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The first methods for tolerating more than a small number of worst-case faults in commonly-used networks such as the butterfly, the mesh of trees, and other hypercubic networks. Previously, work on the fault-tolerance properties of these networks was limited to showing how to overcome a single fault by adding an extra stage of hardware to the networks.

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Contents

1 Overall Summary

Substantial progress has been made on several problems involving parallel and distributed computing and combinatorial optimization. This research is reported in the numerous papers that are listed in Section 3. In what follows, we will provide a brief description of the research activities of the staff that are supported by the contract. The faculty supported in part by the contract include Baruch Awerbuch, Bonnie Berger, Michel Goemans, Daniel Kleitman, Tom Leighton (the principal investigator), and Shang-Hua Teng.

2 Individual Research Summaries

2.1 Awerbuch

Research directions. The emphasis in Baruch Awerbuch's work this year has been on *Uncertainty-Tolerant Computing.* Ability to predict the future would have been an invaluable asset in many areas of human activities (e.g. investing in the stock market). As it turns out, computer systems and communication networks are not much different — ability to predict the future would have greatly simplified classical tasks such as caching (in storage hierarchy) or routing (in large networks). Unfortunately, in reality *knowledge of the future* is often unavailable; this poses serious obstacles for efficiently utilizing system resources.

Large distributed systems pose yet another obstacle in that *knowledge of the present* is unavailable as well, since individual processors do not know the global state at the remote locations. The main intellectual challenge posed by the distributed systems is that they must confront *double uncertainty*: temporal uncertainty about the inputs to the program, and *spatial uncertainty* about the state of the system.

The goal is design of scalable systems that perform well, in spite of these obstacles. We have developed some new algorithmic machinery for attacking the issues of uncertainty, and are currently working on refining the theory as well as adapting it for practical settings. The main research objective at the moment is to *experimentally* test theoretically-justified methods, focusing on a variety of systems and network tasks, such as:

- *Distributed Directory Service and Mobile Users Communication.*
- *Distributed caching in multi-processors and file servers.*
- *Route selection for point-to-point and multi-cast circuit-switching.*
- *Packet routing in faulty networks with changing topology.*

Research accomplishments for the last year included:

- Together with Mansour, Awerbuch has developed topology update protocols efficient topology update protocols for unreliable networks.
- Together with Berger, Cowen, and Peleg [14] Awerbuch has developed fast deterministic distributed algorithm for network decomposition.
- Together with Berger, Cowen, and Peleg [15] Awerbuch has developed fast deterministic parallel algorithm for network decomposition.
- Together with Kutten, Mansour, Patt, and Varghese [25], Awerbuch developed time-optimal self-stabilizing synchronizers. (Details in individual section of Boaz Patt.)
- Together with Yair Bartal and Amos Fiat [24], Awerbuch has developed first optimally competitive distributed file replication algorithm.
- Together with Bill Aiello, Bruce Maggs, and Satish Rao [4] Awerbuch has developed first load balancing algorithms for networks with dynamically changing topology.

2.2 Berger

Berger spent the year on leave from the Math Department as a Science Scholar at the Radcliffe Bunting Institute. Her research is currently focused on computational biology, and, in particular, protein structure prediction.

Berger with Kellog and Shor [34], in conjunction with Prof. Jonathan King of the Biology Department, studied virus assembly. The study of virus shell structure and assembly is crucial for understanding how viruses reproduce and how anti-viral drugs might interfere with assembly of virus shells. One of the most notable aspects of virus shells is their highly regular structure: they are generally spherical and possess strong symmetry properties. Almost all human viruses, and many plant and animal viruses, are icosahedral. These include the rhinovirus, poliovirus, and herpesvirus, all of which have rounded icosahedral shells. These icosahedral shells are constructed of repeated protein subunits, or coat proteins, which surround their condensed DNA or RNA genomes. A given shell usually consists of hundreds of copies of one protein, but sometimes copies of two or three different proteins.

Many of these viral shells are believed to assemble with only limited aid from cellular machinery; they appear to "self-assemble", or spontaneously polymerize and take shape, in the host cell environment. At first glance, the assembly of the shells seems easy to understand, because the structure is so regular. In fact, it has been difficult to determine the actual pathway through which the subunits interact to form a closed shell composed of hundreds of subunits. In icosahedral viruses this has been particularly difficult to explain because very often the same protein occurs in non-symmetric positions. This has been an unresolved question for some time.

Previous attempts at accounting for the formation of closed icosahedral shells from subunits have focused on the icosahedral symmetry, through the Caspar and Klug theory of quasi-equivalence. This theory classifies icosahedral shells whose protein subunits all have very similar (quasi-equivalent) neighborhoods and form hexamers and pentamers in the virus shell. The general belief was that shells were formed by assembly of these pentamer and hexamer building blocks. However, recent experimental results suggest that this may not be true, and that the emphasis on the final symmetry of the structure has been a barrier to understanding how these proteins assemble into such complex structures. We consider what an individual protein "knows", from an information-theoretic point of view. It might appear that each protein needs to know something about the global structure. In fact, if the proteins assume different conformations during the assembly process depending on their relative positions, each protein has enough local information to "know" where to bond. Thus, a protein needs to know nothing about what is going on in the rest of the structure in order to form icosahedral shells.

We have shown that a surprisingly simple set of local rules can explain the assembly of all icosahedral viruses, including one whose structure has puzzled researchers. In fact, for each virus structure there is a set of local rules which, starting with a single interaction between two proteins, will uniquely determine all the other interactions necessary to assemble the entire structure. From a mathematical point of view, these rules can be applied in any order, and the same shell results.

With UROP Muir, Berger is now simulating the assembly process computationally, and they are designing the first "tool kit" that will allow biologists to study virus assembly on the computer screen. Berger and Muir have a working demo simulating 3D virus assembly, and she hopes next to implement the program on an SGI being purchased by Leiserson.

