CWI

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Supplement: Description of Projects

Centrum voor Wiskunde en Informatica
Centre for Mathematics and Computer Science
Amsterdam the Netherlands

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Centre for Mathematics and Computer Science

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The Centrum voor Wiskunde en Informatica (CWI)
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Project List

Introduction

Wherever possible, and as far as funds and personnel availability permit, CWI aims to develop promising new research projects in the fields of mathematics and computer science. To this end cooperation with other research groups and tuning to research carried out elsewhere in the Netherlands (at universities, large technical institutes and in industry) will be pursued. It is frequently the case that new projects will link in with those already in progress and that old projects will cease or continue in a renewed or modified form.

The short descriptions which follow cover those projects CWI expects to be involved in from 1988. Several of these involve interdisciplinary research with input by more than one CWI department. Hence, rather than rigid adherence to departmental order, the descriptions have been 'clustered' around the themes of Analysis, Stochastics, Numerical Mathematics, Algebra & Combinatorics, Software, Algorithms & Architecture, and Interactive Systems. Even so, some projects described overlap into more than one 'cluster'.

Global analysis

The importance of global analysis as research field goes beyond the purely autonomous. It is also a significant aid in mathematical physics. Research at CWI concentrates on the study of differential equations on various manifolds, e.g. projective spaces and Grassmann manifolds. In future the study of invariants will occupy an important place in this research. The subject links up with other, ongoing CWI projects. CWI had in the past dealt with such sub-sections of global analysis as stability theory, ergodic theory, strange attractors and bifurcation — albeit on occasion sketchily. However there is a particular link with research performed as part of a project currently entitled 'Mathematical Physics': this gives special attention to integrable systems (in addition to aspects of global analysis these contain aspects of, e.g. representation theory and algebraic geometry). Examples of integrable systems are Toda lattices, the Korteweg-de Vries equation, the self-dual Yang-Mills equation, non-linear σ-models and some thirty further equations, several of which have important applications: CWI research emphasizes the symmetry aspects. The aim is to allow the Mathematical Physics project to grow in the direction of global analysis. CWI will also bring the ongoing research in analysis on semisimple Lie groups and symmetrical spaces under the Global Analysis project. It is important that CWI keeps its expertise in this field.

Non-linear functional analysis

The classical linear analysis (on Hilbert- and Banach-spaces) has extended into non-linear functional analysis with powerful stimulation from applications in physics and biology. A number of stated problems require improvement to existing techniques and the development of new methods. There are considerable hopes for geometrical and in particular topological methods such as those from the 'Russian school' (Krasnoselski and others). Modern research links up with Poincaré and Julia's methods for dynamical systems which now, after half a century, are once again attracting much interest.

In the Netherlands work concentrates on dynamical systems for as far as these concern so-called Hamiltonian systems, with celestial mechanics as field of application. The CWI project envisages laying the accent on dissipative dynamical systems and study of their applications in both physics and biology. The project also aims to acquire more insight into the structures of solutions of non-linear functional equations. Such equations offer a good framework for the description of, among other things, chaos, strange attractors and invariant measures.

For the qualitative — or geometric — theory of infinite-dimensional dynamical systems traditionally important sources of inspiration are: diffusion problems, wave propagation and retarded cause-effect relations. Recently a new source has been explored, in particular due to biomathematical research at CWI: partial functional-differential equations describing the dynamics of physiologically structured populations. The proper framework for this class of problems is provided by a systematic use of duality. Semilinear problems can be simply and effectively analyzed by applying the perturbation theory for dual semigroups of operators developed thus far. The next steps are now the eleboration in the context of some concrete biological models and rewriting the general theory of functional-differential equations using the new apparatus of notions and propositions. Research will focus on stability and bifurcation theory, but will also consider the possible role of duality in other aspects of the theory. Moreover it will be attempted to form a theory for quasi-linear problems. Also the long-term aim of this project is to achieve an integration of modelling biological phenomena, the analysis of concrete problems and the development of a general functional-analytic framework.

Asymptotics

For many problems in physics and biology, asymptotic methods are important aids in gaining qualitative information on solutions for equations and in constructing approximations to problems. This way gives insights into the independence of parameters in the problems which are not always available via numerical methods.
The considerable experience built up in recent years has made CWI a brains-trust for problems in complex analysis, integral and differential equations. The constant flow of interesting problems from outside — problems relevant to CWI's own research — helps justify the continued manpower input.
The systematic research into standard methods and techniques is being continued. An important part of this research concerns asymptotics of integrals and, in particular, uniform expansions. A monograph on this subject is in preparation. Functions from physics and statistics often provide the spark for development of new ideas and established methods. Although the approach to this project is general enough, work concentrates on application-oriented problems with attention to numerical utility as well.

System and control theory

The purpose of system and control theory is to formulate and analyse mathematical models for dynamic phenomena and to develop algorithms for control and prediction problems. Practical importance is reflected in a widespread demand for automatic control and data processing for industrial robots, traffic and computers, the processing of speech signals, air and water pollution warning systems, etc.
This has resulted in CWI research into the area of *realization* and *system identification, control theory* and *filter theory.* The system theory is studied from two directions: deterministic and stochastic. A central element of the first is the study of linear systems as occurring in e.g., mechanics, electrical networks and economics. Particular attention goes here to realization theory, metrization and approximation, and control and prediction. Detailed work involves representation theory of systems with a Hamiltonian or gradient structure: among other things, this is important for the dynamics of large, highly flexible mechanical structures. Many control and prediction problems are partly stochastic in nature e.g., overload control in telephone exchanges and image processing. Thus one aim is to arrive at a theory for stochastic systems. With this in mind, stochastic aspects of the above mentioned research fields are studied in various situations. Further research concerns systems with a generalized state space (descriptor systems). These are not necessarily causal linear systems for which CWI hopes to expand the geometric approach which proved so successful with causal systems. CWI would also like to work on a system and control theory for systems on infinite spaces: there is demand for this in communication technology and computer science. Specific problems are: signal processing of discrete valued signals; representation and control problems in computer science (especially for relational databases and knowledge bases); and the control of automated production systems.
Finally, CWI has two STW financed projects in the field of system and control theory: prediction and control problems for freeway traffic and overload control in communication systems.

Processing and reconstruction of images

In many areas one is increasingly confronted with information in image form, for example television pictures. X-ray or gamma ray images, satellite photos, and radar and sonar charts. The (re)construction, processing and analysis of such images — unthinkable without the computer — now offer a promising field of study on the border line between mathematics, computer science and technology.

The broad range of application is reflected in the wide spectrum of mathematical disciplines involved: analysis, algebra, topology, numerical mathematics, statistics and system theory; and, of course, computer science also plays an essential role. Ideally, all the ingredients for this archetypal multi-disciplinary research project should be located under one roof, and indeed that is the case at CWI. Within the Centre, various subdisciplines maintain close contacts in this subject.

