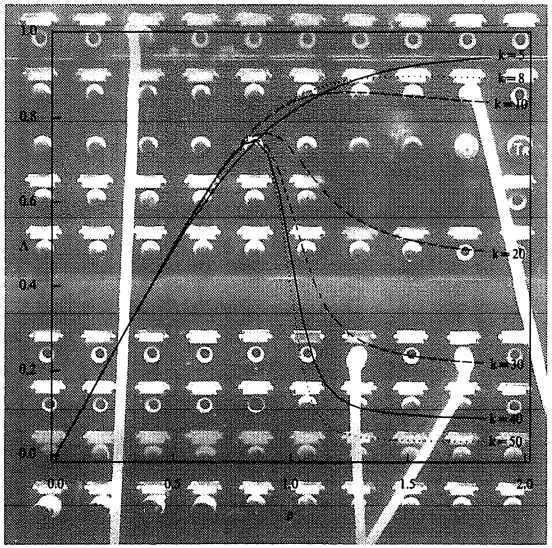
A simple example of a multi-queue model with cyclic service is a road with one half blocked. There are three queues, two for cars and one for pedestrians. The traffic lights form a cyclic service system. Such systems frequently occur in computer networks, in particular Local Area Networks, where data from various stations are all transmitted through one communication channel. CWI derived a conservation law for such systems which unifies and generalizes many existing results. The law states that, although individual queueing times are very difficult to calculate, there is a simple expression for their weighed sum, thus admitting a simple approximation of individual queueing times.

System and Control Theory

System and control theory aims both at the modeling and analysis of mathematical models for dynamic phenomena and at the development of algorithms for control and prediction problems. There is an increasing need in society for automatic control and signal processing, e.g. in connection with robots, electricity networks, satellites, road traffic, computer networks, speech processing and prediction of environmental pollution.

In the area of deterministic systems, the Department studied transformations of systems of coupled differential equations; results were presented in an invited lecture at an international conference in Como (Italy). Now, a closer look is being taken at systems with a special structure. A quantitative study was made of the effect of uncertainty in the model on robust stability as part of the 'Large Flexible Space Structures' project sponsored by STW. A similar analysis is being made of the Strongback Solar Array (a Fokker design).

The classification of all stochastic realizations of factor analysis models was investigated. A dynamic factor system was defined and its stochastic realization problem formulated. A stochastic control model was constructed for a load balancing problem in a telephone-



It is an established fact that overload means major service reduction in a communication system. A typical example is a 'Stored Programme Controlled' trunk exchange, where the calls are handled by a computer. In order to reduce the effect of peak loads as much as possible, a control regulates access to the exchange by limiting the number of admitted calls in accordance with the processor load. Both incoming calls, and various actions inside the communication system, are stochastic in nature. In an STW sponsored project CWI is studying a stochastic control problem in order to design a more efficient admission system. In its general formulation the model is also applicable to computer networks and other systems.
The graph shows the rate of successful call completions in a model explicitly accounting for customer patience. The performance of this model without regulation is strongly dependent on the buffer space k for the maximum number of admissible calls.

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exchange, and a control algorithm for this problem analyzed. A new approach was formulated (with the emphasis on multivariable processes), for the approximating stochastic realization problem for Gauss processes. The dynamic behaviour of freeway traffic was modeled and its stability properties analyzed.
A study was made of adaptive filtering problems for systems with counting process observations, and of self-exciting counting process systems with finite state space. Further, an adaptive pole assignment algorithm was synthesized and theoretically analyzed.
The modeling phase was completed in the STW sponsored project on prediction and control problems for freeway traffic. The model describes the traffic behaviour in a realistic way. A second order approximation of the optimal prediction algorithm led to satisfactory results. A contribution on this project was submitted to the 10th International Symposium on Transportation and Traffic Theory which will be held in Boston (USA) next year.
Overload control in communication systems is being studied in a STW-project, in particular the modeling of Stored Program Controlled trunk exchanges as a system of queues. There are contacts on this problem with Philips Telecommunication and Data Systems and the Netherlands Postal and Telecommunications Services (PTT). Finally, criteria were analyzed for the approximations of a time series by a Gaussian stochastic system, and studies made of the specific approximation problem with a Gaussian distribution on a finite-dimensional space.

Consultation
As in previous years, the Department was involved in a number of outside consultations including:

- research into processing corporation tax returns, commissioned by the Finance Ministry;
- a project on behalf of a shipping company wishing to get the maximum use out of its containers (mathematical modeling led to a successfully implemented interactive optimization programme);
- development of a decision support system for allocating aircraft to gates at Schiphol Airport (planning issues were drawn up and the definition phase of seasonal planning completed in 1986);
- a joint investigation with the Delft Hydraulics Laboratory involving models for water resource management and taking into account the energy production requirements of hydro-electro stations and drinking and irrigation supplies.

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Numerical mathematics concerns the design and analysis of approximating methods of solution for mathematical problems. Many problems originate from the natural sciences and are formulated in terms of differential or integral equations, or large algebraic systems. The Department is especially interested in numerical aspects of partial differential equations in connection with flow problems and semi-conductor problems. Research ranges from the very fundamental to utilization oriented. The field is permanently influenced by changes in computer hardware, not only by the increase in memory size and calculating speed, but also by changes in architecture. Parallel computation is expected to play an important role in the near future. Indeed many expensive and cumbersome laboratory experiments (e.g. wind tunnel tests) can be simulated on a supercomputer, using parallel techniques. Since CWI has access to such a supercomputer at SARA, the Amsterdam Academic Computer Centre, departmental research is also directed at vectorising techniques and parallel aspects of numerical algorithms. CWI aims to achieve a central role in this field, by building up a library of numerical algorithms designed for parallel computers, and by (co-)organizing a national colloquium.

The current research projects are:

- Discretization of initial value problems (Blom, Boon, De Goede, Van der Houwen, Hundsdorfer, Louter-Nool, Sommeijer, Ten Thije Boonkkamp, Verwer, Wubs);
- Multigrid methods for boundary value problems (Hemker, Koren, Spekreijse, Wesseling, De Zeeuw);
- Computational number theory (Lioen, Te Riele, Winter);
- Numerical software (Bergman, Blom, De Goede, Hemker, Lioen, Louter-Nool, Te Riele, Schlichting, Sommeijer, Van der Vorst, Winter, Wubs, De Zeeuw).

Discretization of initial value problems

The aim of this project is the development and analysis of algorithms for the numerical solution of initial boundary value problems. These algorithms have applications in physics, chemistry, biology, the technical sciences, etc. It is important to gain insight into their stability and the accuracy of the numerical solution. Moreover, efficiency remains a permanent matter of concern, given that the increase in calculating speed is outweighed by a considerably larger size of the calculations. Research concentrates on aspects of partial differential equations such as stability and convergence, adaptive grid techniques, the incompressible Navier-Stokes equation and difference schemes for hyperbolic differential equations. The use of supercomputers has greatly increased the interest in this subject, and its practical importance.

Using the method of lines, it was shown that most Runge-Kutta methods undergo order reduction when applied to semi-discrete partial differential equations. On a fixed space grid this phenomenon shows up in exceptionally large error constants which can increase indefinitely with the mesh width. Results were reported at the ODE conference in Albuquerque (USA). In applying Runge-Kutta methods to stiff differential equations, the order of B-convergence is an appropriate measure for the expected accuracy. In the case of dissipative nonlinear problems it was

shown that the order of *B*-convergence is one higher than the 'stage order' in only a small class of Runge-Kutta methods. Conditions for monotonicity in some simple Rosenbrock methods were formulated and applied to prove global convergence for modifications of Newton's method.
The stability of the hopscotch method was analyzed in connection with linear initial boundary-value problems, in particular the odd-even scheme for the one-dimensional convection diffusion equation. This scheme was also applied to the calculation of free convection in a square cavity, for which an accurate reference solution is available. It turned out that the odd-even hopscotch solution oscillates if the initial conditions are discontinuous. Methods of confining those oscillations were shown. Three simple adaptive grid methods in which the integration takes place on a moving grid by a coordinate transformation were investigated. The problem of very steep transitions in space and time can be dealt with in this way. The first results with a Crank-Nicolson type method are very encouraging.
The work on hyperbolic differential equations covered discretization in time and space and the study of Lax-Wendroff schemes. Solution methods were devised for the integration of differential equations with oscillation-dominated solutions. Work on discretization formulas for spatial derivatives in Cauchy problems was completed. Smoothing techniques were applied in order to increase the stability of Lax-Wendroff schemes.
The implementation of the programme for solving shallow-water equations was almost completed. It can now be used in practice by coupling to the WAQUA system of The Ministry of Public Works, e.g. for the Eems-Dollard estuary. The calculation method is highly vectorisable. Certain smoothing techniques for problems with non-periodic boundary conditions were analyzed in connection with semi-discrete parabolic and hyperbolic differential equations. Experiments with the previously developed collocation method for nonlinear Volterra equations of the second kind were concluded with the publication of the FORTRAN code COLV12.

