1993
ANNUAL REPORT

International Computer Science Institute

February 1994
# Contents

1 Research Results .............................................. 1
   1.1 Applications of Massive Parallelism ...................... 1
       1.1.1 Natural Language, Knowledge Representation and Learning 1
       1.1.2 Modelling and Computer Vision .......................... 1
       1.1.3 Environment and Tools .................................. 2
   1.2 Theory of Computation .................................... 3
       1.2.1 Learning and Parallelism ............................... 3
       1.2.2 Randomization ......................................... 6
       1.2.3 Foundations of Complexity Theory and Scientific Computing 8
       1.2.4 Other Applications .................................... 11
   1.3 Realization of Massively Parallel Systems ................ 16
       1.3.1 Systems Design ....................................... 16
       1.3.2 Software Design ...................................... 18
       1.3.3 Applications Work - Speech Recognition .............. 19
       1.3.4 Architectural Studies ................................. 21
   1.4 Very Large Distributed Systems and High-Speed Networking 21
       1.4.1 Real-Time Communication Services .................... 22
       1.4.2 Continuous-Media Networking Applications ........... 28

2 Project status compared to the original research plan ........... 29

3 Prospects to reach original research goals .................... 29

4 Impact of third party R&D results on the project ............... 29

5 Changes and modifications in the research goals ............... 30

6 Inventions, Patent applications, etc. ........................ 30
1 Research Results

1.1 Applications of Massive Parallelism

1.1.1 Natural Language, Knowledge Representation and Learning

The major event in this area was the decision of Dr. Lokendra Shastri to join ICSI as a full-time member of the research staff. Dr. Shastri has worked with our group for several years, but the collaboration has now become much broader and deeper. He is involved in the development of a system shell for existing hardware platforms such as CM-5 that would be capable of encoding knowledge bases containing up to a million rules and facts and obtaining responses to a class of queries in less than a second. This work leverages results of a related project which attempts to understand how networks of simple and slow neuron-like elements can encode a large body of knowledge — containing several million items — and perform a wide range of interesting inferences within hundreds of milliseconds.

Our effort has developed an additional probabilistic and applied branch in cooperation with the speech project centered in the Realization group. A major accomplishment of this period was the first version of our integrated linguistically driven speech system. Another success was the application of the finite-state grammar learner to a problem in speech pronunciation modeling. A general study group on stochastic language modeling is very active. Several of the results of this work are now being applied in the speech effort at ICSI and elsewhere.

In addition, the L0 project on language learning is continuing to explore foundational questions in language and cognitive science. Several new students and post-docs have joined the project. We have written a new article, “L0 - The First Four Years”, and submitted it for journal publication. Two doctoral students have begun dissertation projects in this area and Andreas Stolcke should complete his thesis in 1994.

1.1.2 Modelling and Computer Vision

C. Bregler and S. Omohundro have been making good progress on a new learning algorithm and its application to lip reading. They presented the paper “Surface Learning with Applications to Lip Reading” at the 1993 Neural Information Processing Systems conference. The learning algorithm aims to induce a smooth non-linear geometric constraint between a set of variables. It includes a representation for such constraints which supports a number of important new queries: completion of partially specified coordinates, global determination of the nearest point on the surface to a query point, interpolation on the surface between two specified points, prediction on the surface. These queries arise in a natural way in a variety of tasks in vision, graphics, robotics, and other geometric domains. The learning algorithm is capable of discovering the dimension of a constraint surface and of inducing our representation. They demonstrated its performance on a variety of synthetic problems (e.g. spheres, cylinders, “peanut” shapes, etc.) and demonstrated excellent performance (e.g. compared to nearest neighbor approaches) with a small number of training samples.

We are applying the surface-learning algorithm to the problem of learning and representing the space of “lip configurations” for a system to do lip reading. Our basic
approach to tracking the lips is based on an energy minimization algorithm similar to
“snakes” and “adaptive templates”. These methods are subject to getting stuck in local
minima and are fairly knowledge free. The algorithm would settle on an incorrect solution
(often including portions of the nose) in a significant percentage of the lip images.
We introduced domain knowledge into the lip tracker by combining it with the surface
learning approach described above. The idea is to learn the space of lip configurations
and to use the deviation from this as a component in the “energy” of the snake. This
can be interpreted in a Bayesian way: the posterior from surface learning is the prior for
the lip model and the likelihood comes from the match with the image. This combined
approach does a much better job at tracking the lips and does not get stuck in the poor
local minima. The model of lip space also allows the generation of lip contours. The
ability to intelligently interpolate between given lip configurations will be used to bring
the visual data rate up to the auditory rate when combining lip reading with speech
recognition.

There are also some smaller vision oriented efforts. Lokendra Shastri has an effort
developing a spatio-temporal connectionist network model of visual pattern recognition
that can deal with context effects and continuous inputs. It is being applied to the
recognition of hand-printed characters. There is also increasing attention to the parallel
computation issues arising in vision in our pSather and CNS-1 projects.

1.1.3 Environment and Tools

We’ve been making good progress on the development of Sather 1.0. The specification
is in its fourth revision and has undergone some significant improvements due both to
user’s suggestions and to issues that arose during the implementation of the compiler.
The type system is now statically type safe, any type may be a descendant of an abstract
type, type parameter bound now use simple inheritance, we introduce the “over” clause
which gives more flexibility in adding abstract types, the syntax for iter calling and
creation is much more intuitive, the approach to value objects is much more coherent,
and the constructor syntax and bound routine calling syntax has been vastly improved.
In addition, we have made great improvements in the design and underlying philosophy
of many of the library classes. The integer types have been rethought with regard to
exception handling. The floating point types now follow the IEEE standard and are
much more comprehensive. The fundamental container classes have undergone much
revision and are now safer, more efficient, and easier to use.

Work on the compiler/interpreter is proceeding and making good progress. David
Stoutamire has been building the parser and this process allowed us to discover some
small problems in the syntax. He is constructing a pretty printer based on it which
has already found some syntax errors in the new 1.0 library. We have been working on
the later phases of the compiler. It is being written in Sather 1.0 to allow us to gain
experience with the language as we proceed. There will be a bootstrapping phase to
do the first compiler. We wrote a GNU Emacs mode to properly indent the 1.0 syntax.
The type extraction and type checking phase of the compiler is nearly complete, as is
the simple translation of code to an internal format. The initial version will not perform
sophisticated optimization steps.

Excellent progress is also being made on the parallel version of Sather, pSather
and on its applications. A major technical report outlining the definition of pSather was completed and presented at conferences. The complete functionality of the new design is operational on the CM-5 and is being used on a variety of applications. After the completion of the Sather 1.0 translator, the pSather additions will be worked in. Chu-Cheow Lim has completed his doctorate and his thesis has received considerable attention. Two Swiss post-docs (R. Griesemer, S. Murer), a German post-doc and a visitor (M. Minas, H. Haertig) and a new doctoral student (J. Bilmes) have contributed strongly to our progress. We are now working on a portable version of pSather that should run on the full range of parallel systems.

There were also encouraging results on the ICSIM connectionist simulator effort. ICSIM was used in the U.C. Berkeley neural networks course to good effect. A new parallel version of ICSIM based on pSather is being designed as part of the doctoral research of B. Gomes. Both pSather and ICSIM are being targeted to our new computer CNS-1 and this has led to some modifications to the original design.

1.2 Theory of Computation

1.2.1 Learning and Parallelism

In [102], Karp, Culler, Patterson, Sahay, Schauer, Santos, Subramonian and von Eiken present a new parallel machine model, called LogP, that reflects the critical technology trends underlying parallel computers. It is intended to serve as a basis for developing fast, portable parallel algorithms. The model is based on four parameters that specify abstractly the individual sequential processors and the communication network that links them together. In [107], Karp, Sahay, Santos and Schauer present optimal algorithms within the LogP model for several fundamental broadcast and synchronization operations.

Eunice Santos and Abhijit Sahay have continued to work with Richard Karp on the analysis of parallel algorithms within the LogP model. Santos has derived tight upper and lower bounds on the execution time of parallel back-substitution algorithms for solving a triangular system of equations. Sahay, in collaboration with Ramesh Subramonian, has implemented a FFT algorithm on the CM-5 and demonstrated that the LogP model predicts its performance with reasonable accuracy.

In [105], Karp, Luby, and Friedhelm Meyer auf der Heide present algorithms for the randomized simulation of a shared memory machine (PRAM) on a Distributed Memory Machine (DMM). In a PRAM, memory conflicts occur only through concurrent access to the same cell, whereas the memory of a DMM is divided into modules, one for each processor, and concurrent accesses to the same module create a conflict. The delay of a simulation is the time needed to simulate a parallel memory access of the PRAM. Any general simulation of an m processor PRAM on a n processor DMM will necessarily have delay at least m/n. A randomized simulation is called time-processor optimal if the delay is $O(m/n)$ with high probability. Using a novel simulation scheme based on hashing, Karp et al. obtain a time-processor optimal simulation with delay $O(\log \log(n) \log^* n)$. The best previous simulations use a simpler scheme based on hashing and have much larger delay.

In the talk Ertel gave at ICSI about his thesis, he presented random competition (RC), a simple way of parallelizing randomized algorithms. As one of the results he
presented, depending on the input data, the speedup of RC can be superlinear or sub-linear.

As a reaction to Ertel's talk, Mike Luby had the idea of designing a strategy that minimizes the expected value of the running time for a given randomized algorithm $A(x)$ of the Las Vegas type. It turns out, that in many cases it is better to stop $A(x)$ after a certain time and to repeatedly restart it.

Michael Luby and Alistair Sinclair, together with David Zuckerman of MIT, considered systematic approaches to the problem of minimizing the expected time required to obtain an answer from a randomized algorithm [116]. They devised a surprisingly simple strategy that is universal, i.e., requires no prior knowledge about the algorithm itself, and which comes within only a logarithmic factor of the best possible running time that can be achieved by any strategy, even one which has full statistical details of the runtime behavior of the algorithm. They also showed that no better universal strategy exists.