An important element in image reconstruction is computer tomography, with particular application in medical science, but also, e.g., in the analysis of seismic data in oil exploration. The mathematical basis which in principle provides the solution of the problems — the Radon inversion formula — dates back to 1917. However, in practice there are numerous obstacles such as instability of the numerical procedures. Statistical techniques are increasingly important due to the large quantity of data to be processed, the inevitable noise which occurs in practice and the necessity of using à priori (statistical) information about the object.

In digital image processing much attention is paid nowadays to mathematical morphology, a systematic theory of image transformations and functionals mainly designed to formulate quantitative statements about images. The most important principles of mathematical morphology are translation invariance and semi-continuity. Another interesting development is the use of Markov fields and 'statistical cooling' by Geman & Geman (1984) in the segmentation and restoration of images distorted by noise. Here many elements from statistical physics are found, for example stochastic Markov fields, Gibbs distributions and Ising models.

Over the next few years CWI work on this project will concern four subjects.

- *Reconstruction of NMR images,* the study of reconstruction problems relating to moving images; research has already begun and involves contact with Philips Medical Systems Division.
- *Mathematical Morphology.* It turns out that the algebraic structure of the object space (complete lattice) is important in characterizing morphological transformations (and functionals) and that translation invariance is just one of the many possibilities. Another possibility is rotation invariance in combination with scaling. First of all the fundamental algebraic and topological aspects of mathematical morphology will be studied. It is expected that gradually also attention will be paid to applications.
- *Inverse scattering and image processing of seismic data* - which involves reconstructing the structure of earth layers, a joint study with Royal Dutch Shell Exploration and Production Laboratory; work has already started.
- *Statistical Analysis of image data* — the aim of which is to arrive at a general methodology for attacking classic statistical problems — ranging from explorative data analysis and model-building to estimation and testing problems — with data in image form rather than series of numbers. CWI collaboration on this with TNO and CSIRO (Australia) includes the use of common case-study material. A specific statistical study of image data from electron-microscopy is already underway.

In a statistical analysis, one attemps to draw up a stochastic model with parameters corresponding to questions which are important to the researcher. In general an image contains such a quantity of information that most operable models are incapable of generating them. CWI wants to concentrate on partially specified models, the stochastic analysis of which requires new principles. It is expected that *stochastic geometry* (the study of stochastic geometrical objects) and *fractal theory* could supply useful building blocks for such models: for instance fractals in the measurement and analysis of textures (a highly important subject still lacking theoretical foundation). Stochastic geometry already plays an important role in stereology (statements on spatial objects derived from low-dimensional cross-sections). Both disciplines have strong links with mathematical morpho-

logy, in particular as regards the use of 'structural elements'. It is likely that stochastic geometry can also contribute to the solution of *discretization problems* (discrete sampling of continuous objects).
Consideration is also being given to subjects such as the application of *cellular automata* in image processing and the use of *multi-resolution methods* for moving images.
Most of this research requires the availability of an *image processing capability* and the appropriate software; help on this will be required from the Interactive Systems department. CWI aims for the speedy introduction of these aids.

Computational statistics

Traditionally, Dutch statistical research has always been highly theoretical. However, a meaningful expansion of fundamental statistical research at CWI must involve the innovative use of modern hardware and software. This will be speeded by the formation of a research group on computational statistics.
Computational statistics is a new project (at this time still part of the project Applied Statistics). The explosive growth in power and means of calculation has made available a whole range of previously impossible statistical models and methods of analysis: this in turn has led to interesting new mathematics such as semiparametric models and Efron's bootstrap method. Expertise in this area is essential if the results of scientific research into mathematical statistics are to be put into practice and meaningful consultation offered in statistics. CWI is involved in joint efforts for the practical application of statistics e.g., the long running consultation project with The Public Works Department and the national meteorological institute KNMI on flood levels along the Dutch coast. The success of such projects will both significantly promote future cooperation and the wider use of results produced. Work is also underway with developmental psychologists and ethologists on development of a package for data analysis of ongoing observation protocols. CWI is also preparing two STW applications concerning the statistical analysis of software reliability (debugging models) and spline smoothing in the Wicksell problem (stereology).
This project ties in with traditional CWI research activities such as the study of semi parametric models — a subject from fundamental statistical theory which has also attracted significant international interest. Spectacular findings at the meeting point of mathematical statistics and numerical mathematics can be expected from this quarter, e.g. in connection with selection of discretization/smoothing parameters. CWI will research computer implementation of semiparametric estimation methods; in the longer term this will contribute to an integration of algorithmics and stochastics in statistics.

Semiparametric statistics

Given the ever growing interest in this sector of theoretical statistics, long running CWI research will be continued in several new directions. Fundamental CWI research concentrates on situations with parameters or observations from infinite dimensional spaces ('abstract inference'). The purpose of this project is the derivation of statistical procedures and the determination of their properties in semi-parametric models (with both parametric and non-parametric in elements), and the application of techniques from parametric statistics to non-parametric models — estimation theory in particular.
In semiparametric estimation theory attempts are made to model parametrically only that part of a phenomenon which is of specific interest. Hence, quantitative conclusions on that part can be drawn without the necessity of making further, unrealistic assumptions. In relation to the question of how to construct optimal estimators, the results of research on the NPMLE (non-parametric maximum likelihood estimator) will now be formulated as generalized M-estimator for a general normed vector space. The theory must include and explain special cases like the Cox regression model. Research into application of modern empirical process theory on semi-parametric models will also be carried out as part of the National NWO project 'Statistics for large parameter spaces', and CWI will cooperate with statisticians from Nijmegen,

Leiden and the two Amsterdam Universities. Bootstrap methods are used in many statistical problems to estimate variability of statistical quantities. They are semiparametric in a broader sense, namely that non-parametric methods based on empirical distribution functions are used to measure the accuracy of estimators in (among other things) parametric models. Research will be continued in the following directions: construction of bootstrap confidence intervals based on generalized L-statistics; smoothness assumptions in the proof of asymptotic optimality properties of the bootstrap; and the asymptotic behaviour of jack-knife and bootstrap estimators in situations where classic methods are inoperable. A course for potential bootstrap users from industry will also be organized.

Stochastic processes

Stochastic aspects arise in several of the projects described here, e.g. overload control in telephone exchanges, image processing, performance analysis for computer and communication networks and in algorithms for combinatorial optimization. There is also ongoing research into dynamic systems with reference to the effect of stochastic disturbances — and the determination of transport parameters in connection with stochastic walks on random networks. Research in this project concentrates on stochastic processes seen from the angle of statistics and probability theory. At CWI, stochastic processes are studied in space *and* time, including stationary processes and stochastic models for traffic flow. Attention is also being paid to the fundamental theory of statistical analysis of stochastic processes.

In researching which stationary processes can be described as functionals on a Markov-chain, CWI attempts to use insights from physics (where certain processes are described through 'interaction'). Special attention will go to a multi-dimensional lattice of stochastic variables and the time evolution thereof. Research into the unicity of the Gibbs distribution for such a lattice (there are links here with the phenomenon of phase transition) continues. There are meeting points with such problems as queue forming in traffic theory and the development of cellular automata in computer science.