Multigrid techniques for boundary value problems

The numerical analysis of boundary value problems mainly concerns solution methods for elliptic and hyperbolic partial differential equations and integral equations. These equations often arise in technical applications and numerical methods are the most important tool to derive quantitative information from them. Boundary value problems form such a wide field that this project is restricted to multigrid techniques. With these techniques the very large systems of algebraic equations that arise in the numerical solution of boundary value problems, can be solved very efficiently.
In the study of multigrid algorithms and related defect-correction techniques, particular attention was given to convergence proofs and the convergence analysis of nested iteration techniques. Results were applied to the stationary Euler equations for non-viscous gas flows and reported at the ISAM-86 conference in Weisig (GDR). A combination of accurate unstable and inaccurate stable operators was also applied in a defect-correction process in order to resolve contact discontinuities for the Euler equations. Results were reported at the BAIL IV conference in Novosibirsk (USSR).
In the application of multigrid methods to flow problems the previously developed and highly efficient FMG-FAS method for the Euler equations was refined in various ways: tau-extrapolation for reaching higher precision, a streamline-upwind version of Osher's scheme for more precise transonic flow calculations, a remedy against 'sonic glitches', a boundary condition treatment for curved fixed walls, and the discretization of source terms were studied. A second order precision monotonous solution scheme was developed for nonlinear scalar hyperbolic conservation laws, by introducing limiters in space discretization. The efficient solution of these schemes by using a spectral block-Gauss-Seidel relaxation was considered. A publication on the research related to the Euler equations appeared in the proceedings of the 10th ICNMFD conference. Various methods to solve the Euler equations for non-viscous flow by multigrid techniques were reviewed in collaboration with G.M. Johnson (Colorado, USA).
In the STW supported project on application of the Euler equations to flow problems,

In 1986 the STW sponsored project at CWI 'Euler Equations' attained its goal of developing an accurate and efficient numerical solution method for a mathematical model describing steady, compressible, inviscid gas flows (the steady Euler equations) on behalf of the Dutch aerospace industry (Fokker and NLR). The main industrial application is the prediction of the aerodynamic properties of aircraft designs at subsonic and transonic speeds. This flight simulation of possible future aircraft will ultimately call for the solution of the more general Navier-Stokes equations. The numerical method developed to date may be regarded as a step on the route to this goal.

Photo: The first prototype of the new Fokker-50 flying over The Netherlands (1985).

automatic grid adaptation proved useful in flow calculations on a transonic wind tunnel section. Several second order discretizations and the defect-correction process were studied for calculations on airfoils. Different discretizations give optimal results, depending on the type of flow, but in all cases defect-correction turns out to be a very efficient solution method. Production of high quality results using the method devised at CWI was clearly shown by flow profiles at a workshop on Euler equations. Finally, flow profiles around a propeller were modeled as Euler equations with source terms. The model was both efficient and led to good results.
Further, it proved possible to solve the Navier-Stokes equations for large Reynolds numbers by considering them as a perturbation of the Euler equations and applying previously developed defect-correction techniques to these equations. Second order accurate discretizations of the convective and diffusive part of the Navier-Stokes equations were used. Three operators, to be inverted in the defect-correction process, are being studied in order to improve this technique for intermediate values of the Reynolds number.
A robust and efficient blackbox multigrid solver was developed for linear systems with a 9-point band structure as a result of the research on multigrid methods. By the use of matrix-dependent prolongations and restrictions, this algorithm is particularly efficient for elliptic equations with highly discontinuous coefficients.
Consideration of the multigrid technique for the solution of the system of three equations in one space dimension was started as part of a preliminary study of the stationary semiconductor device simulation equations.

Computational number theory
The aim of this project is to approach certain problems in number theory (some of very long standing), with the help of a computer. In recent years CWI has accumulated considerable expertise in the field of computational number theory, e.g. on the Riemann hypothesis; the Mertens conjecture; amicable pairs and hyperperfect numbers; and the factorization of very large numbers. Since Rivest,

$$(7^{104} + 1) / (2.17.169553) =$$

$$134713700481110087340701368296944466832826953650272907684293106522504176112002880 1 =$$

$$177129884618994230816453483 53 \star 760536262815722999802014193236991501654956219516156 17$$

CWI established a new world record in December 1986 by factorizing an 82-digit number into two large prime factors on the Control Data CYBER 205 supercomputer of the Amsterdam Academic Computer Centre SARA. The number occurs on a list of hundreds of 'wanted' numbers, published by the American Mathematical Society. The previous record - a number of 71 'ones' factorized on a CRAY X/MP - had been held by Sandia Laboratories, USA, since 1984. An 87-digit number has been factorized by 7 to 11 'ordinary' SUN systems computing in parallel in the USA. However, that took 3900 hours of CPU-time against CWI's calculation in only 60 hours.

Products of large prime numbers are used to code and decode confidential messages. As it is almost impossible to reconstruct the prime factors from such a product, the encryption is considered very safe. 'Safe' numbers need to be considerably higher than the CWI record.

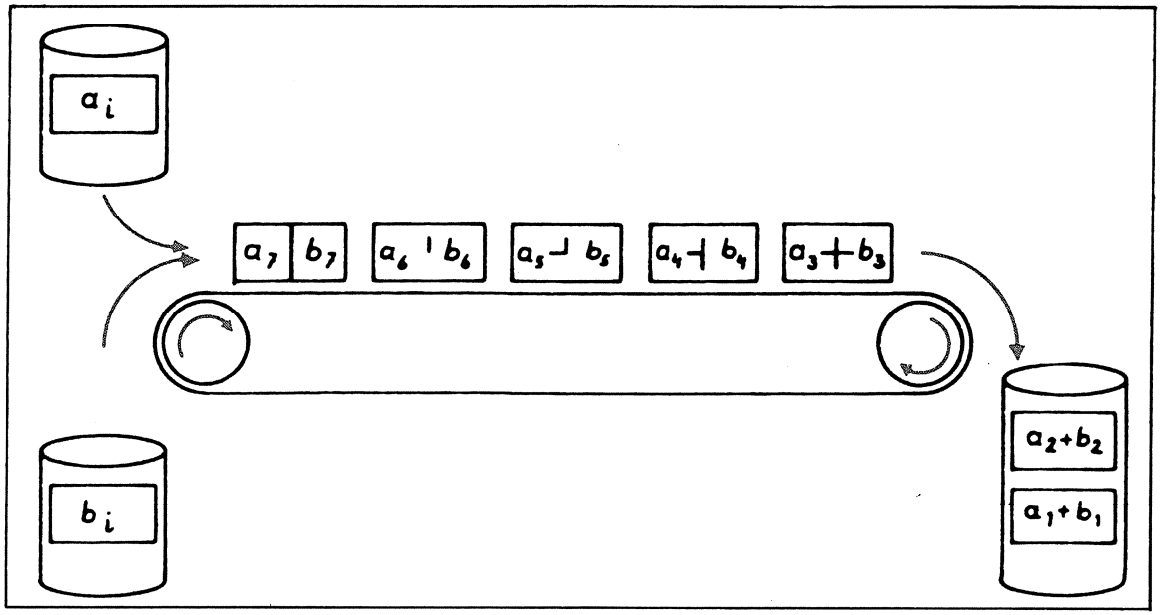
Shamir and Adleman's application of factoring to cryptography, interest in what modern computer technology can achieve in this field has greatly increased.
A survey of all known amicable pairs between 10^{10} and 10^{52} was published. By the end of 1986, the total number of known pairs, including some hundreds of additional pairs found by researchers outside CWI, had risen above 12.000. New results on the sign of the difference $\pi(x)-li(x)$ were published. Because of its implications for the safety of cryptographic systems it is of interest to determine the largest number that can be factorized within a reasonable time with the best known method on the fastest computer. To that end, C. Pomerance's quadratic sieve factoring method supplied with a multiple-polynomial change proposed by P. Montgomery, was implemented on SARA's CYBER 205 supercomputer. Several very large numbers were factorized in this way, among which the largest ever found with the quadratic sieve method on a single computer: $(7^{104}+1)/(2\cdot17\cdot169553)$, an 82-digit composite number, which turned out to be the product of a 29-digit and a 53-digit prime. The necessary computer time was provided mainly by the ZWO Working Group on the Use of Supercomputers.

Numerical software
This is a two-part project: software in the Ada language and software for vector computers.

Numerical software in Ada
In the first place Ada was designed for real-time computation. However, it is generally assumed that it will also be widely used in large-scale scientific computations. It is therefore necessary that large basic software libraries are made available for numerical computations in Ada. The introduction of Ada is strongly encouraged by the Commission of the European Community.
Work on the construction of a prototype Ada numerical software library for large-scale scientific computations was continued in collaboration with British and Irish mathematicians. Alongside the implementation, testing, and documentation of portable elementary mathematical functions in Ada and of operations from linear algebra, efforts were made to establish a standard definition for these functions.
Methods for applying the so-called Karlsruhe arithmetic to more complex numerical algorithms were studied with German and British mathematicians as part of the ESPRIT program DIAMOND. Reports were presented at the meetings of the Ada-Europe Numerics Working Group in Brussels, the SIGAda Joint Meeting in Pittsburgh (USA), the GAMM Workshop in Karlsruhe (West Germany) and the seminar 'Numerical Computation and Libraries in Ada' in Linköping (Sweden).