They show that scheduling strategies which are optimal or close to optimal for sequential computations, can be easily parallelized and are still close to optimal. For the case of known distributions almost linear speedup can be achieved. This represents a partial explanation for the previously mentioned problem of strongly varying speedup results. Due to the independence of the parallel computations this parallelization method can be implemented very efficiently and with almost no effort on large networks of workstations. Subsequently, Ertel and Luby investigated simulation strategies for parallel computers [91]. The described strategy of repeated stopping and restarting is of special interest for the optimization of combinatorial search algorithms. With this strategy the running times are often polynomial in the depth of the first solution in the search tree, whereas e.g. breadth first search requires exponentially long runs for the same problem instance. This strategy was applied by Ertel to the automated theorem prover SETHEO and is now being evaluated.

While visiting ICSI, Noam Nisan (Hebrew University) worked with Michael Luby to develop a fast parallel approximation algorithm for the positive linear programming optimization problem, i.e., the special case of the linear programming optimization problem where the input constraint matrix and constraint vector consist entirely of positive entries [115]. They introduce an algorithm that takes as input the description of a problem and an error parameter $\epsilon$ and produces both a primal and a dual feasible solution such that the values of these two solutions are within a multiplicative factor of $1 + \epsilon$ of each other, and hence both these solutions have a relative error within $\epsilon$ of an optimal solution. This paper was recently presented by Luby at a ESPRIT/RAND sponsored workshop on Randomized algorithms held in Bonn in March, and at the 1993 ACM STOC conference held in San Diego in May.

Geppino Pucci, whose stay at ICSI spanned the period between January to August of 1993, focused on theoretical aspects of parallel computation. More precisely, he investigated problems of bufferless message routing in networks of processors and simulation schemes between different models of parallel computation.

The first research topic concerns the development of routing strategies for a very general model, where the processors of a certain interconnection network exchange messages of arbitrary length. The algorithms of Pucci and colleagues assume that no message queues exist at the processors (unbuffered communication) and that the message
transmission is wormhole-like; that is, a message travels through the network as an uninterrupted sequence of flits. They succeed in devising general routing strategies for the wide family of leveled networks. This family includes popular interconnections like linear arrays, two-dimensional meshes and trees, for which Pucci et al. obtain optimal or quasi-optimal routing schemes. The results of this research are contained in [123].

More recently, Pucci's interest has focused on simulations between the PRAM model of computation and more feasible machines. The PRAM consists of a collection of sequential RAM machines accessing a shared memory in lock-step fashion. The PRAM is a very high-level abstraction of a parallel computer, and its direct realization in hardware is beyond reach of the current (or even foreseeable) technology. They developed a deterministic simulation scheme to emulate PRAM computation on a mesh-connected computer, a feasible machine where each processor has its own memory module and is connected to at most four other processors via point-to-point links. In order to achieve good worst-case performance, any deterministic simulation scheme has to replicate each variable in a number of copies. Such copies are stored in the local memory modules according to a Memory Organization Scheme (MOS), which is known to all the processors. A variable is then accessed by routing packets to its copies. All deterministic schemes in the literature make use of a MOS whose existence is proved via the probabilistic method, but that cannot be efficiently constructed. In contrast, Pucci and colleagues devised a constructive MOS, called \( k \)-levelled Balanced Incomplete Block Design (BIBD) and showed how to employ it to simulate an \( n \)-processor PRAM on an \( n \)-node mesh-connected computer. Their MOS has weaker properties than the nonconstructive one, but the large diameter of the mesh allows them to amortize the deficiencies of the scheme, so to achieve almost optimal slowdown. The above results are described in detail in the paper "Constructive, deterministic PRAM simulation on a mesh-connected computer," co-authored by A. Pietracaprina and J. Sibeyn [124], and were presented in a talk at ICSI in August, 1993.

In [75], Giuseppe Attardi and Maria Simi present a formalization for the notion of "viewpoint," a construct meant for expressing several varieties of relativized truth. The formalization consists in a logic which extends first order predicate calculus through an axiomatization of provability and with the addition of proper reflection rules. The extension is not conservative, but consistency is granted. Viewpoints are defined as set of reified meta-level sentences. A proof theory for viewpoints is developed which enables one to carry out proofs of sentences involving several viewpoints. A semantic account of viewpoints is provided, dealing with issues of self referential theories and paradoxes, and exploiting the notion of "contextual entailment." Notions such as beliefs, knowledge, truth and situations can be uniformly modeled as provability in specialized viewpoints, obtained by imposing suitable constraints on viewpoints.

In a technical report [96] detailing his work here at ICSI, Armin Hemmerling and colleagues consider the target-reaching problem in plane scenes for a point robot which has a tactile sensor and can locate the target ray. He notes that it might have a compass as well, but it is not able to perceive the coordinates of its position nor to measure distances. The report explores how the complexity of an algorithm is measured by the number of straight moves until reaching the target, as a function of the number of vertices of the (polygonal) scene. It is shown how the target point can be reached by exhaustive search without using a compass, with the complexity \( \exp(O(n^2)) \). Using
a compass, there is a target-reaching algorithm, based on rotation counting, with the complexity $O(n^2)$. The decision problem, to recognize if the target cannot be reached because it belongs to an obstacle, cannot be solved by our type of robot. If the behaviour of a robot without compass is periodic in a homogeneous environment, it cannot solve the target-reaching problem.

1.2.2 Randomization

Michael Luby, Nati Linial (Hebrew University), Michael Saks (U.C. San Diego) and David Zuckerman (M.I.T.) have worked to develop a polynomial time deterministic algorithm for the problem of finding a hitting set for combinatorial rectangles in high dimensional space [111]. This problem has been studied extensively in the classical case when the dimension is a fixed constant. One natural reason for considering the problem when the dimension is an input parameter is that a solution yields an explicit polynomial size sample space for a large number of random variables (the number of variables is the dimension of the space) that approximates the independent distribution on the random variables.

Michael Luby, Boban Veličković (York University) and Avi Wigderson (Hebrew University) developed deterministic algorithms which, for a given depth-2 circuit $F$, approximate the probability that on a random input $F$ outputs a specific value $\alpha$ [117]. Their approach gives an algorithm which for a given $GF(2)$ multivariate polynomial $p$ and given $\epsilon > 0$ approximates the number of zeros of $p$ within a multiplicative factor $1 + \epsilon$.

Together with Dana Randall, a graduate student at U.C. Berkeley, Alistair Sinclair has been investigating algorithms for studying the behaviour of self-avoiding walks (SAWs) [126]. A self-avoiding walk in $d$ dimensional Cartesian space is a walk that starts at the origin and passes through any point at most once. SAWs have been studied for many years as a model for the spatial arrangement of linear polymer chains; despite an extensive literature, no efficient algorithms are known for computing many fundamental quantities associated with them. Randall and Sinclair have devised an algorithm that generates a SAW of any specified length uniformly at random; using this algorithm, much useful information about SAWs can be computed. The algorithm is guaranteed to work efficiently assuming a widely-believed conjecture about the behaviour of the number of walks of length $n$ as a function of $n$. It also has a nice robustness property: if the conjecture happens to fail, then the algorithm will detect this fact and provide a counterexample.

Michael Luby completed a substantial part of a monograph titled “Pseudorandomness and Cryptographic Applications”, to be published by Princeton University Press as the first in their new Computer Science Series [113]. The abstract of the monograph follows. A basic goal of cryptography is to be able to send information secretly between locations that are physically far apart. A protocol achieving this goal can be easily implemented using a pseudorandom generator. The first half of the monograph develops the ideas used to construct a pseudorandom generator from any one-way function. The second half of the monograph shows how to use a one-way function to construct other useful cryptographic primitives and protocols such as pseudorandom function generators, pseudorandom permutation generators, signature schemes, hidden bit commitment protocols and zero-knowledge interactive proof systems.
There is a close connection between randomized algorithms and deterministic algorithms for which a certain distribution over the input space is assumed. A general analysis of the average case complexity of computational problems seems much more difficult compared to the worst case, and it is not clear whether the right notions and measures have already been found. Rüdiger Reischuk has worked on this subject and proposed a new approach in this direction. During his visit at the ICSI he has continued his investigations on the relations between different average case complexity classes and also with respect to standard worst case classes. Among others, proofs for several tight separation results have been worked out [127].

Marco Pellegrini has been investigating randomized and derandomized methods for space decompositions in high dimensional spaces with applications to finite elements decompositions and motion planning in robotics. A recent number of publications has focused on planar triangulations under a variety of constraints and objectives (e.g. non-obtuse angles). On the other hand many basic problems are still open in the area of 3-dimensional triangulations, which are important for applications in finite elements meshes, constructive solid geometry and manipulation of spatial objects. This lack of results is due to the weakness of traditional techniques when applied to the 3-dimensional setting. Stimulated by this situation, this research has achieved the first deterministic worst-case optimal \( \Theta(n^2) \) algorithm for triangulating a 3-dimensional non-convex non-simple polyhedron with \( n \) edges. This research is reported in Pellegrini's ICSI Technical Report "Building convex space partitions induced by pairwise interior-disjoint simplices" [121].

The techniques developed for the triangulation problem for high dimensional spaces find applications in robotics where it is customary to map a 3-dimensional collision detection (or motion planning) problem for a system with \( k \) degrees of freedom into a point location problem in in a \( k \)-dimensional space. An extension of Pellegrini's work tackles the problem of triangulating arrangements of simplices in high dimensional spaces and has produced the first data structure for point location among simplices in high-dimensional space with polylogarithmic query time and storage proportional to the number of vertices in the given arrangement [122]. This performance was achieved before only for dimension two and three.

