**GEORGIA INSTITUTE OF TECHNOLOGY**
OFFICE OF CONTRACT ADMINISTRATION
**SPONSORED PROJECT INITIATION**

Date: August 28, 1979

Project Title: Theory of Systems of Asynchronous Parallel Processors

Project No: G-36-638 Green card

Project Director: Dr. Nancy A. Lynch

Sponsor: U. S. Army Research Office; Research Triangle Park, N. C. 27709

Agreement Period: From 8/1/79 Until ~~7/31/82~~ 7/31/83 (R&D Perf. Period)

Type Agreement: Contract No. DAAG29-79-C-0155

Amount: $149,197 (Incrementally Funded at $39,263 thru 7/31/80)
(GIT cost sharing (G-36-332) for period 8/1/79 - 7/31/80 = $2,066)

Reports Required: Semi-Annual Progress Reports; Interim Tech. Reports/Publication Reprints; Final Technical Report

Sponsor Contact Person.(s):

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(thru OCA)

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Defense Priority Rating: n/a

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Date March 15, 1984

Project No. G-36-638 School/~~Lab~~ ICS

Includes Subproject No.(s) _____

Project Director(s) Dr. Nancy Lynch GTRI / ~~GTE~~

Sponsor U.S. Army Research Office

Title Theory of Systems of Asynchronous Parallel Processors

Effective Completion Date: 7/31/83 (Performance) 7/31/83 (Reports)

Grant/Contract Closeout Actions Remaining:

- [ ] None
- [x] Final Invoice or Final Fiscal Report
- [ ] Closing Documents
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# THE GEORGIA INSTITUTE OF TECHNOLOGY

# RESEARCH PROGRAM IN

# FULLY DISTRIBUTED PROCESSING SYSTEMS

Quarterly Progress Report Number 2
1 December, 1979 - 29 February, 1980

April, 1980


Supported by

Office of Naval Research (ONR)
Contract: N00014-79-C-0873
GIT Project: G36-643

U.S. Air Force Rome Air Development Center (RADC)
Contract: F30602-78-C-0120
GIT Project: G36-649

International Business Machines,
General Systems Division (IBM)
Agreement: GSD-210189
GIT Project: G36-648

National Science Foundation (NSF)
Contract: MCS77-28305
Subcontract from Univ. of Wisc.: 144-L729
GIT Project: G36-630

U.S. Army Research Office (ARO)
Contract: DAAG29-79-C-0155
GIT Project: G36-638

U.S. Army Institute for Research in
Management Information and Computer Science (AIRMICS)
Contract: DAAK70-79-D-0087
GIT Project: G36-647



School of Information and Computer Science
Georgia Institute of Technology
Atlanta, Georgia 30332

# 1. INTRODUCTION

This is the second quarterly progress report prepared on the Georgia Tech Research Program in Fully Distributed Processing Systems (FDPS).

## a. Program Description.

The Georgia Tech Research Program in Fully Distributed Processing Systems is a comprehensive investigation of data processing systems in which both the physical and logical components are extremely loosely coupled while operating with a high degree of control autonomy at the component level. The definition of the specific class of multiple computer systems being investigated, and the operational characteristics and features of those systems is motivated by the desire to advance the state-of-the-art for that class of systems that will deliver a high proportion of the benefits currently being claimed for distributed processing systems. The scope of individual topics being investigated under this program ranges from formal modeling and theoretical studies to empirical examinations of prototype systems and simulation models. Also included within the scope of the program are areas such as the utilization of FDPS's and their interaction with management operations and structure.

## b. Program Support.

The principle support for the program is a Selected Research Opportunity contract from the Office of Naval Research; however, there are a number of other sources of funding which also support the program. A complete list of these is given below.

Title: "Research on Fully Distributed Data Processing Systems"
Funding Agency: Office of Naval Research (ONR)
Contract Number: N00014-79-C-0873
GIT Project No.: G36-643
Principle Investigator: Philip H. Enslow, Jr.

Title: "Research on Distributed Control"
Funding Agency: U.S. Air Force Rome Air Development Center (RADC)
Contract Number: F30602-78-C-0120
GIT Project No.: G36-649
Principle Investigator: Philip H. Enslow, Jr.