Numerical software for vector and parallel processors
Since the arrival of the CYBER 205 vector computer at SARA in 1984, CWI has researched on vectorized and parallelized algorithms. It is expected that many algorithms will need revision if they are to run efficiently on the new class of vector computers. The recent realization in practice of several types of parallel computers (Alliant, Intel, etc.) has provided considerable impetus to research in this field. This year CWI organized a highly successful national colloquium on Numerical Aspects of Vector and Parallel Processors.
The possibility of working with negative increments was added in BLAS (Basic Linear Algebra Subprograms) for the CYBER 205, and a double precision implementation was

The highly successful national colloquium on Numerical Aspects of Vector and Parallel Processors, organized by CWI, in collaboration with the Technical University of Delft and the University of Amsterdam, attracted more than 75 participants on average.



The principle of vector computing explained in terms of an assembly line. In this example, the addition inside the computer is visualized by the gradual build-up of the symbol + in five time steps. Once the assembly line is filled after a start-up time it produces the result of one addition every time step. In serial mode every addition would require five time steps.

designed. The research on algorithms for solving large bidiagonal systems on a CYBER 205 was completed. The NUMVEC library (numerical software for vector and parallel processors in FORTRAN) was extended with the following contributions: BDMG (time integration of a semi-discrete scalar parabolic differential equation); BLAS (elementary vector operations from linear algebra); CCRMCF, CCRPCF and GAUJOR (solution of the matrix equation $AX=B$, where B can be a vector or a matrix); and MGD1V and MGD5V (solution of linear systems originating from 7-points discretization of two-dimensional elliptic partial differential equations).

Consultation

Philips/CAD-Centre/MSW commissioned research on time-dependent semi-conductor equations. A number of integration techniques for numerical simulation programmes were studied with a scalar convection-diffusion problem as model. The well-known BDF method turned out most suitable for realistic problems of this kind. A follow-up study involves use of the Newton process in solving the discretized, nonlinear semi-conductor equations. The research focuses on the one-dimensional stationary equations which model a transistor.

Department of Software Technology

J.W. de Bakker (head of department)

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M. Bezem	P.R.H. Hendriks	F.W. Vaandrager
F.S. de Boer	P. Klint	A. Verhoog
N.W.P. van Diepen	J.W. Klop	J.C. van Vliet
S. van Egmond	J.N. Kok	J.B. Warmer
A. Eliëns	H.W. Lenferink	*trainees*:
L.C. van der Gaag	M.H. Logger	M.H.J. Berndsen
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The Netherlands Computer Science Stimulation Programme (INSP) stresses the importance of research in computer science. CWI has received additional funds from this programme, in order to grow into a *centre d'excellence* in the field of computer science. The selected research fields in the three computer science departments of CWI are to a large extent related to the rapid, ongoing, drop in hardware prices and the increase in processing power. As a consequence, distributed processing is now an important issue, and the greatly increased demand for high-quality software has stimulated research in software engineering, programming languages and environments, and the design of information systems. In the department of Software Technology a considerable part of the research is carried out in the framework of ESPRIT.

The current research projects are:

- Concurrency (De Bakker, De Boer, Eliëns, Kok, Rutten);
- Formal specification methods (Bergstra, Van Glabbeek, Goeman, Klop, Rodenburg, Vaandrager);
- Extensible programming environments (Van Diepen, Heering, Hendriks, Klint, Logger, Rekers, Verhoog);
- Interactive text processing (Van Egmond, Heeman, Van Vliet, Warmer);
- Expert systems and other aspects of artificial intelligence (Bezem, Eliëns, Van der Gaag, Lenferink, Lucas).

Concurrency

In the 1970's, distributed data processing acquired a central position in computer science. New developments in the architecture of computer systems have been of great importance in this respect. The research in this project is concentrated on programming concepts for concurrency. In cooperating processes the main problem is to synchronize the operations of the separate processes and to organize the communication between the processes. At present the research within this project concentrates on five subjects.

Within ESPRIT project 415 (Parallel Architectures and Languages for AIP: a VLSI directed approach) participation in the working group Semantics and Proof Techniques (chairman De Bakker) continued. Another section of the work was carried out in subproject A (Philips), with a central role for the language POOL (Parallel Object Oriented Language). A language was defined which contains the dynamic process creation as it occurs in POOL, but in which processes communicate/synchronize through instructions which are a generalization of the way in which CSP processes communicate. A proof system was devised for this language, based on correctness assertions describing the input/output behaviour of a program (pre-post conditions). An attempt to find a temporal proof system led to a new approach for the axiomatization of sequential composition in temporal logic. Results on the operational semantics of POOL were presented at the ACM POPL 86 conference. As for the denotational semantics of POOL, a second model is under construction containing several levels of abstraction. In early 1987 a report will

appear on the related problem of the solution of reflexive domain equations in a metric framework. Furthermore, the relation between operational and denotational semantics of POOL was analyzed in collaboration with P. America (Philips) and - partly - J.I. Zucker (SUNY at Buffalo, USA), and reported on at the Advanced School on Mathematical Models for the Semantics of Parallelism in Rome. Finally, De Bakker co-chaired the programme committee of the PARLE conference, Parallel Architectures and Languages Europe, to be held in June 1987.

A compositional model for a data-flow net with 'fair merge' nodes was devised in the semantics of data flow, and reported at the ESOP conference in Saarbrücken. However, the model was flawed: assuming that only input/output behaviour is observable in a data-flow net, the model contained surplus information. Hence, an abstraction was carried out which turned it into a 'fully abstract' model. Networks were also studied, in particular their description in a parallel logical language. The first step was how to provide Concurrent PROLOG with a compositional semantics.

Key notions from parallel programming languages were compared for a variety of models: operational/denotational; metric/order-theoretic; uniform/nonuniform; and finite/infinite. This occurred in close collaboration with J.-J. Ch. Meyer (Amsterdam), E.-R. Olderog (Kiel, West Germany) and J.I. Zucker (SUNY at Buffalo, USA). Various

$x+y=y+x$	A1	$x\tau=x$	T1
$x+(y+z)=(x+y)+z$	A2	$\tau x+x=\tau x$	T2
$x+x=x$	A3	$a(\tau x+y)=a(\tau x+y)+ax$	T3
$(x+y)z=xz+yz$	A4		
$(xy)z=x(yz)$	A5		
$x+\delta=x$	A6		
$\delta x=\delta$	A7		
$a \mid b=b \mid a$	C1		
$(a \mid b) \mid c=a \mid (b \mid c)$	C2		
$\delta \mid a=\delta$	C3		
$x \Vert y=x \mathbin{\mathbb{L}} y+y \mathbin{\mathbb{L}} x+x \mid y$	CM1		
$a \mathbin{\mathbb{L}} x=ax$	CM2	$\tau \mathbin{\mathbb{L}} x=\tau x$	TM1
$ax \mathbin{\mathbb{L}} y=a(x \Vert y)$	CM3	$\tau x \mathbin{\mathbb{L}} y=\tau(x \Vert y)$	TM2
$(x+y) \mathbin{\mathbb{L}} z=x \mathbin{\mathbb{L}} z+y \mathbin{\mathbb{L}} z$	CM4	$\tau \mid x=\delta$	TC1
$ax \mid b=(a \mid b)x$	CM5	$x \mid \tau=\delta$	TC2
$a \mid bx=(a \mid b)x$	CM6	$\tau x \mid y=x \mid y$	TC3
$ax \mid by=(a \mid b)(x \Vert y)$	CM7	$x \mid \tau y=x \mid y$	TC4
$(x+y) \mid z=x \mid z+y \mid z$	CM8		
$x \mid (y+z)=x \mid y+x \mid z$	CM9	$\partial_H(\tau)=\tau$	DT
		$\tau_I(\tau)=\tau$	TI1
$\partial_H(a)=a$ if $a \notin H$	D1	$\tau_I(a)=a$ if $a \notin I$	TI2
$\partial_H(a)=\delta$ if $a \in H$	D2	$\tau_I(a)=\tau$ if $a \in I$	TI3
$\partial_H(x+y)=\partial_H(x)+\partial_H(y)$	D3	$\tau_I(x+y)=\tau_I(x)+\tau_I(y)$	TI4
$\partial_H(xy)=\partial_H(x) \cdot \partial_H(y)$	D4	$\tau_I(xy)=\tau_I(x) \cdot \tau_I(y)$	TI5

publications followed, e.g. in the book *Current Trends in Concurrency,* Springer Lecture Notes in Computer Science, Vol. 224. Given the need for a 'fair merge' operator in the construction of a denotational model for POOL, the 'fairness' problem is being studied in the framework of De Bakker and Zucker's process semantics.

Recent definition techniques for concurrency were compared in a study of the programming language OCCAM, particularly in respect of the instruction 'WAIT a period of time'. The contributions to the National Project Concurrency concerned both organization and content.