Ertel and colleagues propose an alternative definition for the speedup of parallel algorithms. Let \( A \) be a sequential algorithm and \( B \) a parallel algorithm for solving the same problem. If \( A \) and/or \( B \) are randomized or if we are interested in their performance on a probability distribution of problem instances, the running times are described by random variables \( T_A \) and \( T_B \). The speedup is usually defined as \( E[T_A]/E[T_B] \) where \( E \) is the arithmetic mean. This notion of speedup delivers just a number, i.e. much information about the distribution is lost. For example, there is no variance of the speedup. To define a measure for possible fluctuations of the speedup, a new notion of speedup is required. The basic idea is to define speedup as \( M(T_A/T_B) \) where the functional form of \( M \) has to be determined. Ertel also argues that in many cases \( M(T_A/T_B) \) is more informative than \( E[T_A]/E[T_B] \) for a typical user of \( A \) and \( B \). Ertel and colleagues present a set of intuitive axioms that any speedup function \( M(T_A/T_B) \) must fulfill and prove that the geometric mean is the only solution. As a result, they now have a uniquely defined speedup function that will allow the user of an improved system to talk about the average performance improvement as well as about its possible
variations. A paper on that subject was submitted to PARLE'94.

This work which lies at the boundary of practice and theory has greatly profited from various discussions with many colleagues at ICSI about the axioms for speedup. Even more helpful was the support from Prof. Aczel at University of Waterloo in Canada, who is one of the few real experts in functional equations worldwide. Just before the end of Ertel’s year at ICSI, he had the opportunity to meet Prof. Aczel at U.C. Irvine where he started a three-month research sabbatical. As a result of this meeting, a joint paper on the above subject will be written.

The paper [109], co-authored by R. Karp and Y. Zhang, derives tail bounds for certain supercritical branching processes, and applies the results to an analysis of a classical algorithm for AND/OR tree evaluation, a computational process that arises both in logic programming and in game tree search.

1.2.3 Foundations of Complexity Theory and Scientific Computing

Lenore Blum and Steve Smale have defined notions of entropy of computation which measure the growth rate of the number of computation paths (or equivalently the growth rate of the number of branchings) in the Blum-Smale-Shub model of computation. One definition of entropy of a machine is the lim sup of the ratio of the logarithm of the number of halting paths of length \( n \) to \( n \). If the derived language of the computation paths is finite state, then the tools of Symbolic Dynamics enable us to calculate entropy. Indeed this entropy is the logarithm of the largest positive eigenvalue of the transition matrix for the edge graph associated with the (branching) graph of the machine.

Generic search algorithms (say for finding an approximate root of a polynomial) have zero entropy whereas generic bisection (divide and conquer) algorithms have positive entropy. It is tempting to conjecture that fast algorithms for hard problems will have positive entropy. A goal of this work is to understand to what extent this is the case.

Bruno Codenotti, Mauro Leoncini, Joe Traub, and H. Woźniakowski have begun research to investigate the complexity of continuous problems (as in, the classical problems dealt with by Information-Based Complexity), using finite computation models, both sequential and parallel. The aim is to exploit certain aspects of the numerical problems on finite models, such as conditioning, to obtain complexity bounds for the most crucial computational resources (sequential and parallel time and sequential space). Preliminary results have been obtained for some interesting problems, such as the integration of Lipschitz functions. This work has strong connections with Information-Based Complexity, the work of K. Ko on the complexity of real functions, and the work of Blum, Shub, and Smale on the foundations of Numerical Analysis.

Mauro Leoncini has studied the parallel complexity of Gaussian Elimination with Partial Pivoting (GEPP), a central problem in numerical linear algebra which is well-known to be \( \text{P} \)-complete. Assuming that not all the problems in \( \text{P} \) have polynomial speedup with polynomially many processors (which is stronger an assumption that \( \text{P} \neq \text{NC} \), but still believed to hold), then no parallel algorithm solving GEPP can run in time \( O(n^{1/2 - \epsilon}) \), where \( n \) is the order of the matrix and \( \epsilon > 0 \).

Bruno Codenotti completed research on complexity measures for Boolean functions, which are particularly relevant for parallel complexity classes, e.g., the notion of sensitivity. In particular, he used Harmonic analysis of the cube to prove that symmetric
functions in the class $AC^0$ have exponentially decreasing average sensitivity [83].

Codenotti is also currently working on some relations between computations over
discrete structures and computations over continuous structures, e.g., over the reals.
The main goal of this work is to find appropriate models of computation for floating
point arithmetic.

Rüdiger Reischuk has finished research work on complexity classes defined by Turing
machines with a sublogarithmic space bound. Deterministic, nondeterministic as well
as alternating machine models have been considered. For the corresponding complexity
classes hierarchy and nonclosure properties are shown. Several optimal space lower
bounds have been obtained for particular languages and for nontrivial context-free
languages in general. [112] gives a detailed description of the current state of knowledge
for these complexity classes.

Johannes Blömer worked on an improved quantitative version of the Primitive Element
Theorem. The Primitive Element Theorem states that any algebraic extension $Q(\alpha, \beta)$
of the rational numbers can already be generated by a single element $\gamma$, i.e., $Q(\alpha, \beta) =
Q(\gamma)$. In particular, for all except finitely many $c \in Q$ the element $\gamma = \alpha + c\beta$ will
generate the extension. The classical proof of this theorem shows that the number of
exceptions is bounded by the product of the degrees of $\alpha$ and $\beta$ [84]. Blömer was able
to reduce this bound to the minimum of the degrees of $\alpha$ and $\beta$. Examples found by H.
W. Lenstra show that the number of exceptions is at least logarithmic in the degrees.

Algorithms to determine a primitive element for an extension $Q(\alpha, \beta)$ are used in
many algebraic algorithms. For example, in Collins’ cylindric algebraic decomposition
algorithm for quantifier elimination. In practice current algorithms for this problem
behave much better than can be shown by theory. The above mentioned results are a
first step to explain the actual running times. The goal of future research is to close
the gap between the upper and lower bounds and to find improved algorithms that
determine the exceptional values of $c$.

Jeff Edmonds has made progress toward proving time-space lower bounds on branch-
ing problems, in a joint work with R. Impagliazzo and M. Luby. The goal is to prove
a time-space tradeoff on the branching program model. They have a lower bound for
$st$-connectivity on the NNIAG model. A communication game is defined that charac-
terizes what is needed to prove the same result for branching programs. A lower
bound for this game would also give a more significant time-space tradeoff for element
distinctness. The game is also of interest in its own right because it characterizes a
feature of information theory that intuitively should be true (but as seen below is not).
Towards proving a lower bound on this game, the game is reduced to a natural and easy
to define combinatorial problem. Further progress was made by obtaining surprising
upper bounds for the game. First, they found a surprising algorithm that changed our
thinking about the game, but that could still be explained easily using an altered in-
formation theoretic argument. The research, however, was seriously upset when Pavel
Pudlák and Jiří Sgall obtained a very elegant upper bound whose complexity is not so
low that it is no longer useful for a branching program lower bound, but is low enough
that it destroys any intuition into the true complexity of the game.

Thorsten Werther continued his work in analyzing the computational complexity of
interpolating and learning sparse polynomials over various basis. In this context, the
generalized Vandermonde determinant defined over these bases plays an important role.
It is a well known fact that this determinant can be expressed as the product of the standard Vandermonde determinant and the so-called Vandermonde polynomial. T. Werther has given a division-free expression for the Vandermonde polynomial in terms of generalized elementary polynomials. For the special case of the Chebyshev basis he shows [128] that the coefficient of the Vandermonde polynomial are nonnegative, which can be viewed as a generalization of Michell's result for the power basis. The consequences of this result include the nonsingularity of the generalized Vandermonde matrices provided that the indeterminates take distinct values outside the interval of orthogonality and linear upper bounds on the number of real roots of sparse polynomials over the Chebyshev basis. Similar results are also obtained for the Pochhammer basis. The results answer the question posed by Lakshman and Saunders about the relationship of the number of real roots of a polynomial and its sparsity with respect to the Chebyshev and Pochhammer bases. Using techniques from [108], tight lower and upper bounds on the Vapnik-Chervonenkis dimension of the class of polynomials of bounded sparsity over the Chebyshev and Pochhammer basis are given.

Carlos A. Di Prisco, visiting from IVIC (Caracas, Venezuela) continues research on combinatorial set theory, in particular on several aspects of Ramsey Theory. Two main lines have been pursued. The first one investigates partitions of sets of finite sequences (of natural numbers or of ordinals below an uncountable cardinal). Different types of homogeneity for these partitions, and the way they are interrelated are studied. The second line deals with partitions of the set of infinite sets or infinite sequences of natural numbers. Among other results, Di Prisco and colleagues proved the consistency of the existence of perfect homogeneous sets for each partition together with the existence of an ultrafilter on the set of natural numbers. Two articles are currently in preparation: one on partitions of finite sequences [85] and the second on perfect set properties [87]. Some of these results were presented at: the Logic Colloquium of the Mathematics Department, University of California, Los Angeles (January); the Logic Colloquium, University of California, Berkeley (February); and the Sacks Symposium, Massachusetts Institute of Technology, Cambridge, MA (May).

Erich Novak (Universität Erlangen) studied different questions related to the complexity of continuous problems in numerical analysis [118]. In the real number model of computation one assumes that arithmetic operations with real numbers and comparisons can be done with unit cost. In numerical analysis one often deals with problems where the information is only partial. This is an essential assumption for problems defined on function spaces, such as numerical integration, zero finding, or optimization. In information-based complexity it is assumed that certain functionals can be evaluated by an oracle and each call of the oracle costs $c$, where $c > 0$. One major question is whether adaptive methods are better than nonadaptive ones. This question is deeply related to different $n$-widths that are studied in approximation theory. Novak and colleagues study the problem of optimal recovery in the case of a nonsymmetric convex class of functions. In particular they show that adaptive methods may be much better than nonadaptive methods. They define certain Gelfand-type widths that are useful for nonsymmetric classes and prove relations to optimal error bounds for adaptive and nonadaptive methods, respectively. In [119], they also study the adaption problem and prove that adaption may help for randomized algorithms although adaptive deterministic algorithms are not better than nonadaptive ones.
1.2.4 Other Applications

A new collaboration, led by Andres Albanese and Michael Luby, between the Networks and Theory groups at ICSI has recently been established to explore a novel approach for sending information over high speed networks. The new method, dubbed Priority Encoding Transmission (PET), allows the user to specify priorities on information to be sent. Based on the priorities, the sender uses an encoding scheme to convert the information into packets for transmission over an unreliable medium. The scheme ensures a smooth rate of recovery of the information (in order of priority) by receivers as a function of the amount of the encoding that is received in transmission. This work has immediate applications to multi-media and high speed networks applications, especially in applications with multiple receivers with heterogeneous capabilities. A general encoding/decoding algorithm for implementing this scheme for any set of user priorities has been developed by Jeff Edmonds, Michael Luby, and Madhu Sudan (IBM). This algorithm shows promise of being practical. On the other side, they give an information-theoretic proof that there is no algorithm that can achieve a higher rate of information transmittal than achieved by their algorithm.