The probabilistic aspect of image analysis will also be explored, particularly in relation to the methods of image restoration based on work by Geman & Geman (digitalization leads to discretization and anisotropy effects). Knowledge of statistical behaviour of certain measured parameters, such as average speed and interval time, is highly important for good detection of irregularities and changes in traffic flows. With this in mind, stochastic models in space *and* time for flows are being designed in close cooperation with the Public Works Department and later tested using their data. Such models describe the origin and course of shock waves and the movement and build-up of disruptions.

As far as the statistical analysis of stochastic processes is concerned, special attention goes to analysis of observations on a semimartingale on the basis of its Grigelionis characteristics which describe the infinitesimal probabilistic development of the process. Simultaneous use is made of the modern theory of asymptotic statistics, based on local asymptotic normality (Ibragimov and Has'minskii). An important theme is research into partially specified models. Regression analysis and time-series analysis in which only the first and second order characteristics of a process are modelled spring to mind. An optimality theory for estimators in such models scarcely exists. Many aspects of this research tie in with the Semiparametric Statistics project.

Analysis and control of information flows in networks

This project covers performance analysis of computer systems and telecommunication networks. Emphasis is on the study of congestion and control mechanisms for these. Alongside traditional applications in telephony, CWI research concentrates on communication in-and-between computer systems and through satellites. The fast growing influence of computer and communication systems on daily life adds to the wider importance of this project. Traffic flows in these systems are stochastic in nature. The major part of mathematical theory of complex stochastic systems is still in its infancy.

The model to be studied consists of a network of service units with queues of customers waiting for service. The main quantities of

interest are waiting and sojourn times, queue lengths and blocking probabilities. CWI research is concerned with both fundamental and applied sides of the subject.
In the analysis of queueing models the emphasis is on exact analytical techniques, in particular for boundary value problems, time dependent behaviour and interaction between internal and external traffic flows.
Telecommunication is in a state of major ongoing change. Increasing digitalization in communication will result in the transmission of speech and image, alongside computer data, over the same network (ISDN = Integrated Services Digital Network). Queueing theory is the ideal aid for quantitative insight into the performance of such a network. In coming years CWI will study overload control (also see *System and control theory*) and integration of various traffic types, as well as flexible manufacturing.
In the performance analysis of computer systems, research on various protocols (token ring and others), feedback mechanisms (among others — in relation with time-sharing) and machine sequencing problems. In line with the international trend CWI will intensify its engagement in software tools such as standard packages for queueing analysis.
Finally, research will start into the reliability and availability of systems subject to breakdowns and wear (modelled as a stochastic process). There is a strong resemblance here with queueing analysis of complex networks. The initial stage will deal with decision rules for systems with two components; systems with more components will be dealt with later.

Numerical software

The project divides its attention over the programming language Ada and parallel numerical computation.
The *programming language Ada* (US Department of Defence, 1983) was initially designed for 'real time computation'. However, it is generally accepted that the language will be used in many other areas including large-scale scientific computations. Given that numerical calculations occur in a very many scientific and computer applications, there is a clear necessity for an Ada numerical software library. The portability requirement rules out the possibility of supplying simple interfaces with existing software libraries in other languages. The making of a portable program packet demands total uniformity for use of Ada's considerable potential such as new types, operators, hierarchical classification of libraries, program build-up, separate compilation and the linking of program modules, error recovery and parallel processing. The introduction of Ada as part of efforts to produce large-scale, reliable, efficient and portable software is receiving powerful support from the European Commission.
CWI will contribute to the following goals as part of the Ada-Europe Numerics Working Group and an EEC subsidized project:

- Expansion of Ada via the proposition and introduction of a universal standard for elementary functions.
- Achievement of a high degree of accuracy in end results of compound floating-point calculations (project supervised by Siemens, Munich).
- Research into a possible successor (as part of ESPRIT) for a completed pilot study for the production of a complete numerical program library in Ada.

Parallel numerical computation hovers in anticipation that the next break-through in the area of computer application will occur with the aid of parallel processors. Initial thought is of numerical applications such as the modelling and simulation of processes in physics and chemistry (three-dimensional flows round an aircraft, water flows, pollution effects, molecular structures, many-particle problems), as well as processes with a non-numerical flavour (economic models, traffic simulation, translation projects, artificial intelligence). A significant number of parallel systems is already operative (CRAY X-MP, iPSC, Sequent, Alliant, Connection Machine) with extensive software (operating systems, C-, Pascal-, Fortran 77-compilers), and are highly successful in practice. Many major international companies, research laboratories and universities use these computers. Hence, researchers at these organizations have been able to build up a significant lead and their research programmes have received a major boost.
The aim of the proposed CWI project is to research parallel numerical methods for the solution of mathematical problems arising from the modelling of applications as listed above, and hence to play a national coordinating role. It should be noted that develop-

ment of this research is largely dependent on availability of an existing parallel system. Unfortunately, CWI does not at present have access to such a system.
Some years ago CWI started a similar project in the vector computing sector. The subject attracted considerable interest in the Netherlands, as did CWI's national colloquium. In autumn 1987 CWI organized a course 'Vector and Parallel Computing'.

Numerical solution of stationary problems

Research in this project is directed at the development and analysis of modern techniques for the efficient solution of boundary value problems. The equations linked to these problems often occur in technical applications (theory of strength, hydrodynamics, electricity and the like). Given the extent of the research field, CWI focuses its activities on the study of multi-grid techniques; these permit the efficient solution of very large systems of algebraic equations.
One section of the project involves continuation of existing research into fundamental analysis of multi-grid algorithms and the link with other defect correction techniques, study of singular perturbed boundary value problems, the use of adaptive methods with (nearly) discontinuities in the solution of a partial differential equation, and background research for the development of efficient methods for compressible Navier-Stokes equations.
Current research commissioned by the European Space Agency (ESA) is directed at convergence speed-up of the Finite Volume Euler-discretization method with the aid of the multi-grid method. This builds on results achieved in the development of a fast solving algorithm for the stationary Euler equations for two-dimensional flows on the basis of multi-grid techniques. Research is directed at two-dimensional flows (also with discontinuities) in various types of channels or around aircraft profiles.
New research concerns the study of numerical methods for semi-conductor calculations. These are of crucial importance to the electronics industry. In the last ten years computer simulation — alongside and instead of prototype production — has become essential in the development of semi-conductors and chips. The mathematical model consists of a system of coupled strongly non-linear partial differential equations. The current situation is extremely unsatisfactory — numerical methods being far too slow and their reliability suspect into the bargain. More computer facilities will not help: the numerical techniques are insufficient and require fundamental research. The actual problems are: strong non-linearity, variables varying widely in order of magnitude, strongly singular perturbed behaviour, and a complicated geometry. Research aims are: mathematical analysis, development of adjusted discretization techniques, adaptive grid generation, non-linear multi-grid methods and three-dimensional problems.
Research in this field is conducted at institutions including the Technical University of Vienna, Bell Laboratories, Stanford, and Philips ISA at Eindhoven. Contacts with Philips have already resulted in contract research. However, the project envisaged is far more fundamental in nature and should be considered as quite new. It will be conducted as part of the national Innovative Research Programme (IOP) in IC-technology.