Formal specification methods

One of the central problems in the development of software is the control of complexity, both of problems to be solved and tools used. A systematic approach is essential, given the often major scale of problems posed by automation projects, hence the increased interest in formal methods - and related discussions between CWI researchers and their opposite

The axiom system ACP_τ*, Algebra of Communicating Processes with abstraction. Starting from atomic actions or events a, b, c,* $\cdots$*, larger processes can be constructed with sum or alternative composition* $(+)$ *and product or sequential composition* $(\cdot)$*; for instance* $a \cdot (b+c)$ *is the process that first performs 'a', then chooses between execution of 'b' or 'c'. The product sign* $\cdot$ *is often suppressed. There is no distributive law equating* $a(b+c)$ *to* $ab+ac$*; thus information on timing of choices in a process is preserved. (This is important to model process features such as deadlock behaviour.) In the axioms x,y, and z denote general processes;* δ *is the process 'deadlock' and* τ *is the 'invisible' action first used by R. Milner in his Calculus of Communicating Systems. The parallel operator* $\Vert$ *('merge') together with the auxiliary operators,* $\mathbb{L}$, $\mid$ *describe 'handshaking' communication between processes (e.g. read-write communication). Using systems of recursion equations to denote infinite processes (as in* $X=aX$*), every computable process can be finitely specified in* ACP_τ*. After an extension with some proof rules, the system has also been used for process verifications, such as verifications of communication protocols and correctness proofs of systolic algorithms.*

members in such major industrial and (semi-) state organizations as Philips and PTT. The bulk of research in this project falls under ESPRIT projects METEOR and VIP/VDM (METEOR: A Formal Approach to Industrial Software Development; VIP/VDM: specification for the interface of the Portable Common Tool Environment). The main themes are process algebra, module algebra, term reduction systems and the specification language ASF.
A simple 'sliding window protocol' was analyzed in a report covering verification and specification of protocols. As a next step P. Urzyczyn (Warsaw) described the well-known 'dining philosophers' problem in terms of process algebra. Activity around the theory of algebraic specifications involved a description of modularized specifications and the specification of parametrized data types.
Efficient reduction strategies in lambda calculus were studied in collaboration with H.P. Barendregt (Nijmegen), and R. Sleep and R. Kennaway (University of East Anglia, UK). The continued collaboration with E.-R. Olderog (Kiel) concerning 'failure semantics' in connection with process algebra, led to an axiomatization for process divergence. Using the POOL language as an example, it was shown that process algebra can generate a semantics for a realistic concurrent programming language. A new construction was given of a process algebra model, together with an upper limit for the number of 'features' that can be simultaneously given a meaningful algebraic semantics.
Finally it transpired that the question of whether two context-free grammars in Greibach normal form specify the same process, can - under certain restrictions - be decided.

Extensible programming environments
Programming environments consist of a collection of tools for software development, e.g. systems for editing and debugging. However, many applications require an extension of the environment with separate languages. The aim of this project is to make such extensions user friendly. The problem of specifying the semantics of a new language in such a system

CWI participation in ESPRIT projects

Project	*Title*	*Partners*
METEOR (432)	An integrated formal approach to industrial software development	Philips (PRLB, PRLE), CGE Paris, AT&T/Philips, COPS, TXT, Univ. Passau
GIPE (348)	Generation of Interactive Programming Environments	INRIA, SEMA, BSO
415	Parallel Architectures and Language for AIP - a VLSI directed approach	Subcontractor of Philips
DIAMOND (1072)	Development and Integration of Accurate Mathematical Operations in Numerical Dataprocessing	NAG, Siemens, Univ. Karlsruhe
VIP (1229(1283))	VDM Interfaces for PCTE	Praxis, Dr. Neherlab. PTT, Océ, Univ. Leicester

is attacked algebraically. As in the previous year, the research was carried out as part of the ESPRIT project GIPE (Generation of Interactive Programming Environments).
From a study of the algebraic semantics of module composition there emerged an axiomatic system BMA for modules of first order axioms with the operators *union, export, reparsing* and *selection of visible signature.* Practical experience came from algebraic description of the dynamic semantics of a simple language with go-to statements and the static semantics of POOL. As a result, the semantics of ASF, the specification formalism used could be defined and described more precisely. A new formalism SDF was developed to give the user better facilities to define his own syntax. A first implementation was based on Tomita's universal context-free parsing algorithm. Polymorphic type-from-context inference in the functional language ML was described in a combination of ASF and SDF and made operational in various ways.

Interactive text processing
Phototypesetters produce complex documents with a variety of text types, special symbols and graphic representations. Input is prepared on a text editor and consists of a mixture of text and commands for the formatting process. This process is complicated, time consuming and usually occurs off-line. The results are difficult to visualize on a screen and, in case of complicated texts with tables, formulas, etc., their processing is difficult to predict. The goal of this project is to design and implement an interactive system for such documents, which makes the final output immediately visible on a high resolution screen - during text input.
In 1986 the work was mainly directed at the design and implementation of subsystems for the interactive processing of tables and mathematical formulas. A significant problem is posed by the need to recalculate sizes of rows and columns after a change in a table by the user. Efficient algorithms for keeping this administration up-to-date were implemented experimentally. The system was extended with the option of processing matrices; its efficiency was also strongly improved. A study was initiated on SGML, the ISO-standard for the description of document structures. CWI is working together with Samsom Grafische Bedrijven (a Dutch company specializing in the field) to achieve initial implementation of this standard.

Expert systems and other aspects of artificial intelligence
Recently developed AI-systems usually have a separate knowledge bank and an inference machine which applies the knowledge, together with the supplied data, to a problem. The research in this project focuses on expert systems where this separation is usually realized in expert system shells. It is based on experiences with the DELFI-2 system developed at the Technical University of Delft. The group is involved in PRISMA (Parallel Inference and Storage Machine), a project directed by Philips Research Laboratory.
The inference machine of DELFI-2 was extended with a data-driven method and its explaining facility extended with a 'why-not' facility. An editor was implemented for the generation of the declaration part of a knowledge bank, which satisfied the syntax required by DELFI-2. A production rule checker was also developed capable of being used for tracing redundant and circular production rules in a knowledge bank. The development of inference machines in PROLOG was continued. Various representations were tested in connection with the processing speed of a middle-sized knowledge bank. Research started under the PRISMA-project umbrella should eventually lead to a parallel knowledge-processing system in the language POOL-X. A joint testing plan was set up with A.R. Janssens (Leiden) and R.W. Segaar (Rotterdam) to test the medical expert system, HEPAR, involving comparison with a statistical method (the COMIK-rule) developed in Denmark.

As in previous years, members of the Department contributed to the annual national post-academic course 'Modern techniques in software engineering'. In 1986 CWI also gave a course on PROLOG.

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M. Snyder
H. Tempelman
E. Verweij
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The swift advances made by computer science in recent years have made a wide impact. Research in this field is closely tied to social and technological developments in information processing and telecommunications. The price of hardware on the market suits most pockets and personal computers (PC's) are taken for granted. The pace of microcomputer development is matched by that in very large computer systems and supercomputers. All this has stimulated research in networks, VLSI design, operating systems, and distributed systems. At the same time there is a growing need for software, which in turn has stimulated research in software engineering, and language design.

The current research projects are:

- Complexity and algorithms (Kirousis, Kranakis, Vitányi);
- Architectural transparency (Boeve, Jansen, Janssen, Mullender, Shizgal, Snyder, Steiner, Van der Zee);
- Computer systems and ergonomics (Boenink, Budd, Cathalina, Van Dijk, Geurts, Krijnen, Meertens, Nijbacker, Pemberton, Roorda, Van Rossum, Tempelman, Zwaan, Zwart);
- Distributed adaptive information systems (Advokaat, Kersten, Van der Meer, Schippers, Siebes);
- Constructive algorithmics (Ebergen, Meertens, Verweij).

Complexity and algorithms

Algorithms are at the heart of computer science. Ever since the advent of digital computers the size and complexity of the problems undertaken have increased and so has the need for efficient algorithms to solve them. These technological developments also generate new and difficult algorithmic problems. There are important algorithmic aspects to CWI research on computer networks and distributed information systems. Design, construction and operation are covered, as are applications. In parallel or distributed computations the physics of the model is a key factor, hence the costs of communication are more important than those for calculation. New lower bounds were found for the average communication length of symmetric circuits embedded in a Euclidean space. These bounds are valid for any technology, for example for binary n-cubes such as MIT's Connection Machine, even if it is in the form of an optical computer. It transpires that symmetric circuits with a small diameter are of no use to very large multicomputers. Results were reported at gatherings including the 2nd International Workshop on Parallel Processing and VLSI in Loutraki (Greece).