A major goal of the first phase of the Human Genome Project is to construct a physical map of the entire human genome. This map will determine the locations of 10,000 landmarks along the genome, each of which is the unique site where a particular DNA fragment occurs; these sites are called Sequence tagged Sites (STTs). To assist in the construction of the map, a library of 33,000 clones has been constructed. The clones are fragments of the genome, whose positions along the genome are initially unknown. On the average, a point along the genome is covered by about ten of these clones. Experimental measurements indicate, for each clone and each STS, whether the clone covers the STS. From this experimental data it is desired to reconstruct the order of occurrence of STTs along each chromosome.

Farid Alizadeh, Richard Karp, Deborah Weisser and Geoffrey Zweig have designed algorithms and computer programs to perform this reconstruction process. The problem is complicated by experimental errors of the following kinds: false positives, in which a clone is incorrectly reported to contain a given STS, false negatives, in which a clone is incorrectly reported not to contain an STS, and chimeric clones, which consist of two DNA fragments stuck together, rather than a single fragment. Given a model of the frequencies of the various error types, our algorithms seek the most likely ordering of the STTs along each chromosome. Karp and colleagues' battery of programs includes the following:

- Quick screening procedures for identifying false positives and chimeric clones and correcting the data appropriately;
- Quick procedures for getting a good initial ordering of the STTs;
- A local search procedure which improves this ordering, and eventually obtains a maximum likelihood ordering;
- A postprocessing procedure which flags places where the ordering of the STTs is not sufficiently supported by the data, and seeks to resolve these ambiguities.
Our programs are designed to work in an interactive mode, where they determine likely errors in the data, ask for the questionable data to be rechecked experimentally, and then incorporate the revised data into the computation. We have found that a few rounds of rechecking are usually sufficient to eliminate virtually all errors from the data. The programs have proved to be quite effective on simulated data generated according to our error model, and on a limited set of data from the human genome. This work is reported in [71].

Physical mapping often begins with a clone library and obtains the STSs in an on-line fashion, deriving each STS from one of the ends of a clone in the library. The successive STSs are chosen strategically, with a view to minimizing the number of experiments required to determine the locations of a set of clones that span the genome. Biologists at the Lawrence Berkeley Laboratory (LBL) have devised a strategy for the on-line selection of STSs and have conducted simulations to study its performance. Richard Karp and Ron Shamir (Tel-Aviv University) have begun a mathematical analysis of the strategy suggested by the LBL researchers as well as several other strategies. Their results so far confirm and extend the LBL simulation results, and provide a rational basis for choosing an on-line STS selection.

R.M. Karp has continued to work with Ran El-Yaniv (University of Toronto) on the competitive analysis of on-line financial decision making. This has led to two journal papers which extend earlier conference papers. In “On-Line Trading” [89], a one-way trading game was considered, in which a player is given the task of converting dollars to yen over some period of time. Each day, a new exchange rate is announced, and the trader must decide on-line how many dollars to convert. For several versions of this problem, the paper gives optimal strategies within the paradigm of competitive analysis. The R. El-Yaniv and R. Karp paper, “The Mortgage Problem” [90], studies a simplified model of a complex real-life problem: whether to keep one’s current mortgage or to refinance at a lower rate, thereby incurring a transaction cost. We derive on-line algorithms with optimal competitive ratio for this problem.

R.M. Karp, R. Ostrovsky and Y. Rabani have studied an on-line inventory problem in which, at each step, a firm must order some quantity of a commodity for delivery \( k \) days later. The ordering policy must balance two costs: the opportunity cost of failing to meet demand, and the cost of storage if too much of the commodity is ordered. The problem has been studied extensively under various stochastic models of the sequence of daily demands. They study the problem without resorting to stochastic models. Their assumption is that an adversary chooses the demand sequence subject to upper and lower bounds on each day’s demand. They derive tight upper and lower bounds on the optimal competitive ratio.

Genetic algorithms are a popular heuristic approach to solving hard problems in combinatorial optimization. Although they often work well in practice, their behaviour is poorly understood from a theoretical viewpoint. Using insights gained from previous work by Rabinovich, Sinclair and Wigderson on the foundations of genetic algorithms, Alistair Sinclair has been working with Ari Juels, a graduate student at U.C. Berkeley, on innovations that simplify many genetic algorithms by replacing the genetic “crossover” operation by a carefully chosen deterministic operation. Experimentation has shown that this approach leads to substantial improvements both in speed and in quality of solution over existing implementations of genetic algorithms for a number of
optimization tasks, such as the Travelling Salesman Problem and Jobshop Scheduling [99]. These results suggest that many existing applications of genetic algorithms are not exploiting the full power of the crossover operator, which opens up an intriguing avenue for future research.

In other ongoing work on genetic algorithms, Sinclair has been investigating, together with Yuval Rabani, strategies for simulating the behaviour of a quadratic operator (a mathematical formalization of the crossover operator) using only a small, finite population. Preliminary results reported in [125] suggest that this is possible in some interesting cases, but that it is harder to justify for more general systems.

In [100] Karp derives optimal sequential, parallel and randomized algorithms for the following problem, which is a natural generalization of binary search: let \( f \) be a nondecreasing integer-valued function such that \( f(0) = 0 \) and \( f(n) = n \); determine \( f \) throughout \([0, \ldots, n]\) by performing function evaluations.

In every sport, playoffs and tournaments are used to select the best among a set of competing players. In [68], Karp, Adler, Gemmell, Harchol, and Kenyon consider the design of such systems. The authors seek designs that are optimally efficient, in the sense that they minimize the number of rounds or the number of games needed to select the best player with a stated probability.

In [98], Sandy Irani and Yuval Rabani consider multiple agents optimization games introduced by Deng and Papadimitriou. Several agents cooperate to solve an optimization problem. Interaction among agents is restricted. Irani and Rabani study their performance as a function of the restriction on interaction. They develop optimal deterministic and randomized strategies for load balancing, and give partial results for virtual circuit routing. The model has applications to parallel programming, high speed network management, large scale planning and other fields. It isolates and quantifies the value of information in solving problems in a distributed environment.

Karp, Ostrovsky and Rabani study the question of on-line inventory maintenance. The model has a feature not previously encountered in on-line problems—a delayed effect of past decisions. Karp et al. give deterministic strategies and almost matching lower bounds. In some cases, they can demonstrate that randomization cannot help. They hope to generalize this to all cases. They consider randomization against a new type of adversary that can adapt to the current state of the algorithm, but cannot foresee previous orders made but not yet received.

In [69], Ajtai, Aspnes, Naor, Rabani, Schulman, and Waarts analyze the on-line carpool problem. This problem models scheduling problems where the preservation of fairness is required. They give worst case bounds for deterministic algorithms. They show that randomization against the oblivious adversary gives better bounds. They further analyze the performance of their algorithms against sequences generated uniformly at random. In this case, a remarkable double exponential improvement in performance over the deterministic case is shown. This last result requires the analysis of a dynamical system which is reminiscent of several physical systems of particles.

Arora, Rabani, and Vazirani show in [74] that the discrete version of quadratic dynamical systems, a mathematical tool frequently used to model physical phenomena as well as genetic algorithms, are most likely hard to simulate in polynomial time, as their simulation is PSPACE-complete.

In [129] T. Werther considers the problem of interpolating sparse functions from the
values of their multiple derivatives at some given point. He presents efficient algorithms for reconstructing finite Fourier series and sparse polynomials over Sturm-Liouville bases by embedding the problem in the framework of Grigoriev et al. on the interpolation problems of sparse sums of eigenfunctions of operators. The number of evaluations is linear in the number of nonvanishing Fourier coefficients, resp. linear in the sparsity of the polynomial.

Ulrich Huckenbeck has written a paper that presents two dynamic programming algorithms, which work in a general decision model. Both search strategies include the following graph theoretical algorithms as special cases: the Bellman-Ford-Strategy for acyclic digraphs: For all nodes \( a \), this method finds a cost minimal path \( \psi(a) \) from a fixed start node \( s \) to \( a \); and the Greedy Algorithm for minimal spanning trees: For all numbers \( a \), this method finds a cost minimal forest \( \psi(a) \) with \( a \) edges. In [97], U. Huckenbeck gives a generalization of the above algorithms. The two dynamic programming algorithms in [97] solve this general optimization problem, if several conditions about the structure and the underlying cost measure are given.

In [70], Alizadeh and colleagues study the semidefinite programming problem (SDP), i.e. the optimization problem of a linear function of a symmetric matrix subject to linear equality constraints and the additional condition that the matrix be positive semidefinite. First they review the classical cone duality as specialized to SDP. Next they present an interior point algorithm which converges to the optimal solution in polynomial time. The approach is a direct extension of Ye’s projective method for linear programming. They also argue that most known interior point methods for linear programs can be transformed in a mechanical way to algorithms for SDP with proofs of convergence and polynomial time complexity also carrying over in a similar fashion. Finally they study the significance of these results in a variety of combinatorial optimization problems including the general 0-1 integer programs, the maximum clique and maximum stable set problems in perfect graphs, the maximum \( k \)-partite subgraph problem in graphs, and various graph partitioning and cut problems. As a result, they present barrier oracles for certain combinatorial optimization problems (in particular, clique and stable set problem for perfect graphs) whose linear programming formulation requires exponentially many inequalities. Existence of such barrier oracles refutes the commonly believed notion that in order to solve a combinatorial optimization problem with interior point methods, one needs its linear programming formulation explicitly.