Berger is also working with Prof. Peter S. Kim of the Biology Department and Whitehead Institute on algorithms to predict 3D protein structure from sequence. UROP Tonchev has been assisting in this project. Berger and Kim received a grant from the Science Partnership Fund in the School of Science for this work.

Berger continued developing algorithms for network decompositions in the sequential, distributed, and parallel domains with Awerbuch, Cowen, and Peleg [16]. Portions of this work appeared at SWAT in July and PODC in August, and recent developments will appear in the upcoming FOCS.

2.3 Goemans

During the past year, Goemans has made considerable progress in deriving efficient approximation algorithms for combinatorial optimization problems.

We first would like to give an update on the general primal-dual approximation technique for network design problems that was mentioned in the last report. The technique has proved to be very powerful and has led to numerous results and publications. The original paper [70] was accepted for publication in *SIAM Journal on Computing.* The extension with Williamson, Mihail and Vazirani [108] to problems with larger connectivity has appeared in the proceedings of the 25th STOC. The faster implementation jointly obtained with Gabow and Williamson [57] has appeared in the proceedings of the 3rd IPCO conference. Moreover, during the year, the result has been improved in several directions in joint research with Goldberg, Plotkin, Shmoys, Tardos and Williamson [64] and will appear in the proceedings of the 5th SODA. One of the improvements is that the performance guarantee has been lowered from $2k$ to $2 \ln k$ for the generalized Steiner network problem, where k is the largest connectivity requirement. As a side remark, the generalized Steiner network problem arises in the design of fiber-optic networks, and Bellcore is considering the addition of the approximation algorithm to their network design software package. A computational study of our approximation algorithm in the case of the minimum weight matching problem was performed with Williamson [107] (to appear in the 5th SODA). This has shown that our approximation algorithm not only has a nice worst-case behavior but also performs extremely well in practice. In over 1,400 experiments on random and real-world instances having between $1,000$ and $131,072$ vertices, the algorithm was never more than 4% from optimal. Finally, David Williamson, our first Ph.D. student, has graduated during the summer.

With Williamson [71], we have also further simplified the $\frac{3}{4}$-approximation algorithm for the maximum satisfiability problem that was described in the previous report. The new algorithm is extremely simple and illustrates the fact that the best of two approximation algorithms can have a performance guarantee strictly better than any one of them.

On a different line of research, we have performed a theoretical study of the most succesful computational approach for the traveling salesman problem [63]. This lead to some fairly surprising results. In particular, we have shown that the most commonly used class of cutting planes, the so-called clique tree inequalities, can only lead to a multiplicative improvement of $\frac{8}{7}$, while other classes can lead to an improvement of $\frac{4}{3}$.

Two other results which we would like to report are [56] and [67]. The first result is a result in graph theory, while the second establishes the precise maximum time of survival of a system composed of processors, in which processors can fail and cannot be repaired.

2.4 Kleitman

During the reporting period, Professor Kleitman has been involved in the following research projects for which papers have been prepared for publications:

Area: Combinatorial Geometry
Subject: The Hadwiger Debrunner Conjecture
Co-author: Noga Alon
Summary: We were able to prove this long standing conjecture: that if a collection of N closed convex sets in Euclidean d-space have the property: out of any k sets there is a point in j of them, with $j > d$, then there are $f(j,d,k)$ points (independent of N) such that every set contains at least one of them.

Area: Combinatorial Geometry
Subject: Maximum Diameter of an n sided simplex in d dimensions
Co-author: Gil Kalai
Summary: We were able to improve an argument of Kalai which gives a sub-exponential (but not polynomial) bound for this diameter; Kalai has subsequently used the idea here to develop a probabilistic simplex algorithm with provably good properties.

Area: Graph Theory
Subject: Graphs with independent sets of cardinality at most two
Co-author: Wayne Goddard
Summary: We were able to improve a conjecture of Harary that any such graph on $2n-1$ vertices contain every graph having n edges as a subgraph. (This was proved independently by a different method by Sidorenko).

Area: Graph Theory
Subject: Directed Graphs without even length simple cycles
Co-authors: Fan Chung and Wayne Goddard
Summary: We were able to prove a conjecture of Brualdi and Shader, giving the exact upper bound to the number of edges in such a graph, and also gave a partial characterizations of all graphs realizing this bound.

Area: Extremal Set theory
Subject: Maximal sets of given diameter in product of chains
Co-author: Leonard Schulman
Summary: We were able to show that a certain ordering of the elements in products of n

even-length chains have the property that initial segments in this order will always have minimum cross-distance between them given their cardinalities. Cross distance between two sets is the maximum (Manhattan) distance between an element of one and one of the other. We also related this question to various others.

Area: Extremal Set Theory
Subject: Finding arrangements of lines in the n-cube
Co-authors: Ron Holzman and Alexander Felzenbaum
Summary: We were able to show that given any sequence (C_j) for $j = 1$ to n, of positive integers summing to 2_{n-1}, we can find c_j lines in the j-direction through vertices of the n-cube, all of which are disjoining.

Area: Combinatorial Geometry
Subject: Epsilon nets
Co-authors: Noga Alon, Zoltan Furedi and I. Barany
Summary: An epsilon-net for a set Y in R_d is a set S of points of Y contains an element of S. We show that in the such sets exist having cardinalities dependent only on d and epsilon.

Area: Combinatorial Geometry
Subject: Connecting pairs of points in the plane with mutually intersecting line segments
Co-authors: B. Aronov, P. Erdos, M. Klugerman, J. Pach, and L. Schulman
Summary: We were able to show that given n_2 points we could find at least $n/12$ pairs that could be connected by line segments such that all segments intersect.

Area: Graph Theory
Subject: Convergence of a Transformation
Co-author: Wayne Goddard , Dean Sturtevant
Summary: We obtained upper bounds to the speed of convergence of transformations on weighted graphs that map the weight on a vertex to an extreme value of weight in its neighborhood (including itself). Several problems of this kind are considered.