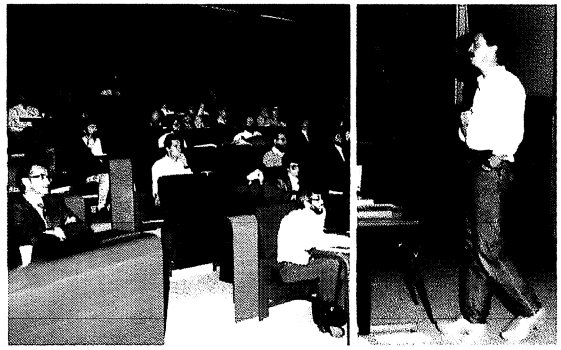
With an eye to the cost of establishing a temporary link between mobile processes in a multicomputer network, lower bounds were found for the average number of point-to-point transmissions between each pair of nodes. Application of this 'Distributed Match-Making' problem are found in 'name servers', 'mutual exclusion' and 'version management'. Various generalizations for matching n ($\geqslant 2$) processes were studied. In building general asynchronous communica-

tion interfaces, the problem is to construct multivalued common registers which can be read and written asynchronously and simultaneously by many processors. Solutions were found for all outstanding problems and reported at the 27th IEEE Symposium on Fundaments of Computing in Toronto and various scientific institutes in the USA.
Using Kolmogorov complexity (near) optimal lower bounds were given for the time required to simulate one data structure with another - whether tapes, stacks of buffers. These bounds are either within a factor $\log n$ from the upper bounds, or coincide with them. This work was carried out in collaboration with Ming Li and L. Longpré (Harvard and Washington Universities, respectively), and reported at the Structure in Complexity conference at the University of California at Berkeley. An approximation principle for projective models of process algebras (on a finite number of atoms) was used to construct a new model for process algebras. The existence and unicity of solutions in the projective model of arbitrary systems of fixed point equations with parameters was proved. A new method of constructing $2m \times 2m$ matrices with elements 0 or 1 was made, so that the sums of rows and columns are all equal to m. Non-trivial lower bounds were given for the number of such matrices. Formulas from temporal logic were studied as representations of characteristic sets of linear time - as a joint project with K. Oikonomou (AT&T Information Systems, USA). A reduction algorithm was found to calculate sets such at these.

Finally, E. Kranakis' book *Primality and Cryptography* was published by Teubner-Wiley.

Architectural transparency

A connecting network is required if data to be exchanged between the proliferating number of computers - and PC's in particular. At present such a network is unpleasantly obtrusive: each machine is autonomous, and special actions are required to make use of the inter-machine communication facilities. This research project studies the principles of designing distributed systems, and aims at the development of software architectures which result in transparant hardware architecture, so that the system user is quite unconscious of using several machines. The project operates in close cooperation with the Computer Science Department of the Free University of Amsterdam under the direction of Prof. A.S. Tanenbaum. It has already resulted in the design and implementation of the Amoeba Distributed Operating System.
Amoeba is one of the best known distributed operating systems in the world. It is an experimental system for the practical testing of the project's research results. As a next step Amoeba could be used as an operating system for daily routine programming or text processing. Given that Amoeba forms a flexible basis for programming environments, an emulator was built for UNIX - the most popular current environment by which programmes under UNIX run without changes or new compilation under Amoeba. Several



In September, CWI was the stage for the Second European SIGOPS Workshop 'Making Distributed Systems Work'. In his introduction workshop host Sape Mullender combined advanced cerebral concepts with more traditional 'pedestrian' ideas.

Amoeba services (Servers) have already been implemented: File, Bank, Directory, Boot and Process Servers to name but a few. 1986 saw the first message transactions between CWI, Hatfield (UK) and Tromsø (Norway) as part of the European Community sponsored COST-11 project. The twelve European institutes involved are working together to build a wide-area network Amoeba based operating system.
In 1986, CWI hosted the highly successful Second European SIGOPS Workshop 'Making Distributed Systems Work'. This biennial workshop is on its way to becoming one of the most important regular events in the field of operating systems.

Computer systems and ergonomics

Cheaper hardware brings personal computing within reach of an increasing number of private and professional users. However, the inflexibility of available application software often blocks the full and effective use of potential. This project, set up in 1982, aims to design, implement and distribute a simple, structured, interactive programming language - embedded in a corresponding environment - to meet modern views on, and the potential of, personal computer use. The language ABC, developed during the project the five years has been running, is designed to meet the need. ABC is both suitable for structured programming and user friendly.

36 proposals for change were adopted and implemented from collated preferences and criticism, including:

- the name ABC, instead of the original, B;
- revised terminology;
- an experimental extension of ABC to describe high-level graphic documents;
- a new functional design for the editor increasing user friendliness and improving error detection, modularization and general efficiency.

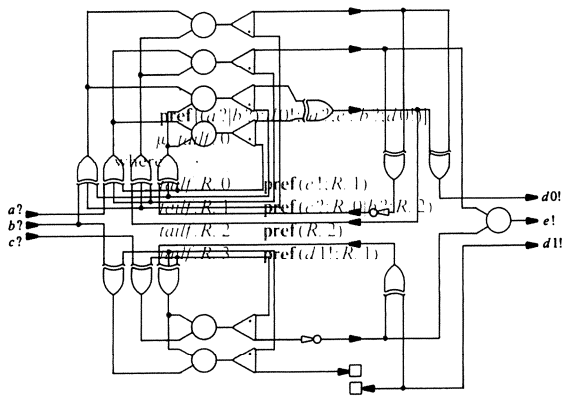
The two separately existing system versions, under MS-DOS and under UNIX, were merged into one. As a side result, the system-dependent parts are now concentrated in a minimal number of locations. An interface was made for the Apple Macintosh, though this is not yet publicly available. Other improvements in the system included: a faster interpretation, with prospect of further improvements; a higher functionality of the environment; and a considerable reduction in file accesses by the system. An implementation made of the Clearing Person Algorithm is useful for realizing complete functionality of the environment. Terminology and error messages were reworked into Dutch. The necessary preparations for the transition of B to ABC were almost complete by the end of the year.

Around sixty requests for the B-system were met in 1986, bringing the total amount of systems distributed directly by CWI to more than one hundred. Inclusion of the B-system in the UNIX BSD 4.3 distribution tape (estimated distribution to date, between one and two thousand copies) makes it impossible to calculate the number of systems installed. Preparations were made for new books: *The ABC Programmer's Handbook* and *Computer Programming for Beginners,* based on earlier, B, versions. Two articles were written for a wider public on the ABC language and environment. A B language stand was organized at three public events.

Distributed adaptive information systems

The present-day approach to building information systems is considered both functionally restricted and inflexible. It is, for example, impossible to treat unstructured and dissimilar data (such as documents, pictures and sound), in the same way as uniform, structured information. Another drawback is that traditional information systems only give a snapshot of a dynamic process. The aim of this project is to design (theoretical) models and develop the required software techniques to build a distributed adaptive information system (DAISY). The architecture envisioned bears the name AMOS, standing for the following levels: Applications, Man-machine interface, Operations, and Storage of objects.

A preliminary definition of the object-



The design of integrated circuits (VLSI) is as important as it is complicated. At CWI the problem is approached in a fundamental way by attempting to reduce it to the design of a programme. This programme can be mapped onto a VLSI-system by a number of fixed transformations.

oriented language was published. This was designed for the construction of adaptive information systems and knowledge-based applications. Essential aspects of this language are: data-flow driven information processing, logic programming, co-operative process structures and an object-centred approach. Here, the class of an object is a dynamic concept: objects can change class in the course of time, and can belong to more than one class. Central to the applications envisaged is the 'guardian' concept: a high-level description of a process which reacts algorithmically to changes in the knowledge bank. A functional prototype of the language was developed in PROLOG.

Although database management systems are widely used, only four database machines are commercially available due to fundamental problems encountered in the development of these systems. A joint project titled PRISMA (Parallel Inference and Storage Machine) was started under the umbrella of the Dutch, SPIN, research stimulation programme. The participants - Philips Research Laboratories (Eindhoven), the Universities of Twente, Utrecht, Amsterdam and Leiden, and CWI - define their goal as the realization of a 'highly parallel machine for data and knowledge processing'. The DAISY-group at CWI will design and realize main-memory database management facilities.

A new, formal approach for modeling databases is currently under study. It was established that the central concepts 'entity' and 'relation' in the frequently used Entity-Relationship model, should be replaced by the concepts 'attribute', 'entity' and 'inheritance' via an ISA hierarchy - thus making it possible to consider the database as a topological space.

Constructive algorithmics

The two most important aspects in the design of algorithms are correctness and efficiency: unfortunately, these are often mutually exclusive. An emerging approach to this problem is the technique of transformational programming. The project aims to increase the usefulness of this approach by unifying the specification formalism and truly algorithmic formalism and by developing (pre-)algorithmic concepts and notations on a high level of abstraction.

Among the research subjects is the design of integrated circuits (VLSI) by reducing it to the design of a programme which can be mapped onto a VLSI-system by a number of fixed transformations. The programme should specify components which communicate delay-insensitively with their environment. An attribute grammar was developed in such a way that any programme satisfying it specifies a delay-insensitive component. The grammar allows programmes with parallelism, tail recursion or projection. A method was found to translate every programme written according to the rules of the grammar in a delay-insensitive composition of basic components. In this translation any composition can be realized with only five components: Sequencer, Fork, C-element, Toggle and Exor-element. Furthermore, the number of basic components is proportional to the length of the programme.

The research on algorithmic notations on a high level of abstraction led to discoveries of an 'as well - as' operator, being dual to the 'indefinite choice' operator and a variant of Hilbert's epsilon operator. A generalization of morphisms on arbitrary structures applied to other than binary structures often yielded familiar functions, e.g. iterated functions for the Peano numbers. New results included discoveries that any injective function on structures is a morphism, and that any arbitrary function is the composition of a restricted number of morphisms. In a first attempt to present a development by means of a transition in the data representation, a factorization of the algorithmic development was found to simplify dramatically the complete development. Finally a calculus of substitutions was developed with a regular algebraic structure. The concept of 'generalized substitution' facilitates insertion in the existing algorithmic framework and broadens application. These results on algorithmic notation were reported at IFIP meetings in Great Malvern (UK) and Bad Tölz (West Germany).