Software protection is one of the most important issues concerning computer practice. There exist many heuristics and ad-hoc methods for protection, but the problem as a whole has not received the theoretical treatment it deserves. In [95], Oded Goldreich and Rafail Ostrovsky provide theoretical treatment of software protection. They reduce the problem of software protection to the problem of efficient simulation on oblivious RAM.

A machine is oblivious if the sequence in which it accesses memory locations is equivalent for any two inputs with the same running time. For example, an oblivious Turing Machine is one for which the movement of the heads on the tapes is identical for each computation. (Thus, it is independent of the actual input.) What is the slowdown in the running time of any machine, if it is required to be oblivious? In 1979 Pippenger and Fischer showed how a two-tape oblivious Turing Machine can simulate, on-line, a one-tape Turing Machine, with a logarithmic slowdown in the running time. Goldreich
and Ostrovsky show an analogue result for the random-access machine (RAM) model of computation. In particular, they show how to do an on-line simulation of an arbitrary RAM input by a probabilistic oblivious RAM with a poly-logarithmic slowdown in the running time. On the other hand, they show that a logarithmic slowdown is a lower bound.

Giorgio Gambosi, Marco Protasi, and Maurizio Talamo introduce new algorithms for the dynamic maintenance of approximated solutions of Min-Weighted Node Cover and Min-Weighted Set Cover ([92]). For what concerns Min-Weighted Node Cover, for any sequence of edge insertions and deletions, the algorithms maintain a solution whose approximation ratio (that is, the ratio between the approximate and the optimum value) is equal to the best asymptotic one for the static case. The algorithms require $O(1)$ time for edge insertion, while an $O(1)$ amortized time is required for edge deletion. For what regards Min-Weighted Set Cover, they present dynamic algorithms whose approximation ratio matches one of the two different and incomparable best approximate bounds for the static case. The time complexity for element insertion and its amortized complexity for element deletion are proportional to the maximum redundancy of an element in the approximate solution.

Noga Alon, Manuel Blum, Amos Fiat, Sampath Kannan, Moni Naor, and Rafail Ostrovsky devise a procedure in [73] which may be helpful to any disorganized carpenter who has a mixed pile of bolts and nuts and wants to find the corresponding pairs of bolts and nuts. The procedure uses their (and the carpenter’s) ability to construct efficiently highly expanding graphs. The problem considered is given a collection of $n$ bolts of distinct widths and $n$ nuts such that there is a 1-1 correspondence between the nuts and bolts. The goal is to find for each bolt its corresponding nut by comparing nuts to bolts but not nuts to nuts or bolts to bolts. The authors’ objective is to minimize the number of operations of this kind (as well as the total running time). The problem has a randomized algorithm similar to Quicksort. Their main result is an $n(\log n)^O(1)$-time deterministic algorithm, based on expander graphs, for matching the bolts and the nuts.

In [110], Eyal Kushilevitz, Silvio Micali, and Rafail Ostrovsky characterize the boolean functions which are complete: they show that a boolean function $g$ is complete if and only if $g$ itself cannot be computed $n$-privately (when there is no black-box available). Namely, for boolean functions, the notions of completeness and $n$-privacy are complementary. On the other hand, for non-boolean functions, they show that these two notions are not complementary. Their result can be viewed as a generalization (for multi-party protocols and for $(n \geq 2)$-argument functions) of the two-party case, where it was known that two-argument functions which contain “embedded-OR” are complete.

Rafail Ostrovsky and Avi Wigderson further explore Zero-Knowledge proofs in [120].

It was known that if one-way functions exist, then there are Zero-knowledge proofs for every language in PSPACE. They prove that unless very weak one-way functions exist, Zero-Knowledge proofs can be given only for languages in BPP. For average-case definitions of BPP they prove an analogous result under the assumption that uniform one-way functions do not exist. Thus, Ostrovsky and Wigderson find that, very loosely speaking, zero-knowledge is either useless (exists only for “easy” languages), or universal (exists for every provable language).

Bernd Becker continued his work on Decision Diagrams (DDs) as (1) a datatype for circuit/system design and (2) a circuit structure well suited for synthesis for testability.
Data structures for Boolean functions build an essential component of design automation tools, especially in the field of symbolic verification, logic synthesis or testing. Efficient algorithms should exist for important operations like satisfiability or equivalence test and Boolean operations. Moreover, many (important) Boolean functions should be representable in (small) polynomial size. The state of the art data-structure is the ordered binary decision diagram (OBDD), which results from general binary decision diagrams (BDDs), also called branching programs, by ordering restrictions. In the context of EXOR-based logic synthesis another type of decision diagram (DD), the (ordered) functional decision diagram ((O)FDD), becomes increasingly important.

In a joint paper with Rolf Drechsler and Ralph Werchner [82] the relation between FDDs and BDDs is studied. Several results on the computational power of FDDs and BDDs are derived. These results have motivated the implementation of an FDD-package, a software tool for the efficient representation and manipulation of FDDs [80, 81]. Experimental results show that OFDDs are superior for a number of arithmetical benchmark functions, although the HWB-function and multiplication require OFDDs of exponential size. This motivates the investigation of hybrid DDs where BDD- and FDD-decomposition is combined. For first results based on very simple heuristics see [88].

Testability properties of Boolean networks derived from DDs have been investigated in [77] for the BDD case. These results can be translated to FDDs [78] and to some extent even to hybrid DDs [79]. Testability can be efficiently analysed at least if the underlying DD is ordered. In many cases the circuits are highly testable or can be modified to be highly testable for various fault models. It is an interesting question, if DD-circuits are well-suited for a random test, i.e. if they can be used for the synthesis of self-testable circuits. These questions will be studied during a visit of Dr. Uwe Sparmann from University of Iowa in January 1994.

Motivated by the pattern matching problems that arise in biosequence analysis, Robert Giegerich investigated suffix tree algorithms in cooperation with Stefan Kurtz from University Bielefeld. Several purely functional algorithms were developed. A new, “lazy” construction was designed whose expected efficiency is $O(n \log n)$, but which compares favorably with the known $O(n)$-algorithms. This work will be presented at the European Symposium on Programming [93]. As a side effect of this study, a surprisingly close relationship was revealed between the known linear-time suffix tree constructions [94].

1.3 Realization of Massively Parallel Systems

1.3.1 Systems Design

In 1993 we continued our system design activities leading up to the Connectionist Network Supercomputer (CNS-1), [131, 132, 144] as well as support activities for our research collaborators who now have the RAP machine [145]. Much system design activity also went towards an initial system that we have been calling the SPERT [134, 149], but which has increasingly become more like the processor for the CNS-1. The custom chip for this system is now called T0, to indicate that it is the base implementation of the Torrent CPU that is the processor used in CNS-1. This year so far we have designed the
T0 micro-architecture [130]. In the course of this we have finished most of the requisite chip design tasks, including:

- Created transistor-level RTL schematics for most of T0.
- Implemented executable RTL model in C++ for T0.
- Translated most of the control portion of the RTL design into a local hardware description language for synthesis.
- Wrote test vectors for T0.
- Designed 16b by 16b tree multiplier capable of signed and unsigned arithmetic.
- Adapted an earlier instruction cache design for T0 requirements.
- Designed 6 different adders required in various parts of T0.
- Developed single-phase storage elements compatible with our standard cells.
- Developed and characterized a large, flexible set of datapath elements - muxes, latches, flip-flops, tristate drivers, and small logic gates.
- Developed the vector regfile - an 8-port, 50MHz design with 60 256b registers.
- Developed the fixed-point clipper unit.
- Developed a complete MIPS RISC core, with T0-specific enhancements.
- Right and left shifter designs.
- Measured metal-to-metal sidewall coupling capacitance for our process, and tested several different ESD protection structures.
- Continuing work on the CAD environment, including improvements on the standard cell synthesis path.

Additionally, a great deal of design work has been done at the board level and above. Major activities have been:

- The SPERT board has been redesigned for a new clock, a refined SBUS interface, a more complete test strategy, and to resolve a number of mechanical/thermal/electrical issues.
- The CNS-1 mechanical model has been completed.
- We have begun work on alternative RAM strategies. In particular, we have looked at tradeoffs between Rambus DRAM, Synchronous DRAM, and SRAM.
- We have designed and implemented a prototype board including a low-voltage swing network interface chip. Results from these experiments will be critical in the design of the next-generation Torrent chip, called T1. This chip will differ from the T0 primarily in terms of having high speed network interfaces (although it will also be ported to a more advanced fabrication technology, and some circuits will be redesigned for a lower supply voltage).
• We have completed a block-level design for the CNS-1 I/O chip, called Hydrant, and have designed relevant structures into a programmable gate array (Xilinx) that will be used to interface the Hydrant to external buses.

• We have begun planning a preliminary form of CNS-1 called the SprachStation that will use the basic CNS-1 chips (T1 and Hydrant), but which will be much smaller (e.g., 4 CPUs). The smaller size will make cooling and mechanical factors less of an issue, and the lower cost will make it more accessible for much of the speech research done here and at collaborating labs.

1.3.2 Software Design

As of January 1994, most of the back-propagation networks trained at ICSI for speech recognition research use the “Boxes of Boxes” (or BoB) software environment [143]. The earlier Connectionist Layered Object-oriented Network System (or CLONES) was used successfully on the RAP in training large backpropagation networks for speech recognition. However, its limitations also became apparent. While CLONES was designed to work well on SPMD or SIMD parallel machines, it was not designed to work on larger machines that might in addition exploit MIMD parallelism. Also, CLONES is not well suited to integrating non-connectionist modules. Finally, we want to reduce the time required for users to learn how to program using these classes. BoB has been written with these issues in mind. Many scientific computational tasks are naturally represented as boxes that represent computations connected by lines that represent transport of data. BoB classes for BOX and PORT make a clean separation between the computation and communication aspects of a data flow graph, allowing the computational code to remain unchanged when the transport of data is changed (for example, when a BOX is moved to a different processor). Boxes are general purpose (with any number of input and output ports). Different versions of a training or application program can be easily recomposed. Since any two PORTs that can move the same C++ class of object can be interconnected, it is easy to pull out a BOX (or set of BOXes) and replace it with a different compatible network. BoB networks can be subdivided onto parallel processors either by subdividing vectors among processors, or by assigning a subgraph of one more interconnected BOX objects to a subset of the processors. BoB’s abstract classes are very lightweight (32 bits for the virtual function table pointer) so that fine grain systems can be developed which require very large numbers of BOXes.