Numerical solution of evolution problems

This project covers the development, analysis and documentation of algorithms for numerical solutions of initial value problems for partial differential equations. The aim is to gain insight into the stability, accuracy and efficiency of the algorithm. The research is amongst others important for computational fluid dynamics. The arrival of supercomputers has helped make this an area of great and growing importance and interest.
An important part of this project is research into adaptive grid techniques. These are involved in the development of numerical software when the aim is maximum user friendliness via maximum automation of the numerical solution process. There is particular demand for this from engineers, chemists, electronics specialists, etc. in the major industrial research laboratories, who have little or no knowledge of the solution method used. A good illustration of this is an evolution equation with a steep wave front as solution. A calculation of this sort demands an extremely

fine, and therefore expensive, grid. Adaptation of this to the local situation, preferably controlled by realistic error estimators, could lead to a significant cost saving. However, much fundamental research is needed. Dutch universities are not working yet on adaptive grid techniques. CWI does have a project underway on the subject and this (STW) project can be seen as a restructuring of it. CWI will be working with Shell which is involved in similar research. Background research will also be conducted into Lagrange methods. The subject is the centre of considerable international interest. Contacts have already been made with international institutes: the Reading Institute for Computational Fluid Dynamics (Oxford), Rensselaer Polytechnic Institute and NASA Langley Research Center, and the Universities of Leeds and Valladolid.
Research is also planned into three-dimensional shallow water equations, as part of joint efforts with the Public Works Department and the Delft Hydraulics Laboratory. The introduction of vector computers has brought the numerical treatment of such problems in sight. Time dependent three-dimensional flow and transport processes will be calculated in a multi-layer model originating from the Rand Corporation (USA). Given the greater computational burden in comparison with a two-dimensional model, the most efficient possible algorithm is highly important. CWI already has considerable experience with explicit techniques for shallow water equations on vector computers.
In 1987 CWI concluded the STW-project 'Evaluation and stabilization of numerical methods for the shallow-water equations'. Based on the software developed in this project, a new STW-project has been applied for, concerning the development of a Boussinesq model.
Other research in this project concerns stability and convergence for non-linear problems, the incompressible Navier-Stokes equation and differential-algebraic equations. Lastly, background material will be supplied for use of numerical standard packages for the mathematics courses to be developed by the Open University.

Cryptography

Strong development can be expected in the future use of distributed computer systems, for instance in electronic payment transfer and in networks in which confidential information is transmitted. Computers within such systems are often linked by insecure or unprotected channels. Information can thus be forged or 'overheard'. Cryptographic techniques help increase the confidentiality of distributed computer systems. Cryptography covers the study both of protecting confidential information via coding and the prevention of forging information being transmitted over an insecure channel. In the latter case information is provided with a 'digital signature' and a protocol for the transmission of the message.
The CWI project is directed at the development and implementation of cryptographic protocols, research into existing systems such as DES (Data Encryption Standard) and the development of the mathematical foundations. Primary subjects for the coming years will be the creation of new protocols for the protection of distributed systems — in particular for the transmission of messages, payments, letters of credence and in general calculations by more than one user.
The intended protocols are based on existing ideas on 'untraceability' and 'limited pseudonymity'. This will demand further innovative research in the area of protocols, cryptographic algorithms and analysis by complexity theory. General theoretical research will also be continued into cryptographic protocols and the study of conventional cryptographic techniques (research into the DES system, design and evaluation of algorithms).
Work will continue on plans for the reinforcement of CWI's role as a clearing house of cryptographic expertise. Activities in this area will cover, for instance, consultancy on the procurement of cryptographic equipment by Dutch non-military bodies, the organization of European cooperation to produce standard cryptographic algorithms, and various consultancy assignments for banks.

Symbolic computation

Symbolic computation and formula manipulation is becoming an increasingly important tool for the mathematical researcher. In many areas the limit has been reached on what can be achieved manually. Examples include the calculation of character tables of groups and calculations of Lie groups of vector fields in connection with non-linear filter theory. In physics a classic example is the elaboration of Dirac algebra in calculations of elementary particle processes with the help of the SCHOONSCHIP program. Computer packages have been on the market for 20 years (SCHOONSCHIP, REDUCE, CAYLEY, MACSYMA, μMATH), and CWI could restrict itself to making these available (CAYLEY and MACSYMA are already available). However, to achieve good and efficient usage, CWI should be actively involved in the further developments in this area. There is still enormous research to be undertaken in this youthful field of computer mathematics. A specific and most welcome aim would be support for various CWI research assignments (process algebra, filter theory, asymptotic expansions in statistics, etc.). For CWI this is a virtually new project. In the Netherlands only the Universities of Twente and Nijmegen conduct research in this field. CWI offers the advantages of unique computer facilities and the associated expertise under one roof.

Combinatorial optimization

Geometrical and randomized methods in combinatorial optimization are subjects of increasing interest.
Geometrical aspects appear in models, proof methods, algorithms and in construction and decomposition methods. In geometry they cover a large area, including Euclidean spaces, finite geometries, homotopy theory and algebraic geometry.
The most striking examples are:

- polyhedral combinatorics, in which linear programming techniques are employed to arrive at the polynomial solvability of a variety of problems and the practical solvability of large-scale decision problems (such as a travelling salesman problem with 2392 cities);
- the basis reduction method for lattices, providing links with the classical geometry of numbers and with applications in combinatorial optimization, cryptography and number theory;
- homotopy methods, for the design of very large scale integrated circuits, using the topological structure of the underlying surfaces;
- 'computational geometry', of importance in areas as pattern recognition, computer graphics, robotics and concurrency control in databases.

In addition we would cite the eigenvalue methods and the corresponding theory of orthonormal representations, the construction of optimal codes, Seymour's decomposition method for binary spaces and Lovász' proofs based on homotopy and homology.
Stochastic aspects are relevant in the formulation of problem types, problem instances and algorithms. Stochastic problem types are related to models in stochastic programming and queueing theory. Stochastic problem instances form the basis for the probabilistic analysis of algorithms that is complementary to the traditional 'worst case' approach. Finally, stochastic or randomized algorithms are solution techniques that, to put it crudely, occasionally toss a coin.
For many types of recognition problems such as primality testing, there are randomized algorithms that work faster than deterministic methods but which carry a small probability that a wrong solution or no solution at all will be obtained. This research has led to a new rich brand of complexity theory. The randomization principle is applied to optimization problems in the context of the construction and iterative improvement of heuristic solutions. There are different types of randomized approximation algorithms that are known under figurative names such as 'extension and rotation', 'selection and clustering' and 'simulated annealing'. Research in this field is in an early stage.
The work on combinatorial optimization at CWI currently concentrates on *interactive* and *parallel* methods. A reorientation in the direction of *geometrical* and *randomized* methods is being considered.

Computer aided number theory

The objective of this modest project is the study of fundamental, often extremely old problems in number theory with the help of modern (numerical) methods and using fast computers. The project uses CWI's existing algebraic expertise.
Problems in number theory are often elegant and can be formulated succinctly. Thus they have both scientific and didactic significance.