Department of Interactive Systems

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

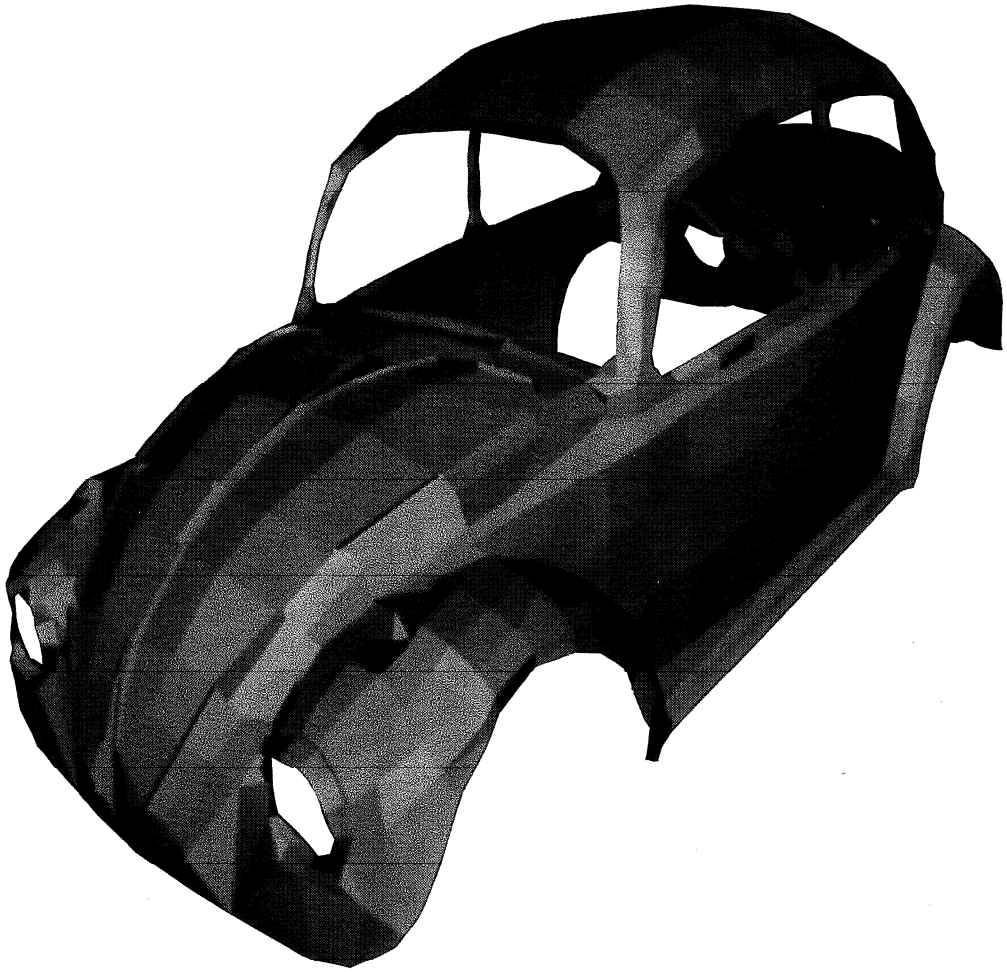
V. Akman	M.M. de Ruiter	*programmer*:
P. Bernus	H.J. Schouten	R. van Liere
C.L. Blom	T. Takala	
W. Eshuis	T. Tomiyama	*trainees*:
J. Kaandorp	C.G. Trienekens	M. van Dijk
A.A.M. Kuijk	P.J. Veerkamp	H.A.G. Hogendoorn
J.L.H. Rogier	Y. Yamaguchi	R.J. Honing

This department's research focuses on the fundamental problems of interaction: the communication between a computer system vis-a-vis the external world. This includes the design and construction of systems to realize this communication. Information exchange can be enacted with a human user or with systems controlling a process (robot, chemical process, etc.). Although technically very different, in both cases, the fundamental problems display much similarity.
One aspect of the recent developments in hardware is the technological improvement of graphic screens, such as raster screens in advanced workstations. The interactive manipulation of data by means of a representation on the screen is a new development of great importance.

The current research project are:

- Computer graphics (Van Dijk, Ten Hagen, Kaandorp, Kuijk, De Ruiter, Trienekens);
- Interactive workstations (Blom, Ten Hagen, Kuijk, Schouten);
- Dialogue programming (Ten Hagen, Hogendoorn, Honing, Van Liere, Schouten, Yamaguchi);
- Intelligent CAD-systems (Akman, Bernus, Eshuis, Ten Hagen, Rogier, Takala, Tomiyama, Veerkamp).

Computer Graphics
The aim of this project is to design functionally complete graphics systems, with special support for interactive use. The integration of the geometrical and representational aspects (colour, line width, real-time motion) of two-dimensional drawings having been accomplished, attention turned to three-dimensional line drawings, images built up from domains as depicted on rasters, e.g. TV-screens, and feedback techniques for interaction.
Work on the three-dimensional Graphical Kernel System (GKS-3D) continued, with participation in international ISO-meetings and further development of various functions. An ISO-draft proposal for a GKS-3D shell around PHIGS (Programmers Hierarchical Interface to Graphics Systems) is now circulating. A provisional GKS-3D implementation has already been transferred to the software industry based on a system containing our implementation of the GKS-3D transformation chain and the HLHSR functions (Hidden Lines and Hidden Surface Removal). The very extensive documentation on C-GKS was completed. By optimalization of the asynchronous basic functions for graphical input GKS can now be used on the new SUN III systems as a kernel for various experimental systems. Frequent real-time reactions in particular can be made both efficient and much easier to follow. Certification of the GKS implementation was gained via the official test suite.
In connection with the development of facilities for raster graphics in programming languages, pattern representation algorithms were implemented and analyzed in order to find a basis for a VLSI implementation of these algorithms. A model was developed for the total workstation architecture in which these chips have to function. A report on this new raster architecture was given at the Eurographics Workshop on Hardware for Graphics in Lisbon (Portugal).
An interactive system was created, on the basis of GKS and GKS-3D, for generating a large number of fractals from the class of self-similar sets. The system is now being adapted for the simulation of biological objects. A GKS application programme was developed for generating fractals emerging



CWI played a central role in the development of the Graphical Kernel System GKS. The two-dimensional version has been accepted as an ISO-standard. Extension to three dimensions, incorporating such functions as Hidden Lines and Hidden Surface Removal, is now under way. The picture of the well-known old Volkswagen type was produced with this system.

from mappings in the complex plane (Mandelbrot sets, Julia sets, etc.).

Interactive workstations

The aim of this joint Industry/CWI project is to develop advanced interactive workstations. Industry provides the hardware and gives important information on application characteristics, especially from the world of CAD. CWI's task is to design the architecture of such workstations and to see to their programmability. The eventual aim is to develop a fifth generation (intelligent) workstation with a built-in mechanism to support the interactive dialogue.