Area: Set Theory
Subject: Set Systems with No Union of Cardinality 0 Modulo m
Co-authors: Noga Alon, Richard Lipton, Roy Meshulam, Michael Rabin and Joel Spencer
Summary: We show that in any collection of sets each set having at most d elements, of cardinality at least $d(q-1)+1$, there is a non trivial subcollection having union of cardinality congruent to O mod q, for q a prime power.

2.5 Leighton

In the area of parallel computation, Professor Leighton (together with Bruce Maggs of NEC and Ramesh Sitaraman of Princeton) has developed the first methods for tolerating more than a small number of worst-case faults in commonly-used networks such as the butterfly, the mesh of trees, and other hypercubic networks. Previously, work on the fault-tolerance properties of these networks was limited to showing how to overcome a single fault by adding an extra stage of hardware to the network. In the new work, Leighton and his collaborators have shown how to overcome large numbers of faults (i.e., $N^{.9}$ worst-case faults) with only a small (i.e. constant) loss in performance. This means that the butterfly is much more tolerant to faults than previously realized. Details of this research were reported at the recent FOCS conference in Pittsburgh.

Prof. Leighton also completed work on his text "Introduction to Parallel Algorithms and Architectures: Arrays, Trees, Hypercubes," which was published by Morgan Kaufmann Publishers. The text has already sold over 5000 copies and is being used as the basis for courses on parallel algorithms and architectures at numerous universities throughout the world.

Prof. Leighton also continued work in the area of randomly-wired networks. Substantial progress was made on problems involving deterministic routing on multibutterflies with multiplicity two. Previous work on multibutterflies only applied to networks with multiplicity three or more. The case of multiplicity two is of greater practical interest, however, and Leighton was able to develop proof techniques that demonstrate that these networks also posses many of the important routing properties held by networks with higher multiplicity.

Prof. Leighton is currently studying worst-case routing problems in meshes. Somewhat surprisingly, he has shown that if the common oblivious greedy algorithm is used for routing in a mesh, and if we have a worst-case routing problem such as the bit-reversal permutation, then 3-d meshes are actually substantially *slower* than 2-d meshes! Also, Prof. Leighton has found examples where even adaptive routers can fail badly for meshes of small dimensions. This work is now being written up for publication.

Professor Leighton and Baruch Awerbuch developed improved algorithms for multicommodity flow. Multicommodity flow is a classic problem with applications to problems such as VLSI routing, communication in networks, scheduling, transportation, and operational logistics. Profs Awerbuch and Leighton have devised a wholly new, and very simple, approach to the multicommodity flow problems which appears to work much better than previously known methods. The new approach appears to be particularly useful for parallel computation and for distributed environments where demands and capacities can vary with time.

Prof. Leighton and Y. Ma (his student) developed a new framework for studying Boolean circuits with faults. As a consequence, they have discovered circuits for the classic sorting problem which can be shown to be optimal in the presence of faults. This work has applications in the domain of circuit switching where messages are often sorted as a preconditioner to routing.

In addition Leighton and Ma discovered,

1) a passive-fault-tolerant sorting circuit with $O(\log n \log\log n)$-depth and $O(n \log n \log\log n)$-

size, which resolves a long-standing open question posed by Yao and Yao to within an $O(\log \log n)$ factor,

2) a reversal-fault-tolerant sorting network with $O(n \log^{\log_2 3} n)$-size provided that the failure probability is upper bounded by a sufficiently small constant, which partially resolves an open question posed by Assaf and Upfal, and

3) a fault-tolerant sorting algorithm that runs in $O(\log n)$ steps on an $O(n)$-processor EREW PRAM, which resolves an open question posed by Feige, Peleg, Raghavan, and Upfal.

All the results are based on a new analysis of the AKS sorting circuit, which is of interest in its own right.

2.6 Teng

In the past year, I have been working in several areas in theoretical computer science and scientific computing. The following summarizes some of these works.

- "Approximating shortest superstrings".
- "Optimal online scheduling of parallel jobs with dependencies".
- "Automated parallel solution of unstructured PDE problems".

  We propose and develop a practical scheme for solving large scale unstructured PDE problem in parallel. The core of this scheme is the geometric mesh partitioning algorithm that I have developed in a joint work with Miller, Thurston, and Vavasis.
- "Moment of inertia and graph separators".
- "Geometric mesh partitioning and nested dissection".
- "Parallel construction of quadtrees and quality triangulations".

  We design the first provably good parallel algorithm for automatically generating well-shaped finite element meshes.
- "How Good is Recursive Bisection".
- "Approximating center points with iterated Radon points".
- "A deterministic linear time algorithm for geometric separators and its applications".
- "k-nearest-neighbor clustering and percolation theory"
- "Automatic array alignment in data-parallel programs".

  We proposed solutions to various problems occurred in compiling for data-parallel machines. Part of my work was done when I was with Xerox and NASA Ames. Our idea of generating local address and communication sets of data-parallel programs have been patented.

- Opportunistic Optimization and Incremental Divide-and-conquer in Sparse Matrix Computations.

- I have designed and implemented a parallel geometric mesh partitioning program in CM-Fortran. Thinking Machine Corporation is planning to incorporate it into its CMSSL (of course depending on some kind of legal agreements between MIT and Thinking Machine Corp. about the copyright.)

3 Publications, Presentations and Theses Supported by the Contract

3.1 Publications

[1] R. Adams and D.J. Kleitman. Some recent results in graph theory. *Graph Theory Notes of New York*, XXIV:17–22, 1993.

[2] B. Aiello and T. Leighton. Coding theory, hypercube embeddings, and fault tolerance. *IEEE Transactions on Computers*, 1994. To Appear.

[3] B. Aiello, T. Leighton, B. Maggs, and M. Newman. Fast algorithms for bit-serial routing on a hypercube. *Math Systems Theory*, 24:253–271, 1991.

[4] W. Aiello, B. Awerbuch, B. Maggs, and S. Rao. Wait-free approximate load balancing. In *Proceedings of the Twenty-Fifth Annual ACM Symposium on Theory of Computing*, pages 632–641, San Diego, May 1993.