Title: "Agreement By and Between IBM and GTRI"
Funding Agency: International Business Machines, General Systems Division (IBM)
Contract Number: GSD Agreement Number 210188
GIT Project Number: G36-649
Principle Investigator: Philip H. Enslow, Jr.

Title: "Foundations of Deterministic Scheduling of Processes for Parallel Execution"
Funding Agency: National Science Foundation (NSF)
Contract Number: MCS77-28305
(Univ. of Misc. subcontract number: 144-L729)
GIT Project Number: G36-630
Principle Investigator: Richard A. DeMillo

Title: "Theory of Systems of Asynchronous Parallel Processors"
Funding Agency: U.S. Army Research Office (ARO)
Contract Number: DAAG29-79-C-0155
GIT Project Number: G36-638
Principle Investigator: Nancy Lynch

Title: "Support of MILPERCEN Data Storage Concept"
Funding Agency: U.S. Army Institute for Research in Management Information and Computer Science (AIRMICS)
Contract Number: DAAK70-79-D-0087
GIT Project Number: G36-647
Principle Investigator: A.P. Jensen

## c. Administrative Changes

During this quarter, additional research contracts supporting the FDPS program have been awarded. Specifically, these are the RADC, IBM, NSF, ARO, and AIRMICS contracts described above. Also during this quarter the final report on one contract was published, completing that project.

Title: "Interprocess Communication in Highly Distributed Systems" (A Workshop)
Funding Agency: U.S. Army Research Office (ARO)
Contract Number: DAAG29-79-C-0010
GIT Project No.: G36-632
Principle Investigator: Philip H. Enslow, Jr.

## 2. ORGANIZATION AND STAFFING

### Faculty

The following members of the ICS Faculty have been identified as participants in the FDPS Research Program.

Crews, Phillip--Assistant Professor
Demillo, Richard A.--Associate Professor
Enslow, Philip H. Jr.--Professor
Griffeth, Nancy--Assistant Professor
LeBlanc, Richard--Assistant Professor
Livesey, Jon--Assistant Professor
(effective September, 1990)
Lynch, Nancy--Associate Professor

Most of these individuals are presently working on specific projects in the program, while others are completing other work already in progress.

### Staff

Jensen, Alton P.--Princ. Res. Eng.
McDonell, Sharon--Sr. Secy.
Myers, Jeanette--Res. Scientist
Pinion, Nancy--Part-time Secy.

### Students

There are 30 students working on various projects in the FDPS Research Program. Of these, 12 are in the Ph.D. program and 5 are preparing their MS Thesis on topics in FDPS.

## 3. CURRENT RESEARCH PROJECTS

The specific research projects have been organized into the major areas identified in the basic program proposal.

### A. Theoretical and Formal Studies

A.1 Studies of the Theory of Asynchronous Processors
A.2 Decomposition of Parallel Systems
A.3 Reliable Systems
A.4 Time Performance of Distributed Systems

A.5 Audit Algorithms
A.6 Ticket Systems
A.7 Synchronous Simulation
A.8 Distributed Resource Allocation

B. Physical Interconnection and Networking

B.1 Heterogeneous Networking
B.2 Local Networking in Fully Distributed Processing Systems

C. Distributed Operating Systems

C.1 Decentralized and Distributed Control
C.2 Resource Allocation and Work Distribution in an FDPS
C.3 Fully Distributed Operating System - Initial Considerations
C.4 TBA (Distributed Operating Systems)
C.5 Process Support in Distributed Systems
C.6 Non-Homogeneous Operating Systems
C.7 FDPS - Preliminary Implementation Studies

D. Distributed Data Bases

D.1 Implementation of Distributed Database Systems
D.2 Support of MILPERCEN Data Storage Concept

E. Fault-Tolerance

F. Special Hardware to Support FDPS

G. Application of Distributed Processing

H. System Design Methodologies

H.1 FDPS Requirements Engineering Techniques
H.2 Coordinating Large Programming Projects