BoB oriented systems have been used as a user interface by others, such as Ptolemy [138]. BoB differs in its design goals from existing systems in its emphasis on efficiency for parallel computers and the simplicity of the base C++ classes. It is designed to be used by programmers, since this provides the ultimate in flexibility. The BoB library also includes a completely separate set of classes that support general and speech oriented databases that may be larger than a single (2GB) disk drive. A single logical database object can hide the fact that it consists of many files that contain data for rectangular regions of the full database.

We have also done considerable development on software required for the Synthetic Perceptron Trainer (SPERT) system, which uses essentially the same CPU as the CNS-1 (minus the network ports and changes to the scalar and vector unit designs to support
the new interfaces). An evaluation was performed on the suitability of fixed point calculations for speech MLP algorithms. This included coding the framework of a fixed point matrix/vector library and implementing the routines necessary for back propagation training. These routines were bit-level accurate simulations of the equivalent T0 assembler language routines, and the resulting program produced results comparable to a floating point implementation.

Various programming tools have been developed for writing and debugging Torrent programs. This includes an assembler, an instruction level T0 simulator and modifications to public domain compilers, linkers and debuggers [133]. A large assembler test suite has been written to test both the T0 simulator and assembler; this same code will also be used for verifying T0 hardware simulations and the final silicon. In addition, semi-random code generating programs have been written. These will be used to produce large numbers of programs which can be run on both hardware simulations and the instruction level simulator. Finally, a basic single user operation system environment has been developed for SPERT. This includes support for using host system IO devices, floating point coprocessor emulation and facilities to aid debugging. Several large C programs have been run under the ISA simulator in this environment.

1.3.3 Applications Work - Speech Recognition

We have continued the development of RASTA robust speech analysis. Using the new J-RASTA form in which a family of log-like curves is parameterized by a rough noise estimate, we have been able to show robustness to both additive and convolutional sources of acoustic error [139]. The core idea is to transform the power spectrum into a domain in which the disturbance is roughly additive, and then filter it out with a linear bandpass filter. This year so far we have concentrated on learning how to incorporate this method in existing recognizers. In particular, we have tried three approaches with template-based and statistical (HMM) recognizers: training multiple recognizers (for different log-family parameters) and taking the one with the best probabilities; processing the data multiple times and incorporating all such forms of the data into training a single recognizer; and finding a mapping to normalize speech that has been processed by different log-like functions. In the latter case we have recently shown that even a linear mapping seems to work well [142]. The consequences of this discovery are that we will be able to construct a single analysis that works over a wide range of noise conditions without complicating training.

Approaches like RASTA provide improved robustness to constant or slowly-varying environmental factors, but they emphasize the effect of transitions more than is optimal for current recognizers, which model speech as a succession of steady-state sounds. We believe that this is responsible for some degradation that RASTA sometimes gives us for clean acoustical situations. Additionally, since significant steady-state regions are actually rather rare in speech, we would like to develop models that better represent the dynamics that we actually observe. We have been examining a number of possible changes to our Markov models. Towards this end we have begun experimenting with systems that explicitly model the temporal evolution of the speech signal during a phonetic segment. While we have yet to develop a recognizer that incorporates this, we have observed that (in at least one full-sized test) the correct knowledge of the temporal
position for each frame (i.e., how far into the segment each frame is) can easily reduce recognition error by 2/3. This was for 1000-word recognition on a standard Resource Management test set.

A collaboration has begun between students in the Applications and Realization group to combine acoustic and visual information to improve speech recognition in the presence of additive noise and crosstalk [137]. Preliminary results showed significant robustness to these disturbances for a connected letters task when both modalities were used.

We have worked to improve our hybrid HMM/MLP speech recognition systems [135, 136, 146, 147]. Most of the recent improvements on our basic system have been done in collaboration with researchers at Cambridge University who were also using the recognizer. In this work we have improved silence models and expanded to multiple pronunciations. For the latter improvement we have incorporated an approach to Bayesian induction of HMMs that was developed here at ICSI by Andreas Stolcke and Steve Omohundro [148]. We have shown that these data-driven multiple pronunciations consistently improve performance, at least for the Berkeley Restaurant 1300-word fluent speech understanding task we have tried it on (see below and [150]). Our current level of performance with this system on standard Resource Management tests appears to be competitive with the best reported systems, while using far simpler models (context-independent monophones with a single density per phone, as compared with most such systems that use multiple densities per model, and each model incorporating multiple levels of context including triphone and word dependencies). Finally, we have tuned our procedures so that we now have a consistent approach to seeding the iterative process for probability estimation. In this approach, we train a phonetic classification network on the labeled TIMIT database, and use this trained network to align the training data for the new database (e.g. Berkeley Restaurant or Resource Management). A new network is then trained, and so on. This appears to work well. Towards the end of 1993 we applied this approach to a 5000-word version of the Wall Street Journal task, training up the largest neural network that has ever been used for speech recognition (we believe). This network used 1,600,000 free parameters and was trained on over 6 million frames of speech (at a 100 frames per second rate for feature extraction).

A similar recognizer (but with 150,000 parameters) has also been incorporated in our Berkeley Restaurant Guide [141, 151]. Additionally, this system uses virtual garbage models as developed by Hervé Bourlard. In this approach, no actual models are trained on possible non-speech or out-of-vocabulary words. Instead, a dynamic threshold from a dummy model is used, and set to be the average probability of the top N candidates in a particular frame. This appears to be extremely effective at rejecting sounds that are not in our lexicon. We have collected much more restaurant training data now, and have a system that is actually usable (though we still are working on reducing the errors through a number of approaches under development). This project has been done as a collaboration between Realization Group members and Dan Jurafsky of the Applications group, who has provided a back end to interpret the noisy word sequences provided by the acoustic recognizer. This back end consists of a probabilistic context-free grammar augmented with simple semantic actions, a bottom-up chart parser which builds a semantic representation of each sentence on-line, a context module that helps by translating such words as “today” into the right day of the week, and a greedy algorithm
to build up pieces of utterances from fragments that the system could understand. We are currently working on a tightly-coupled version of this system that will feed back probabilities to the Viterbi search that is currently only done at the acoustic level (although bigram probabilities do already bring in some linguistic knowledge at the frame level). The current system, which does not yet incorporate tight coupling, has good enough accuracy for further data collection. Many users already find that it is satisfactory for their restaurant queries even at the current performance level.

We have continued our work on acoustic/phonetic-based accent detection. In the first of these experiments, we have used an MLP in a straightforward fashion to derive the probability of a German or an American accent given an utterance. As with our phonetic probability estimators, MLP outputs are used as posterior probabilities of class membership, and multiplied (by adding logs) to get the accent probability. With a few refinements, this simple approach was able to correctly choose the accent 94% of the time on an independent test set in a multispeaker database. However, this approach is less successful for a speaker-independent test. We are currently preparing to test this with a greater amount of data, but the technique is likely to require merging with other knowledge sources (phonological and syntactic) to provide us with reliable identification. The identification also needs to be combined with modeling to provide improvement in recognition, and we have done some preliminary work in this direction.

Finally, we have been conducting experiments in parallelization of network training for speech. The particular approach we have focused on is to train separate networks for each individual speaker, and then merge the resulting networks for speaker independent recognition by computing a weighted average of the phonetic probabilities from each net. Our initial experiments use a uniform weight across each gender, as we have found that cross-gender prediction is extremely poor.

1.3.4 Architectural Studies

The work in this section is now merged with the Systems Design section.

1.4 Very Large Distributed Systems and High-Speed Networking

The Tenet Group is participating in three major multi-institution research projects: BLANCA, Sequoia 2000, and BAGNet. The BLANCA project is part of the Gigabit Testbed Initiative, which is sponsored by the Corporation for National Research Initiatives and supported by the National Science Foundation and by the Defense Advanced Research Projects Agency. The BLANCA project, in its fourth year, includes AT&T Bell Laboratories, the universities of California, Illinois, and Wisconsin, Pacific Bell, and a few research institutes, among which is ICSI. The goal of BLANCA is to design and build two wide-area ATM-based testbeds called Xunet 2 (at 45 Mbps) and Xunet 3 (at 622 Mbps), and demonstrate on them several applications requiring high-speed networking. Most of the applications are of the scientific visualization type, and require the transmission of image sequences and/or video streams. The sequences or streams are to be browsed, stopped, and played forward or backward at speeds slower or faster than the nominal one, by scientists at sites far from those where the sequences or streams are generated or stored.
Sequoia 2000, the second major initiative in which the Tenet Group is participating, aims at building high-speed storage and communication facilities for global-change scientists at remote locations, to allow them to visualize and browse sequences of digitally represented satellite maps and other large sets of data to be used in earth science research. Project Sequoia 2000, the sequel to Project Athena, was awarded in July 1991 by the Digital Equipment Corporation to the University of California system; its network design and research activities are taking place at U.C. Berkeley and U.C. San Diego. The Sequoia 2000 network (S2Knet) connects at T1 speed the Berkeley campus to the Davis, Santa Barbara, Los Angeles, and San Diego campuses, as well as to the Scripps Institution of Oceanography in San Diego and the state’s Department of Water Resources near Sacramento. An experimental T3 link has just been installed between U.C. Berkeley and U.C. San Diego. The network’s bandwidth was increased to 45 Mbps in January 1994.

The testbed for the third project is BAGNet (the Bay Area Gigabit Network). It is the first Pacific Bell ATM service trial that by March 1994 will connect 14 top computing research organizations located in the San Francisco Bay area; the group has received the CalREN award, a research support foundation established by Pacific Bell, for ATM services. These services are to be used for a number of collaborative multimedia applications, the first of which to be implemented will be a “teleseminars” facility. The bandwidth is expected to be 155 Mbps in early 1994 and to be upgraded to 622 Mbps in late 1994.