[5] M. Aigner, D. Duffus, and D.J. Kleitman. Partitioning a power set into union-free classes. *Discrete Mathematics 88*, pages 113–119, 1991. North Holland.

[6] N. Alon and D.J. Kleitman. Partitioning a rectangle into small perimeter rectangles. *Discrete Mathematics*, 103:111–119, 1992.

[7] N. Alon and D.J. Kleitman. Piercing convex sets and the Hadwiger Debrunner (p, q)-problem. *Advances in Mathematics 94, 1308*, 1992.

[8] N. Alon, D.J. Kleitman, R. Lipton, R. Meshulam, M. Rabin, and J. Spencer. Set systems with no union of cardinality 0 modulo n. *Graph and Combinatorics 7*, pages 97–99, 1991.

[9] S. Arora, T. Leighton, and B. Maggs. On-line algorithms for path selection in a nonblocking network. *SIAM Journal on Computing*, 1993. To appear.

[10] B. Awerbuch, Y. Azar, and S. Plotkin. Throughput-competitive online routing. In *34^{th} Annual Symposium on Foundations of Computer Science*. IEEE, 1993. To appear.

[11] B. Awerbuch, Y. Azar, S. Plotkin, and O.Waarts. Competitive routing of virtual circuits with unknown duration. In *Proceedings of the Fifth Annual ACM-SIAM Symposium on Discrete Algorithms*, 1994. To appear.

[12] B. Awerbuch, Y. Bartal, A.Fiat, and A.Rosén. Competitive non-preemptive call control. In *Proceedings of the Fifth Annual ACM-SIAM Symposium on Discrete Algorithms*, 1994. To appear.

[13] B. Awerbuch, Y. Bartal, and A. Fiat. Heat & dump: randomized competitive distributed paging. In *34^{th} Annual Symposium on Foundations of Computer Science*. IEEE, 1993. To appear.

[14] B. Awerbuch, B. Berger, L. Cowen, and D. Peleg. Fast distributed network decomposition. In *Proceedings of the Eleventh Annual ACM Symposium on Principles of Distributed Computing*, August 1992.

[15] B. Awerbuch, B. Berger, L. Cowen, and D. Peleg. Low diameter graph decomposition is in NC. In *Third Scandinavian Workshop on Algorithm Theory*, pages 83–93, 1993. To appear in *Random Structures and Algorithms.*

[16] B. Awerbuch, B. Berger, L. Cowen, and D. Peleg. Near linear cost constructions of neighborhood covers in sequential and distributed environments and their application. To appear, 1993.

[17] B. Awerbuch, L. Cowen, and M. Smith. Self-stabilizing symmetry breaking in polylogarithmic time. Draft, April 1992.

[18] B. Awerbuch, L. Cowen, and M. Smith. Efficient randomized 2-wait-free symmetry breaking. Manuscript in Preparation., May 1993.

[19] B. Awerbuch, G. Itkis, and R. Ostrovsky. Hardware-based self-stabilization. Preliminary draft, April 1992.

[20] B. Awerbuch and T. Leighton. Multicommodity flows: A survey of recent research. In *Proceedings of the Fourth Annual International Symposium on Algorithms and Computation*, December 1993. to appear.

[21] B. Awerbuch and T. Leighton. A simple local-control approximation algorithm for multicommodity flow. In *34^{th} Annual Symposium on Foundations of Computer Science.* IEEE, 1993.

[22] B. Awerbuch and L. J. Schulman. The maintenance of common data in a distributed system. In *Proceedings of the 32nd annual Symposium on Foundations of Computer Science*, pages 505–514. IEEE, 1991.

[23] Baruch Awerbuch, Amotz Bar-Noy, and Madan Gopal. Approximate distributed shortest path algorithms. In *Proceedings of the 1991 INFOCOM*, pages 1206–1213, 1991.

[24] Baruch Awerbuch, Yair Bartal, and Amos Fiat. Competitive distributed file allocation. In *Proceedings of the Twenty-Fifth Annual ACM Symposium on Theory of Computing*, San Diego, May 1993. to appear.

[25] Baruch Awerbuch, Shay Kutten, Yishay Mansour, Boaz Patt-Shamir, and George Varghese. Time optimal self-stabilizing synchronization. In *Proceedings of the Twenty-Fifth Annual ACM Symposium on Theory of Computing*, pages 652–661, San Diego, May 1993.

[26] Baruch Awerbuch, Shay Kutten, and David Peleg. Deadlock-free routing. In *Proceedings of the 10th ACM Symposium on Principles of Distributed Computing*, 1991.

[27] Baruch Awerbuch, Shay Kutten. and David Peleg. On buffer-economical store-and-forward deadlock prevention. In *Proceedings of the 1991 INFOCOM*, 1991.

[28] Baruch Awerbuch, Shay Kutten, and David Peleg. Online load balancing in a distributed network. In *Proceedings of the 24th ACM Symposium on Theory of Computing*, pages 571–580, 1992.

[29] Baruch Awerbuch, Boaz Patt, David Peleg, and Mike Saks. Adapting to asynchronous dynamic networks with polylogarithmic overhead. In *Proceedings of the 24th ACM Symposium on Theory of Computing*. pages 557–570, 1992.

[30] Baruch Awerbuch, Boaz Patt-Shamir, and George Varghese. Local checking and correction of interactive protocols. In *32nd Annual Symposium on Foundations of Computer Science*, pages 268–277, San Juan, Puerto Rico, October 1991. IEEE.

[31] Baruch Awerbuch and David Peleg. Concurrent online tracking of mobile users. In *Proceedings of the Annual ACM SIGCOMM Symposium on Communication Architectures and Protocols, Zurich, Switzerland*, 1991.

[32] Baruch Awerbuch and George Varghese. Distributed program checking: a paradigm for building self-stabilizing distributed protocols. In *Proc. 32nd IEEEE Symp. on Foundations of Computer Science*, pages 258–267, San Juan, PR, October 1991.

[33] B. Berger, M. Brady, D. Brown, and T. Leighton. Nearly optimal algorithms and bounds for multilayer channel routing. *Journal of the ACM*, 1993. To appear.