I. System Utilization

I.1 A Language for Distributed Programming
I.2 System Implementation Language Development

J. Security

J.1 Process Structures

K. System Management

L. Evaluation and Comparison

M. FDPS Testbed

M.1 Establishment of FDPS Testbed Facility
M.2 Remote Load Emulator
M.3 Fully Distributed Operating System Simulation Testbed

## 4. SUMMARY OF PROGRESS

### A.1 Studies of the Theory of Asynchronous Processors (Lynch, Fischer, Lamport, Lazowska, Schönhage, Arjomandi)

Work continues in the development of models, decomposition techniques, and complexity analysis techniques for distributed systems. Visitors this quarter have included Fischer, Lamport, Lazowska, Schönhage, and Arjomandi. Recent work has inspired projects A.2, A.3, A.4, A.5, A.6, A.7, and A.8 described below.

### A.2 Decomposition of Parallel Systems (Lynch, Fischer)

Synchronization algorithms are decomposed using two stage models, with simulation used to eliminate initial simplifications, such as centralized control and multiple shared variables.

### A.3 Reliable Systems (Lynch, Fischer, Lamport)

Redundancy is used to alleviate the effects of "shutdown", "death", and "malicious failure" of processes. Agreement with faulty inputs is difficult and slow, requiring K+1 "rounds" of information exchange to protect against up to K faults. Special cases are being considered.

### A.4 Time Performance of Distributed Systems (Lynch, Fischer, Lazowska, Schönhage)

Application of complexity theory in developing tools to measure worst-case and expected performance of distributed systems under specified operating conditions. Analysis of arbiter problems includes work on lower (time) bounds, with restricted access to communication variables.

### A.5 Audit Algorithms (Griffeth, Fischer, Lynch)

Development of algorithms for auditing distributed assets without delaying transactions, or contradicting information propagated through the system by obtaining a balance that could not have existed at any point in time.

### A.6 Ticket Systems (Lynch, Fischer, Griffeth)

Design and analysis of algorithms for ticket distribution, including careful statement of correctness and performance requirements.

### A.7 Synchronous Simulation (Lynch, Fischer, Arjomandi)

Development and analysis of techniques for converting synchronous, parallel algorithms into equivalent asynchronous algorithms, by devising protocols which insure progress of each process without actually stopping computation to achieve synchronization.

### A.8 Distributed Resource Allocation (Lynch)

Development of a simple but realistic model of the resource allocation problem, a fast solution, and time analysis of the solution.

### B.1 Heterogeneous Networking (Crews, Bray, Greene, Tuberville)

The IBM Series/1 has been connected to the FDPS test-bed (PRIME P-400's) through a unidirectional communication path. This path has facilitated file transfer from the testbed to the Series/1, and consequently has provided necessary software to initiate work on the common command language facility and software tools. At the same time, a link has been established between the Series/1 and CYBER system, and work is underway to establish an interface at the physical code, operating system, and programming language level.

### B.2 Local Networking in FDPSs (Enslow)

A survey of the state-of-the-art in local network technology and equipment has been initiated. It appears that the primary weaknesses of systems currently available or proposed are in the areas of host interaction with the local network and host-to-host interaction.

### C.1 Decentralized and Distributed Control (Enslow, LeBlanc, Crews, Saponas, Wice)

The first goal of this project is to characterize and analyze models of distributed and decentralized control applicable to highly distributed systems. A major problem facing the research team is the development of a technique or framework by which various control models can be described and catalogued. The principle effort thus far in this project has been focused on identifying various possible models and comparing and analyzing these models with the goal of developing a basis for a complete taxonomy. Major progress has been made in this first step, and a paper is being prepared for presentation at the IEEE Commputer Society COMPCON in September, 1980.

### C.2 Resource Allocation and Work Distribution in an FDPS (Enslow, Sharp)

Activity during this period has focused on developing a descriptive framework suitable for preparing a taxonomy of allocation and distribution models. The approach taken has been to prepare descriptions of as many models as possible and then to work backwards to develop the framework. An initial framework has been prepared and is being refined.