The excellent computer facilities at CWI are an effective aid in this often rather dull, but indispensable collection of empirical facts.
Computer aided attempts are being made to extend the frontiers of today's knowledge as far as possible; in this process new 'phenomena' are continuously being observed as are, on occasion, their mathematical proofs. CWI has collected extensive experience in this area over the years; Riemann hypothesis, Merten's conjecture, Goldbach's conjecture, special numbers such as 'amicable' pairs and 'hyperperfect' numbers and the factorization of very large numbers.
In the foreseeable future the programme will include: research into factorization methods for very large numbers on vector computers and parallel computers (CYBER 205, ETA^{10}, NEC SX/2, CRAY X/MP) and progress of the research into construction methods for numbers with a special structure (particularly in the case of amicable pairs CWI is internationally playing a key role).

Concurrency

Distributed processing, in particular processing by more processors, is currently a central theme in theoretical and applied computer science. Developments in the architecture of computer systems fulfill an essential role here. In CWI's concurrency project the problem formulation is directed at parallelism in programming languages with extensions on the one side towards mathematical foundations such as domain theory and on the other side towards computer architecture inspired by parallel computation models.
Of the many studies on languages for concurrency we mention two of a revolutionary character: Hoare's 'Communicating Sequential Processes' and Milner's 'Calculus for Communicating Systems'. Both works introduce a number of fundamental concepts in concurrency and have been the source of inspiration for an impressive number of follow-up studies. Mathematical modelling for concurrent programming concepts is fundamentally more difficult than for sequential programs. In the latter, research into input/output behaviour in the form of an associated function is often enough. However, with parallel programs, it is generally necessary to pay attention to the history of the processing by showing in a structured way the actions undertaken and states encountered on the way. In addition, infinitely recurring calculations crop up in concurrency research. New techniques are required here — taken for instance from the theory of infinite words. One also meets new problems such as those in 'fair scheduling'.
In general the semantics of concurrency show commonality with formal language theory (for example trace languages) that do not occur in the sequential case. In the project metrical process theory is used for the foundation of various semantic models. Traces of computations reoccur in the form of Plotkin's 'resumptions'. A further objective of the project is to make contributions to semantic research in specific languages for concurrency and research into the soundness and completeness of formal systems to be able to describe characteristics such as correctness, termination and deadlock freedom of concurrent programs.
Over coming years the following associated subjects will receive (more) attention:

- attempts to unify the semantics of the common heart of the phenomenon concurrency as its appears in imperative, declarative and 'logic' languages;
- depth studies into semantics and proof theory of object-oriented languages, in particular POOL (Parallel Object Oriented Language);
- semantics of the data flow computational model.

Additionally a choice will be made from subjects as: concurrency aspects of database languages, massive parallelism and learning systems, and concurrency in relation to epistemical logic.
CWI will strive to continue the cooperative links forged within this project (National Project Concurrency LPC, ESPRIT). For the LPC we foresee continuation with the NFI project REX (Research and Education in Concurrent Systems).

Formal specification methods

Programming languages are extremely important in software engineering — and so are specification languages: these have the objective of mathematically describing the intended functionality of a software or hardware system and should therefore possess a formal

mathematical semantics, hence the current description, 'formal specification languages'.
This CWI project involves research into fundamental properties of these specification languages. This is particularly with reference to concurrency where primarily process algebra is used, and the description of data where specific use is made of algebraic specifications.
A wide spectrum of problem areas exists around formal specifications with as central theme the *design*, *verification* and *validation* of specifications (with the aid of automatically generated prototypes). These themes can be seen as successors to structured programming from the 1970's, the program verification themes of the late 1960's and automatic programming with roots in the 1950's. A considerable number of techniques and methods is already known for each of these themes. They will be studied in this project and if possible further developed.
Although the techniques applied in this project originate from software engineering, these sometimes appear to be usable for the specification of hardware components. This is the case in calculations on integrated logic circuits by means of process algebra. Research in the applications of formal methods in the specification of hardware is a secondary element of the project. Over a longer term expertise must be developed within this project on a broad range of formal specification methods, although the emphasis will remain on the development and fundamental analysis of a small number of mathematically accessible methods.

Extendible programming environments

This is a joint project with the Dutch software house BSO, the French research centre INRIA and the French software house SEMA in the context of ESPRIT project 348 GIPE (Generation of Interactive Programming Environments) which ends in 1989. The objective, with formal language definitions as basis, is to generate interactive programming environments in which there are facilities for syntax managed editing with simultaneous type verification, incremental evaluation and symbolic debugging of programs in that language. In the longer term efforts will be directed towards an interactive environment for the development of languages that is extendible in the sense that, with a newly developed language specification, a new (sub) environment will be automatically generated in which one can work with the language.
Realizing this objective will demand short and long term research in a number of areas:

- *Theory and practice of algebraic specification.* With regard to the static and dynamic semantics of languages this project is based on algebraic definitions of semantics.
- *(Incremental) parser generation for general context-free grammars.* By combining language definition modules, each containing its own syntax definition, the problem arises as to how the associated parsers can be combined as quickly as possible to provide a new parser for the combined grammar. The problem is brought to light more clearly in interactive syntax controlled editing of modules that define their own syntax.
- *Derivation of incremental algorithms from non-incremental specifications.* In making a formal language definition it is an advantage that no consideration has to be given to the required incremental behaviour of the type checker and evaluator to be generated.
- *Compilation of algebraic specifications.* Algebraic specifications cannot simply be carried out but require a compilation phase.
- *The generation of compilers from algebraic language definitions.* The GIPE project is limited to the interpretive evaluation of programs in the environment generated — but more rapid evaluation must be possible by initial program compilation.
- *Partial evaluation.* Partial evaluation is a general method to derive efficient, specialized programs from general versions. This method already plays a role in the derivation of incremental type checkers, but will win further importance in connection with the generation of compilers.

Expert systems

The research in this project is directed at the application of methods of knowledge representation (logical formalisms, production rules, frame representations), automatic reasoning (resolution, chaining methods, inheritance, agenda mechanisms) and the handling of incomplete and uncertain information in expert systems. This research is important because current research techniques offer insufficient support in the development and maintenance of extended knowledge bases. A clear declarative semantics of knowledge representation methods must be found. This has not yet been achieved within expert system shells. Semantics like these allow formulation of conclusions on inconsistency. Research will be undertaken into ways a separation might be made between the declarative and operational parts of a knowledge base. Frame systems could be of importance in this research. Frame representations also offer the possibility of a start in modularizing knowledge bases.

In the framework of PRISMA — a SPIN-project under the direction of Philips Research Laboratory in Eindhoven — the application of parallelism in expert systems is studied. This will lead to an expert system shell implemented in the parallel object-oriented language POOL-X. In this part of its research as well as in its other activities, the CWI project group collaborates with various institutions. The aim is to gain insight in the practical utility of the developed techniques. The realization of specific applications of the developed systems is pursued. These may inspire further research.