[34] Bonnie Berger, Peter W. Shor, Lisa Tucker-Kellog, and Jonathan King. A local rule based theory of virus assembly, 1993. Submitted for publication.

[35] M. Bern, D. Eppstein, and S-H. Teng. Parallel construction of quadtrees and quality triangulations. In *Workshop on Algorithms and Data Structures, (WADS)*, 1993.

[36] D. Bhatia, T. Leighton, and F. Makedon. Efficient algorithms for gate array routing. In *Proceedings of WG92*, 1992.

[37] D. Bhatia, T. Leighton, F. Makedon, and C. Norton. Improved algorithms for global wire routing in two-dimensional arrays. In *Proceedings of the 18th Workshop on Graph Theoretic Concepts in Computer Science, Lecture Notes in Computer Science*, volume 657, pages 114–122. Springer-Verlag, 1992.

[38] S. Bhatt, F. Chung, J. Hong, T. Leighton, B. Obrenic, A. Rosenberg, and E. Schwabe. Optimal simulations of butterfly networks. *Journal of the ACM*, 1993. To appear.

[39] S. Bhatt, F. Chung, T. Leighton, and A. Rosenberg. Scheduling tree-dags using FIFO queues: A control-memory tradeoff. Submitted to *26th Annual ACM Syposium on the Theory of Computing*, November 1993.

[40] S. Bhatt, F. Chung, T. Leighton, and A. Rosenberg. Efficient embeddings of trees in hypercubes. *SIAM Journal on Computation*, 21(1):151–162, 1992.

[41] S. Bhatt, F. Chung, T. Leighton, and A. Rosenberg. On optimal strategies for stealing cycles. Unpublished Manuscript, 1992.

[42] S. Bhatt, F. Chung, T. Leighton, and A. Rosenberg. Tolerating faults in synchronization networks. In *Proceedings of CONPAR92-VAPPV, Lecture Notes in Computer Science*, volume 634, pages 1–12. Springer-Verlag, 1992.

[43] Daniel Bienstock, Michel X. Goemans, David Simchi-Levi, and David P. Williamson. A note on the prize collecting traveling salesman problem. To appear in *Mathematical programming*, 1991.

[44] B. Blumofe, T. Leighton, and C. Leiserson. Theory of parallel and VLSI computation, 1992. Lecture notes for 18.435/6.848: MIT/LCS Research Seminar Series #18.

[45] Ernest F. Brickell, Daniel M. Gordon, Kevin S. McCurley, and David B. Wilson. Fast exponentiation with precomputation: Algorithms and lower bounds. Submitted to *SIAM Journal on Computing.*

[46] G. Burosch, J. Demetrovics, G.O.H. Katona, D.J. Kleitman, and A.A. Sapozhenko. On the number of databases and closure operations. *Theoretical Computer Science 78*, pages 377–381, 1991.

[47] S. Chatterjee, J. Gilbert, F. J. E. Long, R. Schreiber, and S-H. Teng. Generating local address and communication sets for data-parallel programs. In *Proceedings Fourth ACM Symposium on Principles and Practice of Parallel Programming*, 1993.

[48] S. Chatterjee, J. Gilbert, R. Schreiber, and S-H. Teng. Automatic array alignment in data-parallel programs. In *Proceedings of the Twentieth Annual ACM Symposium on Principles of Programming Languages*, 1993.

[49] E. Coffman, E. Gilbert, A. Greenberg, T. Leighton, P. Robert, and A. Stolyar. Queues served by a rotating ring. Manuscript to be submitted June 1993.

[50] J. Cooperstock, R. El-Yan, and T. Leighton. The statistical adversary allows on-line foreign exchange with no risk. Submitted to *26th Annual ACM Symposium on the Theory of Computing*, November 1993.

[51] D. Eppstein, G. Miller, C. Sturtivant, and S-H. Teng. Approximating center points with and without linear programming. In *Proceedings of 9th ACM Symposium on Computational Geometry*, 1993.

[52] A. Feizenbaum, R. Holzman, and D.J. Kleitman. Packing lines in a hypercube. *Discrete Mathematics*, 117:107–112, 1993.

[53] A. Feldmann, M.-Y. Kao, J. Sgall, and S-H. Teng. Optimal online scheduling of parallel jobs with dependencies. In *Proceedings of the 25th Annual ACM Symposium on Theory of Computing*, 1993.

[54] A. Felzenbaum, R. Holzman, and D.J. Kleitman. Packing lines in a hypercube. *Discrete Math*, 1991. In press.

[55] L. Finkelstein, D. Kleitman, and T. Leighton. Applying the classification theorem for finite simple groups to minimize pin count in uniform permutation architectures. *Combinatorica*, 1992. submitted for publication.

[56] Zoltan Furedi, Michel X. Goemans, and Daniel Kleitman. On the maximum number of triangles in wheel-free graphs. To appear in *Combinatorics, Probability & Computing*, 1993.

[57] Harold N. Gabow, Michel X. Goemans, and David P. Williamson. An efficient approximation algorithm for the survivable network design problem. In *Proceedings of the 3rd Integer Programming and Combinatorial Optimization Conference*, pages 57–74, 1993.

[58] W. Goddard, M. Katchalski, and D.J. Kleitman. Forcing disjoint line segments in the plane. Submitted to *European Journal of Combinatorics*, July 1992.

[59] W. Goddard and D.J. Kleitman. Convergence of a transformation on a weight graph. *Congressus Numeratium*, 82:179–185, 1991.

[60] W. Goddard and D.J. Kleitman. A note on maximal triangle-free graphs. Submitted to *Journal of Graph Theory*, July 1992.

[61] Wayne Goddard and D.J. Kleitman. An upper bound for the ramsey number $r(K_3, g)$. Presented at British Combinatorics (1991), submitted to *Journal of Discrete Mathematics*.

[62] Michel X. Goemans. Polyhedral description of trees and arborescences. In *Proceedings of the 2nd Integer Programming and Combinatorial Optimization conference*, pages 1–14, 1992.