The contributions of the Tenet Group to all three projects are concerned primarily with the technological foundations, rather than with the end-user applications, and can be classified into two partially overlapping areas: (a) real-time communication services, and (b) continuous-media networking applications.

1.4.1 Real-Time Communication Services

- Enhancements and extensions of the Tenet approach

Several improvements and extensions have been proposed for the original Tenet approach. The enhancements of Scheme 1 are easily portable to Scheme 2.

Service disciplines for real-time communication. Hui Zhang has obtained several new results in his investigation of service disciplines for integrated services packet switching networks. He has been studying a class of service disciplines called rate-controlled service disciplines. Their key feature is the separation of the server into two components: a rate controller and a scheduler. After the rate controller limits the distortion of the traffic introduced by load fluctuations inside the network, the scheduler orders the packets for transmission. Rate-controlled service disciplines provide a general framework under which most of the existing non-work-conserving disciplines such as Jitter-EDD, Stop-and-Go, and Hierarchical Round Robin can be naturally expressed by choosing appropriate combinations of rate controller and scheduler. Trade-off of various rate controllers and schedulers have been investigated. One discipline in this class, called Rate-Controlled Static Priority (RCSP), is particularly suitable for providing performance guarantees in high speed networks. It has flexibility in the allocation of bandwidth and delay bounds to different connections as well as simplicity of implementation. Conditions are given to provide end-to-end deterministic and statistical
performance bounds in a network of rate-controlled servers. Although rate-controlled service disciplines are non-work-conserving, i.e., packets may be held in rate controllers even when the output link is idle, it has been proven that the end-to-end delay bounds are not affected by the holding time. Their ability to provide end-to-end performance bounds is general. Unlike the previously proposed solutions, they can provide end-to-end bounds in networks with arbitrary topology, both feedback (aggregate traffic forming loops) and feed-forward networks, internetwork with variable but bounded link delays, and networks with rate-controlled servers that have different schedulers.

A new method for admission control. Domenico Ferrari devised a new method for admission control. The method can be applied to a wide variety of node models with a wide spectrum of accuracies, and is therefore much more general than the one previously used in Scheme 1 and Suite 1, which was based on a very simple, not very realistic node model. The crucial difference is that, in the new approach, each node visited by a real-time channel to be established may be represented by two or more single servers connected in cascade instead of only one such server. The admission tests and computations are designed and have to be executed for each server along the path of the channel to be established. The new method substantially simplifies the Real-Time Channel Administration Protocol (RCAP) code for establishment in an internetwork, and makes the tests and computations, hence also the code, more portable. On the negative side, it increases somewhat the establishment overhead and the length of the establishment messages.

New admission tests for deterministic service. Hui Zhang has developed new admission control algorithms for providing deterministic service. In the previous version of Scheme 1, the deterministic test ensures that the sum of the peak rates of all deterministic connections is less than the link speed. This condition will result in a low average link utilization if the peak-average-rate ratio is high for real-time traffic. The new study shows that deterministic service can be provided even when this condition is not met. When the traffic is burst, the new admission control algorithm results in a multi-fold increase in the number of admitted real-time connections.

A new approach to statistical guarantees. Hui Zhang and Ed Knightly have developed a new, efficient, and general approach for providing end-to-end statistical guarantees in packet-switching networks. This is achieved by modeling a traffic source with a family of interval-dependent bounding random variables and by using a rate-controlled service discipline inside the network. The traffic model stochastically bounds the number of bits sent over time intervals of different length. The model captures different source behaviors over different time scales by making the distribution an explicit function of the interval length. The RCSP service discipline has the priority queueing mechanisms necessary to provide statistical performance guarantees in integrated services networks. In addition, RCSP provides the means for efficiently extending the results from a single switch to a network of arbitrary topology.

Modifying the ethernet for real-time traffic. Brian Whetten is developing a new algorithm for a more fair ethernet, and plans to simulate it to test its effectiveness. One of the biggest problem that current ethernets have in terms of both utilization and handling of real-time traffic is the inherent unfairness of CSMA/CD. Under heavy loads, packet starvation frequently occurs, which causes a given sender to block for an average of more than 200 ms. The new algorithm fixes these problems, but may have
a lower maximum utilization in some cases. Simulation will allow these trade-offs to be explored.

**Applying Tenet admission control to ATM networks.** Pillalamarri Seshasayi is looking into the problem of providing real-time communication with guaranteed quality-of-service (QoS) in ATM networks. Guaranteeing QoS in such a network requires that the traffic, cell loss, delay and delay variation of a particular channel be characterized deep inside the network. While such a characterization is well understood at the source, it is not clear how it changes after the channel has traversed many switches in a loaded network. He is investigating how the Tenet traffic model and admission control algorithm should be changed for use in ATM networks.

**Priority Encoding Transmission.** Andres Albanese and Michael Luby (from the Theory group) are investigating the applications of polynomials over a finite field to encode real-time data for transmission through a lossy network to multiple receivers. A sender assigns priorities to information objects and encapsulates them in an information block. Based on the priorities, the encoder generates segments to be multicast over the lossy network. This encoding scheme enables a smooth rate of recovery of the information objects (in order of priority) by a receiver as a function of the number of segments received and the receiver’s processing power. Using this technique, real-time data can be recovered first from statistical guaranteed channels carrying also non-real-time data.

- Porting and extending the prototype Tenet real-time protocol suite (Suite 1)

**Porting the Tenet suite to the Xunet 3 testbed.** A HIPPI network has been constructed between Cory and Evans Halls on the U.C. Berkeley campus and Building 50 at Lawrence Berkeley Laboratory. The network uses standard HIPPI within buildings and serial HIPPI between buildings. Bruce Mah is working with Srinivasan Seshan, a graduate student in the RAID research group, to port the Real-Time Message Transport Protocol (RMTP), the Real-Time Internet Protocol (RTIP), and the Real-Time Channel Administration Protocol (RCAP) to RAID-II, a prototype disk array built at U.C. Berkeley. The port of RCAP, designed to support the file system code in the Sprite kernel, is expected to suggest some new implementation alternatives for the next version of the same protocol. When this protocol work is completed, the disk array will provide a high-capacity, high-bandwidth storage service for the HIPPI testbed. Hoojar Razavi and some researchers at LBL are working on porting the Tenet protocols to other pieces of the network testbed.

**Scheduling real-time transmissions over HIPPI switches.** Andres Albanese, Riccardo Bettati and Maurizio Bonuccelli (a short-term visiting researcher from the University of Rome, Italy), have completed an investigation of means to support real-time traffic over circuit-switching networks where circuits are time-shared by the network layer among various connections. The resulting scheme is a combination of channel establishment and deterministic traffic scheduling. The acceptance test for a new channel consists of the explicit construction of the transmission schedule. Once the channel has been accepted, the schedule used in the acceptance test is used for data transmission. Simulation experiments are currently under way to investigate the scalability of this approach and to evaluate different scheduling heuristics. Work has begun to include this
approach as part of RCAP in the existing two-switch HIPPI network connecting the U.C. Berkeley campus and the Lawrence Berkeley Laboratory (the Xunet 3 testbed). Anisoara Nica is modifying the Tenet protocols for this testbed, where RTIP will time-multiplex several conversations over the same HIPPI links and ports.

Integrating RCAP with the Xunet and Fore Systems signalling protocols. Ed Knightly is collaborating with the networking group at Sandia National Labs to investigate providing real-time performance guarantees on several interconnected network testbeds including Xunet, a Fore Systems ATM LAN, and a heterogeneous FDDI network connected with a Gigaswitch. The project currently has several applications running on it, including DAVE (Distributed Audio Video Environment) conferencing tools and an MPEG video distribution system (under development). In addition, several PVM (parallel virtual machines) distributed applications with demanding network constraints are being tested. The next step to providing end-to-end real-time guarantees to these applications involves integrating RCAP (running on all workstations and routers) with the Xunet and Fore Systems signalling protocols. Fukiko Hidano is currently installing RCAP on top of the Xunet Signalling Protocol.

Real-time protocols for mobile computing. Bruce Mah has been working with Kimberly Keeton and Srinivasan Seshan, two graduate students in the RAID research group, on issues related to mobile computing. They have developed several algorithms for supporting mobility in connection-oriented networks such as a network using the Tenet real-time protocol suite. Connection-based networks present some special problems for mobility, in that the network state needs to reflect a new connection path whenever a host moves in the network. To reduce latencies and overhead in each handoff, and to minimize disruptions of continuous-media streams, it is desirable to investigate handoff schemes that modify portions of existing connections, as opposed to creating entirely new connections. Based on a preliminary analysis, an approach using network-layer multicasting looks quite promising. Some of this work will be incorporated into the InfoPad project. The InfoPad is a portable multimedia terminal under development in the Department of Electrical Engineering and Computer Sciences at U.C. Berkeley.

- The next Tenet scheme (Scheme 2) and suite (Suite 2)

The Scheme 2 paradigm. The initial design of the Tenet Group’s second generation real-time networking scheme, Scheme 2, has been completed. The main focus of this work has been to extend the basic real-time communication service provided by Scheme 1 in two important respects: (a) provide support for efficient multi-party communication, and (b) make the client-service interface more flexible. Support for multi-party communication includes networking abstractions and mechanisms to improve the utilization of network resources by multi-party communication. An important networking abstraction introduced is the target set, which is similar to the host group in IP multicast. Destinations join target sets depending on their interest in certain data streams (e.g. video from a certain distributed conference). Sources then establish channels to target sets, causing real-time channels to be established (or at least attempted) to all destinations in the target set. Join and leave primitives support dynamic membership in target sets. Efficient utilization of network resources is achieved by the use of true multicast and of sharing groups, which allow the network to use application-specific
information to share network resources among channels while maintaining the desired performance guarantees. To improve the flexibility of the client-service interface, we allow several input parameters to be specified as ranges rather than point values. The client can then specify a best/desired value and a worst/acceptable value, thus eliminating (or at least drastically reducing) the need for iterative negotiations. The initial design was reviewed by internal and external evaluators in October 1993. Implementation will begin soon after incorporating feedback from the design review. Other features being considered for inclusion in Scheme 2 and Suite 2 are support for virtual real-time networks, advance reservation algorithms, the Dynamic Channel Management system, and fault recovery mechanisms. The design of the Scheme 2 paradigm and interface has been done by a team consisting of Wolfgang Effelsberg, Domenico Ferrari, Amit Gupta, Wendy Heffner, Mark Moran, Eberhard Mueller-Menrad, Jean Ramaekers (a former Tenet Group member from the University of Namur, Belgium), Clemens Szyperski (who is now with Oberon Microsystems, Inc. in Zurich, Switzerland), Giorgio Ventre (University of Naples, Italy), Ron Widjono, Raj Yavatkar, and Makiko Yoshida (NEC, Kawasaki, Japan).