### C.3 FDOS - Initial Considerations (Enslow, LeBlanc, Crews, Akin, Flinn, Forsyth, Fukuoka, Myers, Pitts, Saponas, Skowbo, Spafford, Wice)

The organization and outline for the complete specification of an FDOS is being prepared.

### C.4 TBA - Distributed Operating Systems (Livesey)

No activity this quarter.

### C.5 Process Support in Distributed Systems (Enslow, Skowbo)

A survey and analysis of communication protocols has been initiated to isolate essential features for support of distributed processes. Implications of transport protocols for the IPC interface are being studied.

### C.6 Non-Homogeneous Operating Systems (Ratzel)

No significant activity this quarter. Project is still in preliminary stages.

### C.7 FDOS - Preliminary Implementation Studies (Myers, Enslow, Gaither, L. Newell, S. Newell, Wice)

The design and implementation of the FDOS has been initiated. The approach being taken is to first address those areas on which there is general agreement as to the functionality required/desired. The first area being designed is that of "message transport".

### D.1 Implementation of Distributed Database Systems (Griffeth)

This project is planned to commence in June, 1980.

### D.2 Support of MILPERCEN Data Storage Concept (Jensen, Doyle, Gehl, Bingham)

Applicable literature and reference documentation has been collected. A site visit to the U.S. Army Military Personnel Center, Alexandria, Virginia, has been made, during which briefings were presented and interviews held.

### H.1 FDPS Requirements Engineering Techniques (Underwood, Corley)

No significant activity this quarter.

### H.2 Coordinating Large Programming Projects (Enslow, Smith)

A questionnaire to be utilized to gather historical information and manager's perception of the problems and possible solutions has been prepared. This draft questionnaire has been circulated to a number of individuals for comment and recommendations on a wider population to survey.

### I.1 A Language for Distributed Programming (LeBlanc, Maccabe, Forsyth)

Existing languages with features related to our goals are currently being studied. This includes the implementation of multi-process programs in MODULA.

in order to gain experience with interprocess communication problems. In preparation for our language design work, design goals have been identified and a computational model on which the language will be based has been established. A paper entitled "A Language Model for Fully Distributed Systems" has been submitted to COMPCON '80 Fall. Another paper is being prepared for submission to the ACM Pacific '80 Conference, which has distributed processing as its theme.

**I.2 System Implementation Language Development (LeBlanc, Akin, Strickland)**

UW-Pascal is being transported to the PR1ME-400 with extensions to support the FDPS development. No significant progress this quarter.

**J.1 Process Structures (DeMillo, Lipton, Miller, Davida)**

Investigation of several aspects of parallel and distributed system design, including multilevel security, models of synchronization, and efficiency of interprocess communication.

**M.1 Establishment of FDPS Testbed Facility (Myers, Elshoff, Gaither, Howe, Flinn, L. Newell, S. Newell, Wice)**

The subroutines comprising the Primenet interprocess communication facility are being used and tested by student programmers, and will be used in the near future to implement message transport and message handling.

**M.2 Remote Load Emulator (Myers, Enslow, Forsyth, Howe)**

Programmable "scripts" have been devised to describe a variety of loads. Student programmers have completed a lexical analyzer and parser to translate scripts for fast interpretation.

**M.3 FDOS Simulation Testbed (LeBlanc, Gaither, Maccabe, Myers, S. Newell, Wice)**

The FDOS simulation testbed will provide an environment for the initial testing and analysis of operating system algorithms currently being developed. The overall design is complete; a more detailed design is being written, utilizing SIMULA constructs, and is in its final stages.

## 5. TRAVEL RELATED TO THE FDPS PROGRAM

Dates of Trip: 1 February, 1980
Individuals Travelling: James Skowbo, Steve Newell
Itinerary: Atlanta, Georgia
Purpose: Attend ACM sponsored Professional Development Seminar - Distributed Processing Systems

Dates of Trip: 14 February, 1980
Individuals Travelling: Philip Enslow
Itinerary: Atlanta, Georgia
Purpose: Present briefing on FDPS program and other ICS research projects.