Logical aspects of artificial intelligence

The recent increase in the applications of artificial intelligence has led to a growing need for clarification and verification of its methods and techniques. The objective of this project is the provision of fundamental research into the logical foundations of certain aspects of artificial intelligence. Expert systems are considered in particular. Logical programming and deductive databases play an important role in this research. Logical programming has developed its own methods and techniques that are directly applicable in the construction of expert system shells. Specific questions arise here concerning the role of recursive rules, modularisation, selective control mechanisms, parallelism and meta-reasoning.

Deductive databases represent an extension of relational databases in which some relations are defined with the help of rules. This framework is particularly interesting whenever a specific form of reasoning has to be conducted around an existing collection of facts. The extension of deductive databases is exceptionally helpful in studying and formally defining phenomena such as non-monotonic reasoning, the production of explanations and probabilistic reasoning.

Attention needs to be given to the treatment of time whenever knowledge is described in a natural language. This problem belongs in the area of natural language processing. A successful approach to the problem assumes a good understanding of the use of time in natural languages and demands the proper representation of time and the creation of a time logic that can be linked to non-monotonic reasoning.

Term rewriting systems

Term Rewriting Systems (TRS) form a paradigm for calculation procedures. Lamda calculus, probably the best known TRS, already played a key role in mathematical logic in the 1930s — namely in the formalization of the concept of calculability. Much later the same reduction system played a role in a breakthrough in denotational semantics of programming languages. The associated system of Combinatorial Logic more recently appeared an interesting medium for the implementation of functional programming languages.

Of possibly even greater applicability for this task, and currently receiving particular interest, is Categorical Combinatorial Logic. This can establish a remarkable link between abstract concepts from category theory and elementary steps in machine calculations.

The attractiveness of Term Rewriting Systems lies in their extremely simple syntax and semantics that make good mathematical analysis possible. And, in principle, they lend themselves naturally to implementation of parallel calculations (the study of TRS being of fundamental importance for projects aimed at developing parallel reduction machines).

Another theme in which TRS theory plays a

fundamental role concerns the analysis and implementation of algebraic data-type specifications and 'equational programming'.
Yet another area of application is the capability of TRS to provide a decision algorithm for the 'word problem' in equational theories and for known algebraic structures such as groups and rings. Knuth-Bendix completion algorithms offer important assistance here.
One Term Rewriting System project being considered will cover aspects of fundamentals that have clear relevance for one or more of the numerous applications mentioned. The following studies spring to mind: reduction strategies, inherent sequential versus parallel characteristics of TRS, the capacity of TRS to simulate each other (existence of 'universal TRS'), and hierarchically structured TRS. An important theme is also the introduction of a term rewriting component in logical programming with the objective of integrating functional and logical programming.
Of separate importance is the area of type theories (Martin-Löf, De Bruijn with AUTOMATH, Huet and Coquand with the 'theory of constructions'). There is a natural link with this project through TRS as polymorphic lambda calculus.

Integrated user environments

Using new technical developments (faster processors, larger memories, raster screens) it has become possible to provide the rapidly growing group of end-users with environments that are more user-friendly than the now traditional environments based on control languages. Even so, once the more friendly exterior level is passed, even the more modern environments are not integrated: in principle they consist of separately operating applications that can only be brought into cooperation with the investment of considerable user effort. For most users, who do not program themselves, this is only possible by means of continuous manual intervention. As long as it remains a question of routine activities with tailored applications the problem is rare. However, practice shows that new users chiefly use computers for repeatedly changing tasks that are not defined beforehand. It is no accident that some highly successful commercial software products consist of a number of cooperating applications, but integration is on an ad hoc basis and the product in its totality has a closed character.
This project researches and develops the potential for environments in which the required integration can be achieved. Here applications are not individual units that can be 'called', but operate by means of an end-user, within a particular context, creating or changing objects (such as documents). The object of the project is to arrive at a demonstration version of a prototype of such an environment. Attempts are being made to co-operate with other partners such as in the area of office automation. An important element of the research is creation of a theory and the development of a methodology for application designers. In order to test the demonstration model to be made, it will also be necessary to develop a number of basic and other applications.
A desirable extension of this research would cover the area of end-user programming and visual programming. Here it is a question of creating new, relatively simple applications, that will be within easy reach of more end-users than by conventional programming methods.

Constructive algorithmics

In the recent past there has been important international progress in notation systems, calculi and theories for the systematic development of algorithms from specifications. CWI research has played a significant role in this and the new area is attracting attention at home and abroad. Here it is a question of a method of program development whereby the application of algorithmic laws and propositions allows the systematic derivation of programs from a high level specification. It is analogous to the way in which, for example, results are produced in integral calculus. Typing errors and such like apart (they can be largely mechanically controlled), the correctness of the resulting program is guaranteed.
Important subjects for research will be the transformation of deductive systems (logic programs) and transformation between deductive and other (imperative and applicational) styles, expansion of the concept 'executable specification' and the production of theories for more systems than can be currently handled.
Alongside fundamental research an NFI pro-

ject, oriented to the construction of a transformation system, will be started in co-operation with the Universities of Nijmegen and Utrecht.

Complexity and algorithms

This project has been operating successfully for some years. It involves the design of efficient algorithms, particularly for distributed computations, and fundamental research into the concrete complexity of algorithms. The increasingly large problems that can be handled by the computer significantly boost the need for more efficient algorithms. All types of technological developments, such as the increase in user comfort in programming environments, produce new and difficult algorithmic problems. CWI research into non-conventional architectures such as computer networks and distributed information systems also has a large algorithmic component. The questions cover the design, construction and use of hardware and applications. CWI is looking for solutions to these algorithmic problems via use of networks, parallel architectures and, for example, heuristic algorithms.
In the foreseeable future the research will stay directed on the development of theory for advanced distributed systems such as computer networks, multi-processor systems and integrated circuits. Particular attention will go to: architecture (communication graph), communication protocols and the interaction between the two. Important questions here include 1) the development of a formal computational model for multi-computers whereby communication costs are treated realistically, and 2) the development of theory on asynchronous communication interfaces.
New research concerns the implementation of atomic shared register access by asynchronous hardware in connection with the problem of concurrent reading and writing, and the phenomenon that theoretical algorithms and algorithms used in practice in computer networks use radically different assumptions about 'time'.
Research into distributed algorithms, protocols and architectures, and into the time dependence of algorithms is conducted jointly with the Massachusetts Institute of Technology (MIT).

Processor architectures

Since the late 1950's Dutch research into processor architectures has concentrated on the problem of creating processors with the aid of contemporary technology rather than on fundamental questions on the design of an architecture. There is a frequently advanced argument that research into processor architectures is only productive if on a scale (projects with 20 to 100 people), generally above Dutch resources. Experience proves otherwise: much innovative fundamental research in this area is being undertaken by small groups.
In the past, economic factors obliged designers of processor architecture to limit themselves to a small number of functions in order to arrive at a logical, orthogonal structure. The potential of putting a large number of functions on one chip, whereby virtually anything which can be thought of is possible in practice, has revitalized the demand for fundamental research into functional architecture design. In the meantime it is clear that of the possibilities of baroque architectures in practice only a relatively small part finds application, while some important functions are surrounded by such restrictions that the quality of software suffers. The aim of this project is to make a contribution to the theory in this area taking into consideration the changing use of the computer (such as larger code and data segments, many context switches, and object orientation). It is expected that in the next decade the number of (small-scale) European computer firms will increase when the techique of 'silicon compilation' can be used. In that case this research can be of great importance.