[63] Michel X. Goemans. Worst-cast comparison of valid inequalities for the TSP. Submitted for publication, 1993.

[64] Michel X. Goemans, Andrew Goldberg, Serge Plotkin, David Shmoys, Éva Tardos, and David Williamson. Improved approximation algorithms for network design problems. In *Proceedings of the 5th Annual ACM-SIAM Symposium on Discrete Algorithms*, 1994.

[65] Michel X. Goemans and Michael Klugerman. Advanced algorithms. Research Seminar series MIT/LCS/RSS 17, MIT, 1992.

[66] Michel X. Goemans and Muralidharan Kodialam. A lower bound on the expected value of an optimal assignment. *Mathematics of Operations Research*, 18:267–274, 1993.

[67] Michel X. Goemans, Nancy Lynch, and Isaac Saias. Upper and lower bounds on the number of faults a system can withstand without repairs. In *Proceedings of the Fourth IFIP Working Conference on Dependable Computing for Critical Applications*, 1994.

[68] Michel X. Goemans, Milena Mihail, Vijay Vazirani, and David Williamson. An approximation algorithm for general graph connectivity problems. Technical Memorandum TM-ARH-021743, Bellcore, 1992.

[69] Michel X. Goemans and Young soo Myung. A catalog of steiner tree formulations. *Networks*, 23:19–28, 1993.

[70] Michel X. Goemans and David P. Williamson. A general approximation technique for constrained forest problems. In *Proceedings of the 3rd Annual ACM-SIAM Symposium on Discrete Algorithms*, pages 307–316, 1992. Journal version to appear in *SIAM J. Comput.*

[71] Michel X. Goemans and David P. Williamson. A new 3/4-approximation algorithm for MAX SAT. In *Proceedings of the 3rd Integer Programming and Combinatorial Optimization Conference*, pages 313–321, 1993. To appear in *SIAM J. Disc. Math.*

[72] L. Goldberg, M. Jerrum, T. Leighton, and S. Rao. A doubly logarithmic communication algorithm for the completely connected optical communication parallel computer. In *Proceedings of the 5th ACM Symposium on Parallel Algorithms and Architectures*, pages 300–309, July 1993.

[73] Jerold Griggs and D.J. Kleitman. Independence and the Havel-Hakimi residue. In *Annals of Discrete Mathematics* (in press).

[74] L. Heath, T. Leighton, and A. Rosenberg. Comparing queue and stack layouts. *SIAM J Discrete Math*, 5(3):398–412, August 1992.

[75] R. Holzman and D.J. Kleitman. On the product of sign vectors and unit vectors. *Combinatorica*, 12(3):303–316, 1992.

[76] N. Kahale. Better expansion for ramanujan graphs. In *32^{nd} Annual Symposium on Foundations of Computer Science*, pages 398–404, San Juan, Puerto Rico, October 1991. IEEE.

[77] Nabil Kahale. On the second eigenvalue and linear expansion of regular graphs. In *33^{rd} Annual Symposium on Foundations of Computer Science*. IEEE, 1992. To appear in the Proceedings of the DIMACS Workshop on Expander Graphs.

[78] G. Kalai and D.J. Kleitman. A quasi-polynomial bound for the diameter of graphs and polyhedra. *AMS Bulletin Vol. 26, No. 2*, 1992.

[79] M. Klawe and T. Leighton. A tight lower bound on the size of planar permutation networks. *SIAM Journal on Discrete Mathematics*, 5(4):558–563, November 1992.

[80] D.J. Kleitman. Partitioning a rectangle into many sub-rectangles so that a line can meet only a few. *DIMACS Series in Discrete Math and Theoretical Computer Science*, 9, 1993.

[81] D.J. Kleitman, F. Lasaga, and L. J. Cowen. Asymptotic enumeration of full graphs. Submitted to *Journal of Graph Theory.*, June 1993.

[82] D.J. Kleitman and L.J. Schulman. Minimally distant sets of lattice points. *European Journal of Combinatorics*, 14:231–240, 1993.

[83] M. Klugerman and C. G. Plaxton. Small-depth counting networks. In *Proceedings of the 24th Annual Symposium on Theory of Computing*, May 1992.

[84] R. Koch, T. Leighton, B. Maggs, S. Rao, A. Rosenberg, and E. Schwabe. Work-preserving emulations of fixed-connection networks. *Journal of the ACM*, 1993. To appear.

[85] T. Leighton. Greedy routing on twin butterflies. Manuscript in preparation, 1992.

[86] T. Leighton. Methods for message routing in parallel machines. In *Proc. 24th ACM STOC*, pages 77–96, 1992. Also to appear in *Theoretical Computer Science*, 1994.

[87] T. Leighton. The role of algorithms and theory in meeting the grand challenge. In *Proceedings of the 1992 DARPA Software Technology Conf*, pages 169–177, 1992.

[88] T. Leighton. The role of randomness in the design of interconnection networks. In *Proc. World Computer Congress*, 1992. Also appears in *Proc. Paderborn Workshop on Parallel Computation*, 1993.

[89] T. Leighton. A $2d-1$ lower bound for 2-layer knock-knee channel routing. *SIAM Journal on Discrete Mathematics*, 1993. To appear.

[90] T. Leighton, F. Korsmeyer K. Nabors, and J. White. Preconditioned, adaptive, multipole-accelerated iterative methods for three-dimensional potential integral equations of the first kind. *SIAM Journal on Statistical Methods*, 1993. To appear.

[91] T. Leighton, C. Leiserson, and N. Kahale. Lecture notes for 18.436/6.849 *Advanced Parallel and VLSI Computation.* Technical Report MIT-LCS-RSS-15, MIT Laboratory for Computer Science, 1991.

[92] T. Leighton and Y. Ma. Breaking the $\Theta(n \log^2 n)$ barrier for sorting with faults. In *34th Annual Symposium on Foundations of Computer Science.* IEEE, 1993.

[93] T. Leighton and Y. Ma. Tight lower bounds on the size of fault-tolerant merging and sorting networks with destructive faults. In *Proceedings of the 1993 ACM Symposium on Parallel Algorithms and Architectures*, pages 30–41, June 1993.

[94] T. Leighton, Y. Ma, and G. Plaxton. Highly fault-tolerant sorting circuits. In *Proceedings of the 31st Annual IEEE Symposium on Foundations of Computer Science*, pages 458–469, October 1991.

[95] T. Leighton and B. Maggs. Fast algorithms for routing around faults in multibutterflies and randomly-wired splitter networks. *IEEE Transactions on Computers*, 41(5):578–587, May 1992.

[96] T. Leighton, B. Maggs, A. Ranade, and S. Rao. Randomized algorithms for routing and sorting in fixed-connection networks. *Journal of Algorithms*, 1992. To appear.

[97] T. Leighton, B. Maggs, and S. Rao. Packet routing and job-shop scheduling in O(dilation + congestion) steps. *Combinatorica*, 1993. to appear.

[98] T. Leighton, B. Maggs, and R. Sitaraman. On the fault-tolerance of some popular bounded-degree networks. In *33^{rd} Annual Symposium on Foundations of Computer Science*, pages 542–552. IEEE, 1992.

[99] T. Leighton, F. Makedon, S. Plotkin, C. Stein, É. Tardos, and S. Tragoudas. Fast approximation algorithms for multicommodity flow problems. *Journal of Computer and System Sciences*, 1993. To appear.

[100] T. Leighton, M. Newman, A. Ranade, and E. Schwabe. Dynamic tree embeddings in butterflies and hypercubes. *SIAM Journal of Computing*, 21(4):639–654, August 1992.

[101] T. Leighton and E. Schwabe. Efficient algorithms for dynamic allocation in a distributed memory. In *32^{nd} Annual Symposium on Foundations of Computer Science*, pages 470–479, San Juan, Puerto Rico, October 1991. IEEE.

[102] Rudolph Mathar and Lenore Cowen. Concurrence probabilities for a locally slotted packet radio network by combinatorial methods. *Performance Evaluation*, 17:43–51, January 1993.

[103] Chris Potts, David B. Shmoys, and David P. Williamson. Permutation vs. non-permutation flow shop schedules. *Operations Research Letters*, 10:281–284, 1991.

[104] David B. Shmoys, Joel Wein, and David P. Williamson. Scheduling parallel machines on-line. In *32^{nd} Annual Symposium on Foundations of Computer Science*, pages 131–140, San Juan, Puerto Rico, October 1991. IEEE.

[105] David P. Williamson. The non-approximability of shop scheduling. Unpublished manuscript, 1991.

[106] David P. Williamson. Analysis of the Held-Karp lower bound for the asymmetric TSP. *Operations Research Letters*, 12:83–88, 1992.

[107] David P. Williamson and Michel X. Goemans. Computational experience with an approximation algorithm on large-scale Euclidean matching instances. In *Proceedings of the 5th Annual ACM-SIAM Symposium on Discrete Algorithms*, 1994.

[108] David P. Williamson, Michel X. Goemans, Milena Mihail, and Vijay V. Vazirani. A primal-dual approximation algorithm for generalized Steiner network problems. In *Proceedings of the Twenty-Fifth Annual ACM Symposium on Theory of Computing*, pages 708–717, San Diego, May 1993.

[109] David Bruce Wilson. Embedding leveled hypercube algorithms into hypercubes. In *Proceedings of the 4th Annual ACM Symposium on Parallel Algorithms and Architectures*, 1992.

3.2 Lectures

[110] Lenore Cowen. Improved algorithms for network decomposition. Lecture given at Dept. of Math. Sciences, The Johns Hopkins University, February 1993.

[111] Michel X. Goemans. A combinatorial approximation algorithm for the prize-collecting TSP. Lecture given at ORSA/TIMS joint national meeting, 1992.

[112] Michel X. Goemans. The first approximation algorithm for the survivable network design problem. Lecture given at State University of New York at Stony Brook, 1992.

[113] Michel X. Goemans. Linear programming relaxations. Lecture given at Conference on the Mathematics of Operations Research, 1992.

[114] Michel X. Goemans. Approximation algorithms for a class of combinatorial optimization problems. Lecture given at Université Catholique de Louvain, 1993.

[115] Michel X. Goemans. Approximation through uncrossing. Lecture given at Oberwolfach meeting on combinatorial optimization, 1993.

[116] Michel X. Goemans. An efficient approximation algorithm for the survivable network design problem. Lecture given at Third Integer Programming and Combinatorial Optimization Conference, 1993.

[117] Michel X. Goemans. A new $\frac{3}{4}$-approximation algorithm for MAX SAT. Lecture given at DIMACS Workshop on Approximation algorithms, Third Integer Programming and Combinatorial Optimization Conference, and Dartmouth University, 1993.

[118] T. Leighton. On the role of randomness in the design of parallel architectures. Lecture given at Colgate NSF Parallel Workshop, July, 1992; World Computer Congress, Spain, September, 1992; PARCON Meeting, NYC, September, 1992; Paderborn Workshop on Parallel Supercomputing, November, 1992.

[119] T. Leighton. Reconfiguring networks around faults. Lecture given at Duke Distinguished Lecture Series, May 1993.

[120] T. Leighton. Tight bounds on the size of fault-tolerant sorting circuits. Lecture given at 5th ACM Symposium on Parallel Algorithms and Architectures, Velen, Germany, June 1993.

[121] David P. Williamson. A general approximation technique for constrained forest problems. Lecture given at ORSA/TIMS Joint National Meeting, San Francisco, CA, November 1992.

[122] David P. Williamson. An approximation algorithm for general graph connectivity problems. Lecture given at Columbia University, February 1993. Bellcore, February 1993. DIMACS Workshop on Approximation Algorithms, March 1993. University of Chicago, March., 1993.

[123] David P. Williamson. A primal-dual approximation algorithm for generalized Steiner network problems. Lecture given at 25th Annual ACM Symposium on the Theory of Computing, May 1993.

3.3 Theses

[124] Javed A. Aslam. Inferring graphs from walks. Master's thesis, Massachusetts Institute of Technology, 1992.

[125] Margrit Betke. Algorithms for exploring an unknown graph. Master's thesis, MIT Department of Electrical Engineering and Computer Science, February 1992. (Published as MIT Laboratory for Computer Science Technical Report MIT/LCS/TR-536 (March, 1992)).

[126] Robert D. Blumofe. Managing storage for multithreaded computations. Master's thesis, Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, September 1992. Also: MIT Laboratory for Computer Science Technical Report MIT/LCS/TR-552.

[127] L. J. Cowen. *On Local Representationsd of Graphs and Networks.* PhD thesis, Department of Mathematics, MIT, Cambridge, MA, 1993.

[128] Ranjan Das. A formalization of distributed commit in data-processing systems. Bachelor's thesis, Laboratory for Computer Science, Massachusetts Institute of Technology, June 1992. Supervised by Nancy Lynch. Also, this work was submitted for publication.

[129] Harish Devarajan. Correctness proof for a network synchronizer. Master's thesis, miteecs, May 1993.

[130] Michael D. Ernst. Serializing parallel programs by removing redundant computation. Master's thesis, Massachusetts Institute of Technology, Cambridge, Massachusetts, August 1992.

[131] Rainer Gawlick. Concurrent time-stamping made simple. Master's thesis, Laboratory for Computer Science, Massachusetts Institute of Technology, June 1992. Supervised by Nancy Lynch.

[132] R. Gennaro. On the definitions and properties of zero-knowledge arguments. Master's thesis, Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge, MA, February 1993.

[133] D. W. Gillman. *Learning hidden Markov chains (tentative title).* PhD thesis, Department of Mathematics, Massachusetts Institute of Technology, Cambridge, MA, 1993.

[134] Nabil Kahale. *Expander Graphs.* PhD thesis, Department of Electrical Engineering of Computer Science, Massachusetts Institute of Technology, 1993.

[135] Arthur F. Lent. The category of functors from state shapes to bottomless cpo's is adequate for block structure. Master's thesis, Massachusetts Institute of Technology, 1992.

[136] Carolyn Norton. *Problems in Discrete Optimization.* PhD thesis, Department of Mathematics, Massachusetts Institute of Technology, 1993.

[137] M. C. Papaefthymiou. *A timing analysis and optimization system for level-clocked circuitry.* PhD thesis, Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge, Massachusetts, 1993.

[138] S. Ponzio. The real-time cost of timing uncertainty: Consensus and failure detection. Master's thesis, MIT Electrical Engineering and Computer Science, 1991. Also, MIT/LCS/TR-518.

[139] Roberto Segala. A process algebraic view of I/O automata. Master's thesis, Laboratory for Computer Science, Massachusetts Institute of Technology, May 1992.

[140] Mark A. S. Smith. Fast wait-free symmetry breaking in distributed systems. Master's thesis, Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge, Massachusetts, May 1993.

[141] George Varghese. *Self-stabilization by Local Checking and Correction.* PhD thesis, Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge, Massachusetts, October 1992.

4 Honors and Outside Recognition

Honors.

BARUCH AWERBUCH:

- Member of the editorial Board of the Journal of Algorithms.

BONNIE BERGER

- MIT Science Partnership Fund Award in 1993 for "Predicting Helix-Helix Interactions from Protein Sequences" (cooperative project with Dr. Peter S. Kim).
- Radcliffe Bunting Institute Science Scholarship (9/92–8/93).
- PhD thesis won MIT George M. Sprowles Prize for best research contribution to Computer Science.
- NSF Mathematical Sciences Postdoctoral Research Fellowship.
- Machtey Award for best student paper at 1989 IEEE FOCS conference (with J. Rompel).

MICHEL GOEMANS

- In August, 1991, Prof. Goemans delivered the Tucker Prize Address at the Math Programming Society Meeting.

DANIEL KLEITMAN

- Editor, Networks.
- Associate Problem Editor, American Mathematical Monthly.
- Member of Editorial Board, Journal of Graph Theory
- Member of Editorial Board, SIAM Journal of Discrete Mathematics
- Member of Editorial Board, Studies in Applied Mathematics
- Member of Editorial Board, Journal of Discrete Mathematics
- Member of Editorial Board, Combinatorica
- Member of Editorial Board, Journal of Algorithms
- Member of Editorial Board, Advances in Applied Mathematics

TOM LEIGHTON

- Editor-in-chief, Journal of the ACM
- Member of Editorial Board, SIAM Journal of Computing
- Member of Editorial Board, SIAM Journal of Discrete Math
- Member of Editorial Board, Journal of Algorithms
- Member of Editorial Board, Combinatorica
- Member of Editorial Board, Algorithmica
- Member of Editorial Board, Journal of Graph Theory
- Member of Editorial Board, EATCS Monographs on Theoretical Computer Science
- Member of Program Committee, 1993 Symposium on the Theory of Computation
- Member of Program Committee, IPPS 93
- Member of Program Committee, NETFLOW93
- Co-director of the DIMACS Special Year on Massively Parallel Computing
- Elected ACM SIGACT Chair, 1993
- Invited/Plenary Lecture, National Academy of Science Meeting on Frontiers of Science (11/91)
- Invited/Plenary Lecture, AAAS Annual Meeting (2/92)
- Invited/Plenary Lecture, Int. Parallel Processing Symposium (3/92)
- Invited/Plenary Lecture, ACM Symp. on Theory of Computing (5/92)
- Invited/Plenary Lecture, DAGS Workshop, Dartmouth (6/92)
- Invited/Plenary Lecture, World Computer Congress (9/92)

SHANGHUA TENG

- "Student of outstanding Academic Achievement", University of Southern California, April 1989.
- "Top student of 1981 – 1985", Jiao-Tong University, Shanghai, P. R. China.