Dates of Trip: 25-29 February, 1980
Individuals Travelling: Phillip Crews
Itinerary: San Francisco, California
Purpose: Attend COMPCON '80 Spring

Dates of Trip: 27-28 February, 1980
Individuals Travelling: A.P. Jensen, John Gehl, Jim Doyle
Itinerary: Alexandria, Virginia
Purpose: Site survey of MILPERCEN Data Facilities.

## 6. VISITORS

Dates of Visit: 1 January - 31 March, 1980
Visitor: Michael Fischer
Purpose: Research Collaboration
Individual Contacted: Nancy Lynch

Dates of Visit: 11 January, 1980
Visitor: R.J. Lipton
Purpose: Research Collaboration
Individual Contacted: Richard DeMillo

Dates of Visit: 14-16 January, 1980
Visitor: Robert Cook, U. Wisc., Madison
Purpose: To discuss programming language design and operating system simulation work being done at Wisconsin.
Individual Contacted: Richard LeBlanc, Philip Enslow, Phillip Crews

Dates of Visit: 21-25 January, 1980
Visitor: Leslie Lamport, Stanford Research Institute
Purpose: Research collaboration on problems involving programming in an environment including faulty processors, and choice of primitive operations for models of asynchronous systems.
Individual Contacted: Nancy Lynch, Michael Fischer

Dates of Visit: 4-6 February, 1980
Visitor: Edward Lazowska, Univ. of Washington
Purpose: Research collaboration on problems involving performance evaluations of distributed systems, and design of arbitration protocols.
Individual Contacted: Nancy Lynch, Michael Fischer

Dates of Visit: 18-21 February, 1980
Visitor: Eshrat Arjomandi, York Univ., Toronto, Canada
Purpose: Research collaboration on problems involving relationships between synchronous and asynchronous models for parallel computation, and design of distributed graph algorithms.
Individual Contacted: Nancy Lynch, Michael Fischer

Dates of Visit: 21 February, 1980
Visitor: Tadaaki Bandoh, Hitachi Research Laboratory, Japan.
Purpose: Discuss Bandoh's work in dataflow machines and our work in FDPS.
Individual Contacted: P. Enslow, J. Myers, H. Fukuoka, D. Pitts, T. Saponas, D. Sharp, J. Skowbo, R. Wice.

Dates of Visit: 25 February - 14 March, 1980
Visitor: Arnold Schönhage, Univ. of Tubingen, Germany
Purpose: Research collaboration on problems involving models for parallel computation, stochastic analysis of distributed systems, design of arbiter systems, and techniques for proving lower bounds for arbitration problems.
Individual Contacted: Nancy Lynch, Michael Fischer

## 7. PUBLICATIONS

Author(s): P.H. Enslow, R. Gordon
Title: IPC Workshop Report
Number: GIT-ICS-79/11
Date: December, 1979

Author(s): R.A. DeMillo, R.J. Lipton, R.F. Miller
Title: Stochastic Synchronization
Date: June, 1980

Author(s): R.A. DeMillo, G.I. Davida, R.J. Lipton
Title: Secure Key Distribution
Type: Conference Paper
Date: April, 1980
Comments: To be presented at 1980 IEEE Symposium on Security and Privacy.

Author(s): P.H. Enslow
Title: Quarterly Progress Report - Number 2
Type: Quarterly Progress Report
Date: April, 1980

# Theory of Systems of Asynchronous Parallel Processors

Final Technical Report

Nancy A. Lynch

December 20, 1983

U. S. ARMY RESEARCH OFFICE

Contract Number DAAG29-79-C-0155

GEORGIA INSTITUTE OF TECHNOLOGY

## A. Statement of the Problem Studied

I studied the problem of formal modelling and analysis of distributed algorithms.

## B. Summary of the Most Important Results

There was a very large amount of interesting work which resulted from this grant. The specific results have been described in detail in the earlier progress reports. Here, I include a brief overall review which describes the general results of the project.

The earliest work focussed on mutual exclusion and other distributed resource allocation problems. These problems had previously been studied informally, but there had been little work which was rigorous enough to allow correctness proofs, formal complexity analysis, or proof of impossibility results. Our work provided this area with a rigorous basis, and proved several interesting complexity results. In particular, we proved tight upper and lower bounds for shared space (bandwidth) requirements for implementing various resource allocation problems. (We included treatment of fault-tolerance properties.)