Routing multicast real-time channels. Ron Widjono and Mark Moran have been studying the problem of routing real-time multicast channels for Scheme 2. The main emphasis over the last several months has been on building the simulator (described in the next paragraph), determining a metric for evaluating and comparing routing algorithms, and developing a cost function that will accurately reflect the availability of critical network resources. Routing algorithms will be evaluated on the basis of a direct measurement of the number of channels established from both hand-written and randomly-generated scripts of channel establishment attempts. Several indirect evaluation metrics that be would easier to measure have also been examined; however, these were rejected because they did not appear to be strongly correlated with the main evaluation metric. A preliminary cost function has been developed that reflects the availability of throughput and the schedulability on each link. Since the cost function should reflect the availability of network resources, the suitability of the cost function as an indirect evaluation metric will have to be checked. Routing algorithms are being adapted to incorporate the end-to-end delay bound as a constraint. Cost functions and evaluation metrics will be evaluated by simulations.

Scheme 2 simulator. Ron Widjono, Amit Gupta, Mark Moran, and Wendy Heffner are working on a simulation tool for Scheme 2 based on the Scheme 1 simulator Galileo. Galileo has been enhanced to support the establishment of multicast (1-to-N) channels. The modifications include a routing module, basic multiple destination establishment, resource partitioning, and a new “greedy” resource reservation relaxation policy. The routing module allows for the implementation of multiple routing algorithms and for easy selection from among them. A routing algorithm's view of the network, which includes link costs, can be dynamically updated by nodes to reflect changing resource availability. The resource partitioning work (described in the next paragraph) allows for the processing, scheduling, and buffer space resources to be partitioned in such a way that admission control and resource allocation during channel establishment are bounded by the partition limits. In multicast channel establishment, the relaxation of resource reservations needs to be done more intelligently to avoid inefficiencies brought upon by the conflicting requirements from the multiple destinations. A “greedy” policy
is being evaluated, in which relaxation proceeds from destination to source with each node taking as much as possible. Finally, real-life parameter values are being used in simulation of a subset of the Internet multicast backbone (MBONE) to fine tune the various parameters affecting admission control and relaxation.

**Resource partitioning in real-time networks.** Domenico Ferrari and Amit Gupta have investigated the problem of partitioning the resources of an integrated-services network. An efficient solution to this problem has many potential applications: for example, the construction of virtual private networks, the fast establishment of real-time channels, the re-routing of channels in mobile communication, and the advance reservation of real-time channels. The solution proposed by Ferrari and Gupta works within the context of the Tenet schemes: per-partition tests and computations have been shown to be derivable from those that apply to the entire network in each node; therefore, the subnetworks defined by partitions of each node's resources can be treated during channel establishment and tear-down as though they were independent and isolated networks. The amount of a resource assigned to a given partition in a node may differ from the amounts assigned to the same partition in all other nodes. One of the partitions may be dedicated to non-real-time traffic; its resources will not usually be available to real-time traffic.

**Advance reservation of real-time channels.** In the current Tenet scheme, the network provides the clients with quality-of-service guarantees during data transfer. However, for a service to be truly usable in multi-party applications, the network ought to be able to guarantee the availability of its resources at the time they will be needed. This implies that the clients should be able to reserve channels with given characteristics and guarantees in advance. Domenico Ferrari, Amit Gupta, and Giorgio Ventre (a former Tenet Group member from the University of Naples, Italy), have designed mechanisms for supporting advance reservations in real-time communication networks.

**Dynamic Channel Management algorithms.** Colin Parris is currently implementing the DCM scheme that provides a network with the ability to dynamically modify the traffic and performance parameters as well as the routes of real-time connections. These modifications are subject to a modification contract which specifies the degree of disruption that a client can accept during these modifications. Dynamic Channel Management consists of the DCM scheme and the DCM policy. The DCM scheme is a collection of algorithms that permit the modification of the parameters and routes, whereas the DCM policy is a collection of rules that determine whether modifications should be attempted, and provide the appropriate traffic and performance parameters and the routing constraints to the DCM scheme. The DCM scheme is being implemented using the Simple Network Management Protocol (SNMP) v1. In this implementation, a connection establishment or modification is achieved by doing an SNMP set on the traffic and performance objects related to the appropriate link. SNMP get commands can also be used to read the connection state information in the nodes. SNMP will also be used to monitor RMTP/RTIP, thus providing DCM policies with full monitoring capabilities for real-time traffic, as well as full control capabilities for real-time connections through the DCM schemes. Experiments will be conducted to compare the performance of this SNMP-based implementation with that of the RCAP (a signalling protocol) implementation.

**Fault recovery mechanisms.** Anindo Banerjea and Colin Parris have performed
simulation experiments to investigate the factors influencing fault recovery of real-time channels. The schemes to recover from single and multiple link faults have been classified along a number of orthogonal dimensions and each of these explored under varying network loads. The experiments have been useful in isolating effective approaches to recovery and suggesting improvements to the schemes.

1.4.2 Continuous-Media Networking Applications

Multimedia conferencing tools development and deployment. Steven McCanne has been investigating schemes for efficient and robust transport of video over packet-switching networks. He has built a video conferencing prototype called vic, which employs an extensible architecture to facilitate experimentation with video coding schemes and session protocols. Vic is in production use on the Sequoia 2000 and Xunet 2 testbeds.

Connecting remote users to the MBONE. Andres Albanese, Alberto Gil Solla and Andres Suarez Gonzalez have developed PAT, Phone Assisted Teleconference, which will connect remote users without workstation access to the MBONE using a touch-tone telephone. The connection will permit those remote users either to lecture or to attend a conference over the network. In both cases, the user will have access to audio, some state knowledge, and control of the shared whiteboard.

Characteristics of wide-area TCP connections. In preparation for an investigation of the impact of continuous-media applications on network performance being planned by the Tenet Group, Vern Paxson has been studying the characteristics of wide-area network traffic on today's Internet. He has investigated growth-trend patterns at a medium-sized Internet site, and developed analytic models for characterizing the bulk transfer properties of wide-area TCP connections. He is currently investigating the time-series structure of wide-area bulk transfer connections.
2 Project status compared to the original research plan

All research activities in the Realization and the Application groups are on schedule and many major goals of the research plan have already been achieved. Minor shifts in research emphasis will be undertaken as the need arises.

The progress of the research performed by the Tenet Group has been very satisfactory, in spite of the difficulties encountered by some of the projects in their experimental phase. Indeed, as was anticipated in the previous Annual Report, the delays in the delivery of the equipment for the BLANCA testbed have hampered the testing of the Tenet real-time protocol suite. The new project on multimedia support, which has replaced the traffic characterization project, has already achieved promising results.

3 Prospects to reach original research goals

The prospects for success in Applications group projects has improved; a new senior investigator was recruited and additional U.S. funding obtained. There is growing interest in universal parallel computing and this could lead to additional funding opportunities.

Nearly all of the goals listed in the three-year plan for the end of 1993 have been reached. We have successfully modeled phonetic context with a connectionist system; our recognition system, Y0, works as a demonstration (currently part of the restaurant information system we have designed); we have demonstrated robustness to slowly-varying spectral modifications for speech recognition; and we have completed the architectural and performance specification for the CNS-1.

Another goal was to have completed the construction of the SPERT processor by the end of 1993. We have altered this goal for technical reasons, and the new objective will take 6-12 months longer. The reason for this delay is a basic design change to the use of a standard instruction set (MIPS-II compatible) for the non-coprocessor instructions. This will make our software much easier to extend and maintain. While the chip design itself is nearly complete, a conservative estimate of a completion date for a working board is January 1995.

The Tenet Group is expected to reach all of its most important research goals, even though this could require longer times than originally expected, due to the delays with which test-bed equipment is being delivered and installed.

4 Impact of third party R&D results on the project

There is increasing outside interest in the Sather project, including the establishment of a network news group. This is having a positive effect, but could lead to confusion if too many Sather variants are placed in competition to our system.

A growing interest for the Tenet real-time protocol suite has been shown by some vendors of computing and networking equipment. For example, Digital Equipment Corporation engineers are interfacing the DECspin multimedia conferencing software system to RMTP/RTIP. The collaborations activated with the vendors participating in the two major projects in which the Tenet Group is involved are expected to contribute to an increase in such interest.
5 Changes and modifications in the research goals

The Sather plan has been revised to place more early emphasis on releasing a uni-
processor version compatible with Sather 1.0. This will allow us to get broader feed-
back on pSather before the next round of super-computer implementations. We are
also proceeding with the general pSather virtual machine design that should enhance
portability.

Based on our past progress and goals already achieved, significant changes to the
research plan are not necessary.

Because of our participation in the BAGNet project, ICSI has acquire a commitment
to participate in the transmission and distribution of TeleSeminar within the BAGnet
community. Some effort have to made for producing good quality multimedia presenta-
tions of the various research seminars ongoing at ICSI.

6 Inventions, Patent applications, etc.

Hervé Bourlard of Lernout & Hauspie and ICSI and Nelson Morgan of ICSI received
a patent for the methods behind connectionist context-dependent phonetic probability
estimation.
References


36