Methodology of open architectures

'Open architectures' are playing an increasing role in the developments of standards. In fact, an open architecture is nothing more than a collection of module interfaces. Existing standards developed on the basis of an open architecture approach — and the way such standards have been created — go to show that there is a significant requirement for a systematic methodology for the development of such an open architecture.

The knowledge necessary for this already largely exists and can be found in the literature. But in its current form, without further development, it cannot be directly applied to open system architectures.
Open architectures are also of importance without considering the objective of standardization. A good example is the Euromath project. This aims at an integrated work environment for mathematicians of which telecommunications for the exchange of information between mathematicians and for referencing databases form part. Also included is the processing of mathematical texts and the use of software for formula manipulation and such like. This environment will have to be achieved on a heterogeneous package of equipment and within a certain variation of operating systems, and will be made available in instalments. Such a situation is only possible if the system is structured on the concept of open architecture.

Distributed operating systems

The research in this current project is centred on the design and implementation of the distributed operating system Amoeba. This system consists of workstations, a processor pool, file servers and other specialized server machines, all connected through a fast local network. Users have the capacity of their workstations at their disposal, eventually replenished by processors from the pool. Moreover there are more or less specialized file systems where users can store and exchange information.
Amoeba is operational and its documentation and support is almost ready for general use in daily practice. Research now focusses on two important fundamental problems: extensibility and error insensitivity. Ideally a distributed system should be extendible without limit (*scalability*) in the sense that doubling hardware components leads to double user capacity without change in response times (under equal work load). Furthermore users become more and more dependent on uninterrupted availability of computer systems. Therefore a distributed system should be very reliable and error tolerant. As a consequence it is important to design subsystems which are insensitive with respect to certain classes of frequently occurring failures.
At present some parts of Amoeba have not yet the desired degree of extensibility and error insensitivity. However, Amoeba provides an excellent environment for testing because every function is realized in almost independent *services.* The research now concentrates on:

- *locating migratable objects* in very large networks;
- coupling local, autonomous Amoeba's via wide-area networks and gateways;
- design of a very fast, but error tolerant distributed file server;
- debugging of gross-parallel programs.

Furthermore, research will start into:

- *command interpreters* for controlling distributed (and parallel) applications;
- design of an Amoeba kernel for multiprocessors and load-balancing in the processor pool.

The Amoeba project is being executed in close cooperation with the Computer Science department of the Free University of Amsterdam. There are rather intensive contacts with the Computer Laboratory of Cambridge University (where Amoeba will also be used presently) and with the DEC System Research Center in California. In the context of COST-11 joint research is carried out with 15 institutions in 8 European countries into the aspects of distributed systems specifically related to wide-area networks.

Distributed adaptive information systems

The objective of this DAISY (Distributed Adaptive Information Systems) project that has been running for some years now, is to design models and develop software techniques to achieve an adaptive and efficient information system. It is, for instance, currently impossible to treat relatively unstructured and dissimilar information such as documents, vision and sound in the same way as uniform structured information. The time factor is also missing: traditional information systems only give an instantaneous picture of the dynamically changing, modelled information. On the other hand the future information system must be in a position to be adapted to changes in architecture or (supporting) software without going ‘down’. It must also support the evolutionary process

that each information system undergoes as part of an organization.
The architecture of information systems aimed at in this project globally covers the following four levels: applications, man-machine interface, processing and storage of objects. In the future the research is targeted at the lowest two levels and at the formalization of database models.
There are three projects:

- *PRISMA* (Parallel Inference Storage Machine). This research seeks to obtain knowledge and experience in database machines that are based on very large quantities of directly accessible memory and many processors. It will be executed in the context of the similarly named Philips' SPIN project in which there is cooperation with the University of Twente, Philips Physics Laboratory, and the Universities of Amsterdam and Utrecht. Over the coming years in the DAISY project most attention will be paid to this part and the expected follow-up.
- *GODAL* (General Object-centered Database Language). In particular research will be undertaken into whether the *guardian* concept, in which a process reacts algorithmically to the recognition of a declaratively described database situation, is effective in an object-centred databased approach.
- *Database modelling.* Mostly the conditions under which information can be extracted from a database are insufficiently described. This can lead to problems with certain types of changes in the database (view updates). The objective of this project is to design a model based on topology and category theory with which these problems can be formally described and analysed.

Ergonomy and program construction

There is a number of languages in which software development takes an order of magnitude less time than in for instance Pascal or Ada: Smalltalk, Prolog, SETL (and ABC) and fourth generation languages. What is interesting is that the gain in productivity in these languages is obtained with quite different means. These means are relatively independent and in principle combinable.
A well designed language in which the essentials are available in an integrated form certainly does not have to be a giant (compare the great simplicity of ABC with its enormous power of expression). Each of the languages mentioned has certain disadvantages (Smalltalk — no typing, Prolog — few data structures, etc.) that render them less applicable for extensive applications or particular important application areas. These also can be obviated. A further improvement in usability comes with the application of the insights gained in the Constructive Algorithmics project. For the time being the objective of this project is not to develop a completely new language but to research what possibilities there are to combine various new programming paradigms, what fundamental or practical limits there are within this, to what extent it will be possible to work more simply through new combinations, and what the consequences are in terms of programming productivity. Here thought is definitely not being given to beginners but to professionals in software development and links with modern thinking regarding the methodology of software development.
CWI expertise in programming language design, combined with new views and developments in programming languages, offers a good opportunity for a more fundamental approach.

Computer graphics

This discipline covers two areas: the *description* and *manipulation* of information by means of pictures. The enormous expressive quality of pictures achieves extremely efficient information transfer. The semantic and syntactic wealth in pictures means that their use for this purpose is an extremely complex and calculation intensive process. Current research projects are directed at computer capacities of billions of instructions per second. But this processing capacity still pales in the capacity of picture processing by human means. In order to arrive at user-friendly systems in the treatment of information in the computer by means of pictures the question turns on being able to best exploit the relatively limited computer capacity as efficiently as possible. The main theme in the coming five years is man-machine interaction through pictures of three-dimensional objects, *interactive 3D com-*

puter graphics. Interaction is characterized by incremental changes in the picture. To be able to identify the rapidly changing object or picture aspect the description of the picture must be structured effectively. From this description the new picture generation must be achieved. For advanced interaction further development of both the structure of pictorial information and rapid picture creation is necessary.

The design of incremental algorithms for both purposes as well as research into their parallelizing remains an area still to be investigated. These algorithms could then possibly be incorporated into VLSI components.