Our experience with formal modelling of concurrent resource allocation systems led us to develop a general model for asynchronous parallel computing, suitable for formal description of arbitrary asynchronous algorithms. We proved basic results about this model, such as a fundamental difference in complexity between synchronous and asynchronous parallel systems.

After developing our model for asynchronous computing, we proceeded to study several typical distributed problems within the model. Among the first of the problem areas we examined was distributed database concurrency control. We considered sources of performance problems. In particular, we devised two ways of generalizing the usual strategies for concurrency control in distributed databases, allowing fast processing of read-only transactions, and weakening the usual notion of serializability. We carried out extensive studies of the nested transaction model for concurrent computing.

We worked on distributed network resource allocation algorithms, devising interesting algorithms which had running time which was independent of the size of the distributed network. Algorithms were devised for special cases of the general network resource allocation problem: one in which resource requirements are predeclared, resources are all distinct and are returned after use (e.g. computing resources in a local-area network), and one in which resources are all identical and are not returned (e.g. tickets to a sporting event). The algorithms themselves appear to be of practical value. The analysis techniques also appear to be new and interesting.

We studied the very important problem of distributed consensus (in an error-prone environment), obtaining some very interesting and important results. The most important was a very fundamental limitation of the asynchronous computational model - its inability to solve the basic problem of distributed consensus in the presence of even a single faulty process. This fundamental result has already led to a fair amount of related work of other researchers, in trying to understand its ramifications. Other results include upper and lower bounds on time and communication requirements to solve the problem in a synchronous system.

Work in progress includes software clock synchronization, computing in a model that uses time explicitly, theory of specification of distributed systems, and fault-tolerance.

## C. List of all Publications and Technical Reports Published

### PUBLICATIONS

**Published Papers in Refereed Journals:**

A Technique for Decomposing Algorithms Which Use a Single Shared Variable
(with M. Fischer).
*Journal of Computer and System Sciences 27, 3*
(December 1983)

Efficiency of Synchronous Versus Asynchronous Distributed Systems
(with E. Arjomandi and M. Fischer).
*Journal of the Associaton For Computing Machinery 30, 3*
(July 1983) 449-456.

A Lower Bound for the Time to Assure Interactive Consistency
(with M. Fischer).
*Information Processing Letters 14,4*
(June 1982) 183-186.

Global States of a Distributed System
(with M. Fischer and N. Griffeth).
*IEEE Transactions on Software Engineering SE-8,3*
(May 1982) 198-202.

An Efficient Algorithm for Byzantine Agreement without Authentication
(with D. Dolev, M. Fischer, R. Fowler, and H. Strong)
*Information and Control 52, 3*
(March 1982) 257-274.

Data Requirements for Implementation of N-Process Mutual Exclusion Using a Single Shared Variable
(with J. Burns, M. Fischer, P. Jackson, and G. Peterson).
*Journal of the Association for Computing Machinery*
(January 1982) 183-205.

Upper Bounds for Static Resource Allocation in a Distributed System.
*Journal of Computer and System Sciences 23,2*
(October 1981) 254-278.

On Describing the Behavior and Implementation of Distributed Systems
(with M. Fischer).
*Theoretical Computer Science 13*
(1981) 17-43.

**Papers Appearing in Conference Proceedings:**

Reaching Approximate Agreement in the Presence of Faults
*Proceedings of 3rd Annual IEEE Symposium on Reliability in Distributed Software and Database Systems*
(1983)

Concurrency Control for Resilient Nested Transactions
*Proceedings of Second ACM Symposium on Principles of Database Systems*
(March 1983)

Impossibility of Distributed Consensus with One Faulty Process
(with M. Fischer and M. Paterson)
*Proceedings of Second ACM Symposium on Principles of Database Systems*
(March 1983)

A Simple and Efficient Byzantine Generals Algorithm
(with M. Fischer and R. Fowler)
*Proceedings of 2nd IEEE Symposium on Reliability in Distributed Software and Database Systems*
(July 1982) 46-52.