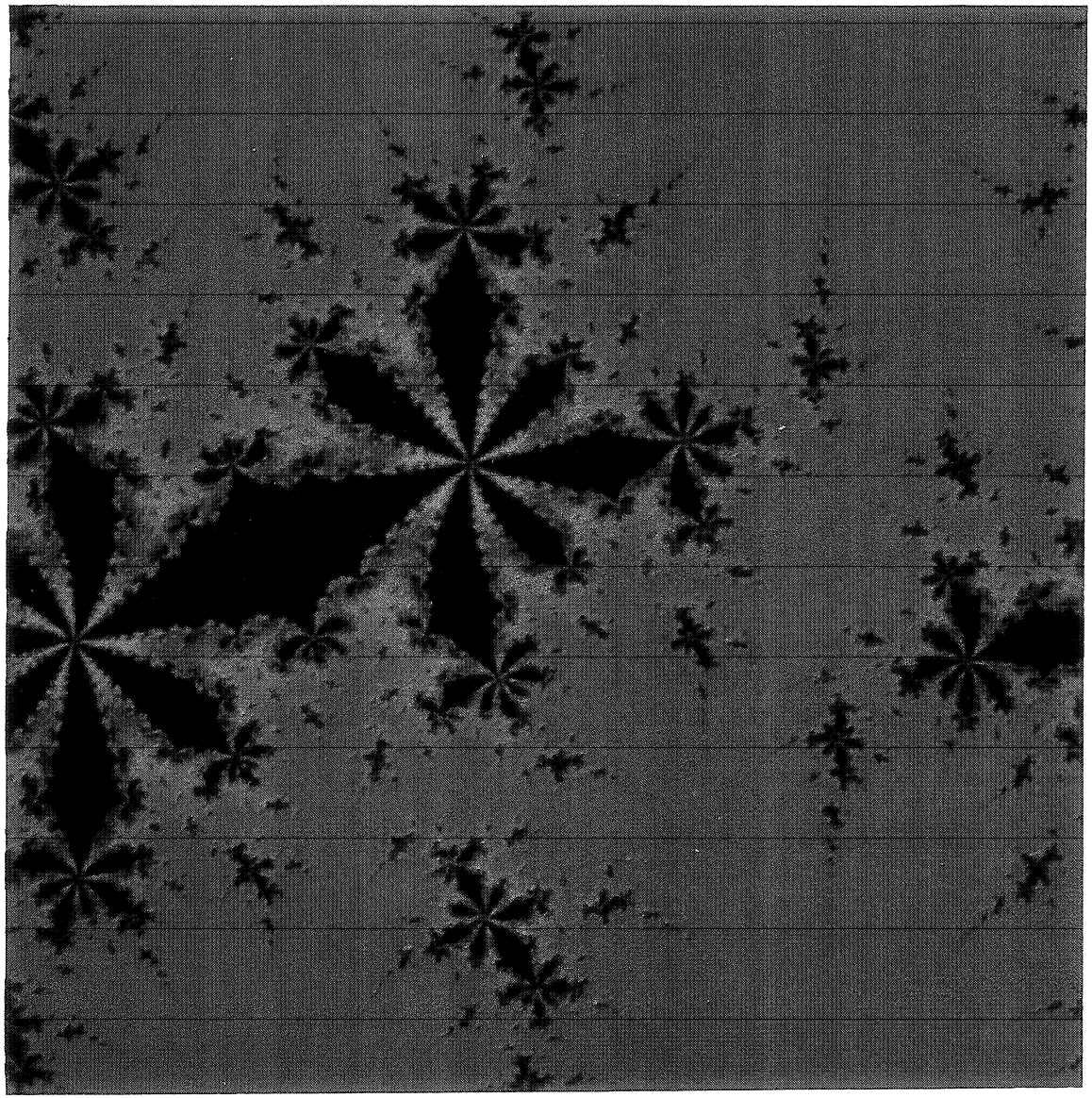
1986 saw completion and implementation of a production oriented version of the interactive GKS workstation, based on the virtual terminal concept with feedback process models. The cyclic workstation process was adapted to enable the inclusion of already existing feedback-interaction mechanisms, e.g. with 'segment dragging'.

Another subject taken up in 1986 was the design of a picture editor, a system for the creation and manipulation of files with graphical information, by means of graphical input and output devices. In contrast to a text editor, a picture editor operates on a sequential picture file containing non-sequentially depicted objects. User difficulty in specifying such characteristics as shape and colour of a graphic object presents a further problem, as does the difficulty of inspecting a picture file rather than a text file.

Dialogue programming

Dialogue is the usual form of communication between man and machine. Dialogue programming denotes the specification of all possible questions and answers, as well as the state of the visible interface at each stage of the dialogue. A method has been developed to specify the dialogue part of an interactive programme as an independent module, a so-called dialogue cell.

In 1986 the bulk of work focused on gaining experience with the implementation of DICE, a specification method based on dialogue cells developed at CWI. This method contains many features rarely considered elsewhere, such as support for parallel input/output and



device-independent specifications. A framework was devised for specifying related - though not identical - data structures. Automatic error dispatch and recovery is made possible by error detection via prior control and retrospective data checking. A history mechanism was devised enabling the user to repeat and evaluate dialogues. Successive versions of the so-called radical system were completed and evaluated. This system for parallel graphical input and output, and the coupling of these, allows for precision determination of real-time behaviour of a graphical interface. The syntax of the radical system makes possible a compact symbolic notation for drawings. Work progresses on embedding the radical notation in the dialogue cell language. Various publications on the subject are under way.

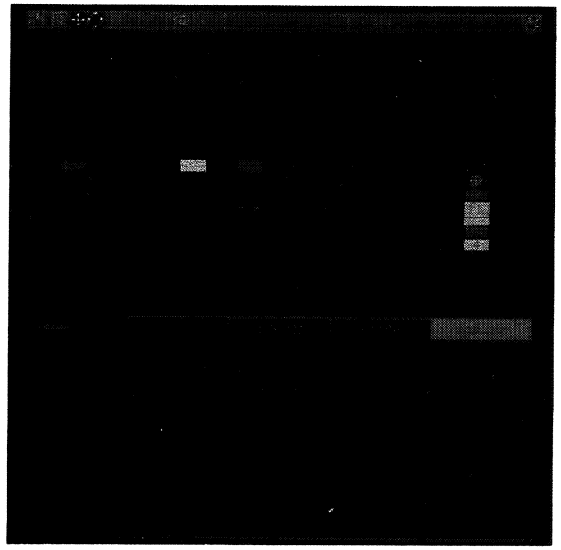
Computer experiments have opened a whole field of possibilities in the theory of dynamical systems. Recently there has been a particular growth in interest in iterative systems (self-similar sets, e.g. fractals), already considered by Julia circa 1920 - this in connection with the study of nonlinear phenomena. At CWI a GKS application programme was developed for generating fractals emerging from mappings in the complex plane (Mandelbrot sets, Julia sets, etc.). The picture represents the set $z_{n+1} = a \sin z_n + b$, *where a, b and z are complex numbers.*

Intelligent CAD systems

CAD, or Computer Aided Design, is a broad field with applications in all technical areas. At present, a CAD system usually consists of a somewhat arbitrary collection of software for the definition, analysis and specification of given design facets. This project aims at developing a method for describing a complete design process as a dialogue between user and supporting software. The study involves fundamental questions including the development of the necessary AI techniques and a uniform, consistent user interface. There is collaboration with the National Aerospace Laboratory NLR. In the area of design theory, work is in progress on a framework for a formal description of the design process in terms of set theory, topology and various theories of logic (model, temporal, etc.). The Department investigated the question of representing design information from the combination of heuristic and deterministic components. The description of design objects in terms of 'qualitative physics' is a third subject of study.

Automation and intellectualization of design are crucial elements in industrial innovation. In this connection a start was made on project IIICAD (Intelligent Integrated and Interactive CAD), the goal of which is to devise a system able to understand the designer's intentions and to assist the design process. Central concept is the 'scenario', a prescribed design procedure. The system checks the design knowledge in the scenarios for completeness, soundness and feasibility and is able to reason about physical processes and the changes they cause. The IIICAD system uses the logical and object oriented programming paradigm to describe the 'intensions' and 'extensions' of the object and thus to elucidate it from various angles.

Method banks are information systems in which data and methods are generated from available data and methods. At CWI they will be used in connection with flow calculations, computer assisted pre-design and production planning (ISNaS, ICADES and SPIN/-FLAIR, respectively). A syntax of the mapping mechanism in dialogue cells was devised to discover which functions of the dialogue cell system can be used to describe the interactions between applications.



On behalf of Dutch Railways, CWI developed a database for marshalling yard storage, in combination with an interactive graphical editor to make changes in the database. The editor makes it possible to shift tracks, change semaphore image cards, etc., assisted by such tools as consistency controls. For example the database could be asked if the distance between two semaphores is sufficient for all possible signal colours. The editor was implemented using the specification method DICE, developed at CWI.

Several members of the Department were involved in the preparatory activities for the EUROGRAPHICS 87 conference in Amsterdam. Ten Hagen acted at the 1986 chairman of the European Association for Computer Graphics.

Supporting Services

Technical Support Sector (STO)

STO operates in two differing areas: programming and publishing. In the past programming support concentrated on direct outside commissions, in 1986 there was a further shift towards internal CWI activities. Increased support went to both scientific departments and such general computing facilities as text processing and office automation. Most support services concern scientific departments and their external commissions; to a lesser extent STO is also involved in the automation of these departments' data handling (e.g. work on the Graphical Kernel System (GKS), ESPRIT project DIAMOND and the STATAL project).

Increased use of CWI's own UNIX™-systems, PC's and external computer system led to a growth in demand for internal, CWI, user support. A separate group was formed to meet this need, one of its major tasks being to support the text processing division.

1986 saw a proliferation of texts produced on the institute's own personal computers. STO developed software needed to suit these texts to the UNIX word processing system.

In the area of office automation, CWI introduced the INGRES database management system and its first applications were made operational. STO is examining INGRES's potential in automation of the CWI library.

As in previous years the sector also accepted direct commissions from other scientific institutes, government bodies, banks and industry. Especially interesting was the calculation of models describing the absorption of solid material from a fluid by active carbon. These models are relevant to the purification of waste water. Ongoing calculations were commissioned by the Dutch firm Norit.

The Publication Department deals with the text processing, editing, layout and reproduction of CWI's scientific Newsletters, Monographs, Tracts, Syllabi, Reports, etc., and other publications including annual reports and doctoral theses. Phototypesetting facilities are available for the text processing. CWI Monographs are produced in cooperation with the North-Holland Publishing Company. A good deal of work is also done for bodies such as the Dutch Mathematical Society.

Library and Information Service

CWI is fortunate in its excellent library. Indeed the extensive collection of journals (1000 current subscriptions), ca. 30.000 books, and a large collection of research reports (ca. 45.000) is of national importance. The library publishes a national catalogue of journals held by the Institutes of Mathematics and Computer Science of the Dutch universities. As requested by the European Mathematical Council, it collects European preprints, research reports, etc., and regularly distributes lists with bibliographic data, so providing a current awareness service on 'grey literature'. For its on-line information retrieval service, the library has access to large international databases on mathematics and computer science.