Continuing to build upon the experience in GKS-3D (three-dimensional Graphical Kernel System) and PHIGS (Hierarchichal Data Structures for Interactive Graphics) an advanced language for the description of pictures will be developed with a complete colour model and the above mentioned structuring facilities. In the context of an STW project new algorithms for incremental 3D graphics will be investigated. These will form part of VLSI components in a completely new graphics workstation architecture.

As an extension of fundamental research in the context of external financing (STW and contract research) research will be undertaken into design methods of large graphics databases with associated user interfaces.

The project group concerned is taking part in many developments in the area of computer graphics, both nationally and internationally, including ISO standardization, cooperation in the context of the European Association for Computer Graphics and support of the software industry. Every attempt will be made to retain this leading position.

User interfaces

A user interface is the collection of mechanisms with which a user obtains access to an information system. It can take many forms: an operating panel, a control language, a drawing system, etc. A user interface contains all necessary functions to translate abstract information in the system into a concrete representation for the user in the form of word, picture and sound.

As a result of the increasing extent and complexity of information systems on the one hand and the desire to make these accessible to users with little training on the other, increasingly heavier demands are being put on the pictorial representation functions at the workstation. An obvious improvement is to equip workstations with the capability of generating or recognizing spoken language, understanding natural language and interpreting pictures. In this project attention is particularly being paid to picture interpretation. This is still a little studied area. The major difference with computer vision (recognition of a picture recorded by a camera) is that the workstation itself builds up the picture and that the emphasis thus does not lie with picture recognition but with the correlation with other information. For this research we are using a picture language model on the basis of which the semantics and syntax of the formal picture language will be studied.

The available interactive functions will serve to obtain a picture language syntax with which a picture description will be built up by components and in a hierarchical manner. Both the components and the structure are of importance for the significance of the picture (the correlation with other information). At the workstation techniques must be found to be able to provide the picture along with its interpretation.

This theme will be approached in three ways:

- *Picture editing,* the syntactic treatment of the picture. Here a host of new problems appear, such as the fact that a picture has no sequential structure and that the user cannot easily guess its syntax. The system should also be highly tolerant with respect to inherently inaccurate specifications.
- *Constructive input,* the support of user's input by the use of semantic information. The system tries, as quickly as possible, to discover the meaning of input and makes this known by influence exercised on the construction process (for example styling and anticipation). The final objective is to provide a user with a 'sketch environment'.
- *Workstation management,* the calling up of the correct context for a given task. This includes connection to the workstation resource management (for example window manager) and the dynamic installation of the correct image syntax parser and semantic interpreter.

On implementation use will be made, amongst others, of logical and object-oriented programming languages.

Dialogue programming

With dialogue programming the objective is to design a specification method with which the behaviour of a system can be precisely defined during interaction. The specification method should make it possible to determine the behaviour of the system on the basis of design criteria. Interaction can take place between a user and a computer but also between an external process and a computer.
Dialogue programming covers the following problems:

- Modelling of external behaviour (user's actions for example). This is the basis of input recognition.
- Formal specification of internal behaviour, especially the control structure. Reaction to which recognized patterns is laid down here (not every recognition is followed by a reaction).
- Generation of internal representations of accepted input configurations for further processing. Rejected input is also handled here.
- Visualization of the above three processes.

At CWI a specification language 'Dialogue Cells' (DICE) has been developed as well as an experimental implementation. Experience here is extremely encouraging. The language lends itself to effectively specifying complex graphical user interfaces.
In coming years the system will be further developed by the addition of advanced facilities such as automatic error recovery, dynamic scheduling as a basis for shifting attention (focus), adaptive control, parameter definable dialogues and a history mechanism.
A second implementation is anticipated on a fifth generation computer such that the inference mechanism can be better assisted. Also extensions of the work are anticipated towards more complex control problems such as robotics and, more generally, machine-machine communication.

Method bases

Method bases are information systems in which databases and program libraries are integrated. This type of systems is necessary in order to allow the many autonomous components of a complex computer system (for example a complete design and manufacturing system) to work together. It is hoped that this approach will bring among others the reality of CIM (Computer Integrated Manufacturing) closer by.
Method bases embody the information technology necessary for the design, use and maintenance of such complex systems. In the method bank concept standards are designed for the exchange of information and external control. These standards are a combination of functional schemes and data formats.
Examples of method bank applications are: a data scheme for design information together with a system of pre- and post-processors, the description of an object to be manufactured, the collection of processing procedures for manufacture together with a procedure to determine a concrete process. Integration is present in each of these examples.
An important aspect of such large systems is the distribution and the simultaneous, multiple use. The view on the system depends on the type of use. Particularly interactive use demands flexibility to distribute decisions and processing as required between user and system. In the coming years work will be especially directed at interactive method banks. That means that the data and the associated processing can be interactively managed or controlled. One of the objectives will be to achieve a large measure of consistency and uniformity between the different user interfaces that are necessary with such a complex system. The work on method bases will be partly carried out in the context of cooperative projects:

- a work preparation systems, as SPIN/FLAIR project together with the University of Twente;
- ISNAS, an integrated system for solving flow problems on the basis of Navier-Stokes equations together with NLR (National Aerospace Laboratory), the Public Works Department and MARIN.

Preparations for further projects in the context of the National Technology Programme and ESPRIT are underway.

Intelligent CAD systems

CAD systems (Computer Aided Design) are currently not employed to support actual design work. They are more often an assist mechanism for the specification and partly the analysis of design decisions. For the design work one must reason rather than record. It goes without saying that to achieve a CAD system based on reasoning use will have to be made of artificial intelligence.
In the IIICAD project (III = Intelligent, Integrated, Interactive) a healthy theoretical basis is being sought for the application of artificial intelligence in CAD. From this fundamental problems can be inferred that could be solved with the help of artificial intelligence (multi-world mechanisms, naive physics, non-monotonic logic, etc.). The solutions will then be integrated into a programming language for IIICAD (design scenario's). A prototype of such a IIICAD system will be designed and built on the basis of the implementation of this language (IDDL = Integrated Data Description Language). The theoretical basis contains a design theory which describes the design process of which CAD is part. This theory creates insights into the role of design information in the design process from which can be deduced the manner of introducing design information in a CAD system. Likewise it contains the theory of objects to be designed. These theories are application-bound.
Thus a limited number of these (existing) theories will be introduced via methods and means including 'naive physics'.
The third and last theory is again of general nature and treats the problem of the representation of knowledge. With the creation of the experimental IIICAD system an analysis will be made of the design process in order to arrive at an allocation of tasks between user interface, scenario's and knowledge modules. The last two can be specified with the help of IDDL, the first with the help of DICE (the dialogue cells programming language). The IDDL implementation takes place in the first instance on the basis of existing Smalltalk-80 and Prolog systems so that a prototype can be available in a short time.
Additional to the IIICAD project, work is being undertaken on the representation of knowledge for design. The many decision situations that arise during the design process make this an ideal research field for knowledge representation.
Important questions are:

- To what extent can the system know/discover the intentions of the designer?
- Can knowledge representation support a creative process?
- Which reasoning techniques are characteristic for designing?

The work on the representation of knowledge will build upon the theory of the IIICAD project.