Probabilistic Analysis of a Network Resource Allocation Algorithm
(with M. Fischer, N. Griffeth, and L. Guibas)
*AMS Workshop on Probabilistic Algorithms (ABSTRACT ONLY)*
(June 1982)

Cryptographic Protocols
(with R. De Millo and M. Merritt).
*Proceedings of 14th ACM Symposium on Theory of Computing*
(1982) 383-400.

Multilevel Atomicity
*Proceedings of the ACM Symposium on Principles of Database Systems. Marina del Rey Hotel, Los Angeles, CA.*
(29-31 March 1982) 63-69

The Design and Analysis of Cryptographic Protocols.
(with R. De Millo and M. Merritt).
*CRYPTO 81*
(1981)

Global States of a Distributed System
(with M. Fischer and N. Griffeth).
*Proceedings of IEEE Symposium on Reliability in Distributed Software and Database Systems (July 1981).* Chosen for submission to special issue of IEEE *Transactions on Software Engineering SE-8,3*
(May 1982) 198-202.

Optimal Placement of Identical Resources in a Distributed Network
(with M. Fischer, N. Griffeth and L. Guibas).
*Proceedings of 2nd International Conference on Distributed Computing.*
(1981)

A Difference in Efficiency Between Synchronous and Asynchronous Systems
(with E. Arjomandi and M. Fischer).
*Proceedings of 13th Annual ACM Symposium on Theory of Computing, Milwaukee, WI.*
(May 11-13, 1981) 128-132.

Mutual Exclusion Using Indivisible Reads and Writes
(with J. Burns)
*Proceedings of Allerton Conference.*
(1980)

Fast Allocation of Nearby Resources in a Distributed System.
*Proceedings of 12th Annual ACM Symposium on Theory of Computing 1980,*
*Chosen for submission to special issue of Journal of Computer and System Sciences*
(1980) 70-81.

Resource Allocation with Immunity to Limited Process Failure
(with M. Fischer, J. Burns and A. Borodin).
*Proceedings of 20th Annual Symposium on Foundations of Computer Science.*
(1979) 234-254.

On Describing the Behavior and Implementation of Distributed Systems
(with M. Fischer).
*Proceedings of 1979 Conference on Semantics of Concurrent Computation.*
*Chosen for submission to special issue of Theoretical Computer Science 13.*
(1981) 17-43.

Shared Data Requirements for Implementation of Mutual Exclusion Using a Test and Set Primitive
(with J. Burns, M. Fischer, P. Jackson and G. Peterson).
*Proceedings of International Conference on Parallel Processing.*
(1978)

**Submitted for Publication:**

Multilevel Atomicity-a New Correctness Criterion for Distributed Databases.
To appear in ACM Transactions on Database Systems.

Optimal Placement of Identical Resources in a Distributed Network
(with M. Fischer, N. Griffeth and L. Guibas).

Probabilistic Analysis of a Network Resource Allocation Algorithm
(with N. Griffeth, M. Fischer and L. Guibas).

New Upper and Lower Bounds for Electing a Leader in a Ring
(with G. Frederickson).

**Technical Reports not Submitted Elsewhere:**

Goree, John
Internal Consistency of A Distributed Transaction System with Orphan Detection,"
M.S. Thesis, M.I.T. Laboratory for Computer Science,
Cambridge, MA. completed January, 1983.

**Work in Progress**

Upper and Lower Bounds for Arbiters
(with M. Fischer and A. Schonhage).

Clock Synchronization
(with J. Lundelius).

The Colored Ticket Algorithm
(with M. Fischer, A. Borodin and J. Burns)

**Journal Papers:**

Turpin, Russell and Coan, Brian
"Extending Binary Byzantine Agreement to Multivalued Byzantine Agreement,"
to appear in *Information Processing Letters*.

## D. List of all Participating Scientific Personnel

Nancy A. Lynch
James E. Burns, PhD
Eugene Stark
John Goree, MS
Brian Coan
Jennifer Lundelius

## Bibliography

See List of all Publications and Technical Reports Published.