Computer Systems and Telematics Sector (CST)

CST's main task is to provide the scientific departments and other supporting sectors of CWI with adequate computer facilities. Work consists of acquisition and maintenance of hardware and its accessory software, as well as research and development of new software.

Alongside CWI's existing computer systems running under UNIX (mainly for the scientific departments), 1986 saw a considerable increase of personal computers (chiefly Macintosh), mainly used for text input. The incorporation of these computers into the existing systems, and their maintenance, required considerable manpower. For many years CWI has been the pivot of EUNET, the European Wide Area Network of UNIX to which more than 10.000 systems are currently connected. Other networks, some worldwide, can be accessed through *gateways*, giving entry to a total of around 30.000 systems. CWI acts as the main EUNET/USENET gateway between Europe and North America. CWI has acquired an important position in Europe in the standardization and developments of networks. Work in this area, and on the integration of existing and/or planned European networks, continued. A text processing project was started to preview matter for the phototypesetter on various output devices (bitmapped displays and laser printers).

In June, a request to participate in the Euromath Project was submitted to the Stimulation Action of the European Commis-

sion. Euromath aims at establishing a network infrastructure for European mathematicians to exchange electronic mail and news, as well as building a European literature database.

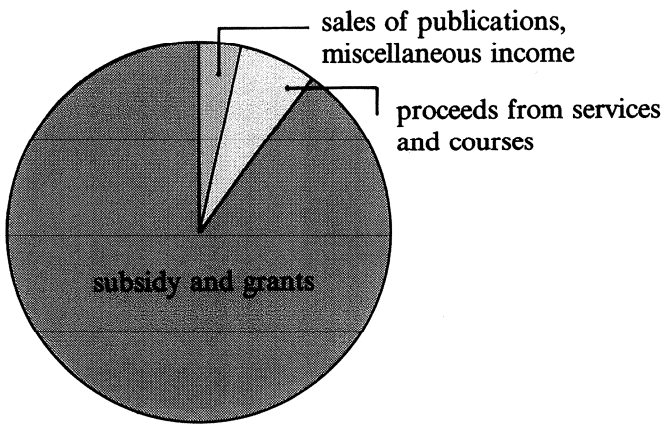
At the end of 1986, the CWI hardware configuration consisted of four VAX-11/750, one VAX-11/78-0, one PDP-11 computer, one SUN-3/180 fileserver, a 3b2 microcomputer, a Data General MV/4000, two IBM-PC/RT, and workstations consisting of two SUN2, six SUN3 and five Whitechapel MG-1's. Almost all of these are interconnected via a local Ethernet network. Peripherals consist of various printers, a Harris phototypesetter, a Versatec and disk storage of around 6.5 gigabytes. There are also 13 Olivetti M-24 and 47 Apple Macintosh microcomputers, mainly for stand alone use, but on occasion as terminals, as well as other microcomputers including an Atari ST, a Grid, and IBM PC's.

Finances

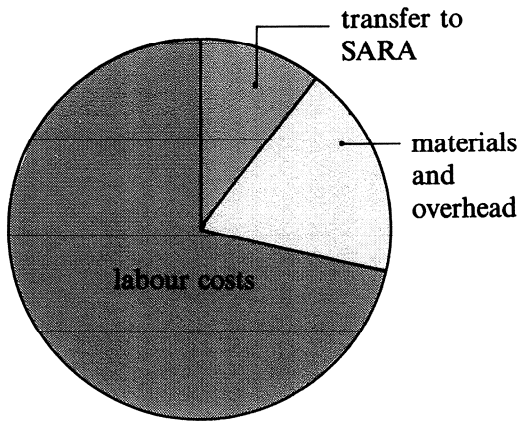
In 1986, SMC spent over Dfl. 18 million, of which about Dfl. 1.8 million was allocated to research by the national working communities and over Dfl. 16 million to CWI.
The expenses were covered by a subsidy from ZWO (Dfl. 13 million), from SION (Dfl. 0.08 million), from INSP (Dfl. 1.75 million), from the Free University of Amsterdam VU (Dfl. 0.075 million), from STW (Dfl. 0.03 million) and from a grant of more than Dfl. 1.26 million from the European Community for its ESPRIT and ADA projects. Finally, an amount of about Dfl. 2.1 million was obtained as revenues out of third-party-services, courses and other sources.
During 1986 CWI also employed 10 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	1800	14387	16187
proceeds from services and courses	-	1517	1517
sales of publications	-	132	132
miscellaneous income	-	488	488
total income	1800	16524	18324
expenses			
labour costs	1824	12035	13859
materials and overhead	12	2678	2690
transfer to SARA	-	1700	1700
total expenses	1836	16413	18249
origin of subsidy and grants			
ZWO	1800	11189	12989
SION	-	82	82
INSP	-	1750	1750
VU	-	75	75
STW	-	30	30
ESPRIT	-	1261	1261
total	1800	14387	16187

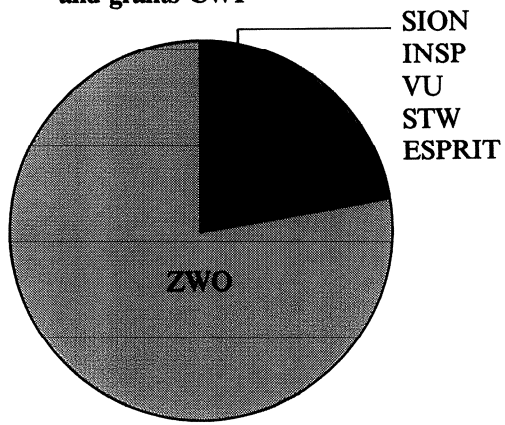
income CWI



expenses CWI



origin of subsidy and grants CWI



Foreign Visitors

Pure Mathematics
J.-Ph. Anker (Switzerland)
E. Badertscher (Switzerland)
M.S. Berger (USA)
L. de Branges (USA)
A. Cornford (USA)
Y. Desmedt (Belgium)
W. Diffie (USA)
H. Dym (Israel)
R. Ferreira (France)
S. Herda (FRG)
E. Horozov (Bulgaria)
H. Imai (Japan)
D.A. Leites (Sweden)
T. Matsumoto (Japan)
P. Nevai (USA)
J.L. Nicolas (France)
R. Peralta (Chile)
S.J. Prokhovnik (Australia)
J. Seberry (Australia)
D. Stanton (USA)
D. Stodolski (Sweden)

Applied Mathematics
J.P. Coleman (UK)
B. Fiedler (FRG)
M. Guevara (Canada)
M. Gyllenberg (Finland)
H. Hirata (Japan)
K.E. Shuler (USA)
J.J. Tyson (USA)
S. Ushiki (Japan)
B. Zwahlen (Switzerland)

Mathematical Statistics
D. Boos (USA)
K.-T. Fang (China)
P. Green (UK)
J. Grüger (FRG)
N.L. Hjort (Norway)
M.R. Leadbettter (USA)
T.A. Louis (USA)
E. Mammen (FRG)
I. Meilysson (Israel)
D. Moore (USA)
D. Siegmund (USA)
E. Valkeila (Finland)
A. Yashin (Austria/USSR)

Operations Research and System Theory
M.L. Balinski (France)
J.A. Ball (USA)
L. Baratchart (France)
R.K. Boel (Belgium)
R. Bordewisch (FRG)
H. Bruneel (Belgium)
C.I. Byrnes (USA)
P.E. Caines (Canada)
N. Christopeit (FRG)
B.L. Fox (Canada)
B.A. Francis (Canada)
I. Gertsbakh (Israel)
A.B. Kurzhanski (Austria)
A. van de Liefvoort (USA)
R. Marino (Italy)
B. Meister (Switzerland)
S. Morse (USA)
G. Prastacos (Greece)
W. Respondek (Poland)
R. Rider (USA)
W.A. Rosenkrantz (USA)
J.-M. Rousseau (Canada)
F. Soumis (Canada)
R. Syski (USA)
H. Takagi (Japan)

Numerical Mathematics
D.V. Anderson (USA)
H. Brunner (Canada)
J.C. Butcher (New Zealand)
J. Dongarra (USA)
P.P.M. Eggermont (USA)
W. Enright (Canada)
M. Erl (UK)
H.C. Fischer (FRG)
R. Haggenmüller (FRG)
G.S. Hodgson (UK)
K.E. Karlsson (Sweden)
D.P. O'Leary (USA)
G. Meurant (France)
M. Nakashima (FRG)
J.L. Nicolas (France)
A.M. Odlyzko (USA)
J.M. Sanz-Serna (Spain)
C. Ullrich (FRG)
P.J.L. Wallis (UK)
J. Wolff van Gudenberg (FRG)
A. Zöllner (FRG)

Software Technology
S. Abramsky (UK)
K.R. Apt (France)
P. Azema (France)
H. Barringer (UK)
D. Clement (France)
M. Diaz (France)
E.A. Emerson (USA)
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ERRATUM

The arrows in the figure on page 14 are wrong and should be given as follows: