

# CONTENTS

ACKNOWLEDGEMENTS.....	i
CONTENTS.....	ii
1. INTRODUCTION.....	1
1.1. Historical notes.....	1
1.2. What is distributed computing?.....	3
1.3. An overview of distributed computing.....	4
1.3.1. Long haul computer networks.....	4
1.3.2. Local area networks.....	5
1.3.3. Multi-processor networks.....	6
1.4. Problems in distributed computing.....	8
1.4.1. Problems dealing with "Cooperation".....	8
1.4.2. Problems dealing with "Communication".....	10
1.4.3. Problems dealing with "Programming and Verification".....	11
1.5. Notions and notations from set and graph theory.....	12
1.6. Important interconnection networks.....	16
1.6.1. The ring network.....	16
1.6.2. The two-dimensional grid network.....	17
1.6.3. The shuffle-exchange network and the 4-pin shuffle.....	18
1.6.4. The cube network.....	19
1.6.5. The cube connected cycles network.....	20
1.7. Notions and notations from complexity theory.....	21
2. DECENTRALIZED EXTREMA-FINDING IN RINGS OF PROCESSORS.....	24
2.1. Introduction.....	24
2.2. New upperbounds for decentralized extrema-finding in rings of processors.....	26
2.2.1. Introduction.....	26
2.2.2. Decentralized extrema-finding in a bidirectional ring	

using a small number of messages on the average.....	30
2.2.3. An improved analysis of Algorithm-P and Algorithm-D.....	35
2.3. Some lowerbound results for decentralized extrema-finding in rings of processors.....	42
2.3.1. Introduction.....	42
2.3.2. Definitions and preliminary results.....	43
2.3.3. Arbitrary versus comparison algorithms.....	48
2.3.4. Algorithms that use time $\leq n$ .....	54
2.3.5. Lowerbounds for algorithms on rings with known ring size...63	
3. DISTRIBUTION OF RECORDS ON RINGS OF PROCESSORS.....	69
3.1. Introduction.....	69
3.2. Elementary facts from the theory of finite Markov chains.....	70
3.3. Token-based protocols for load distribution with tokens moving in the same direction as records.....	74
3.4. Token-based protocols for load distribution with tokens moving in the opposite direction as records.....	83
3.5. Token-based protocols for load distribution with tokens moving in both directions.....	88
3.6. Load-distribution by "direct placing".....	90
3.7. Load-distribution under insertions and deletions.....	94
4. DEADLOCK-FREE PACKET SWITCHING NETWORKS.....	101
4.1. Introduction.....	101
4.2. Definitions.....	105
4.3. Uniform local deadlock-free controllers.....	108
4.4. Optimality of $\mathcal{DSV}$ .....	113
4.5. Final comments.....	121
5. EMULATIONS: DEFINITIONS AND CLASSIFICATIONS.....	123
5.1. Introduction.....	123
5.2. Elementary results.....	124
5.3. Emulations of the 4-pin shuffle.....	128
5.3.1. Preliminaries.....	129
5.3.2. Uniform emulations of $S_n$ on $S_{n-1}$ .....	130

5.3.3. Uniform emulations of $S_n$ on $S_{n-k}$ .....	133
5.4. Emulations of the shuffle-exchange network.....	137
5.4.1. Preliminaries.....	137
5.4.2. Uniform emulations of $SE_n$ on $S_{n-1}$ .....	138
5.4.3. Uniform emulations of $SE_n$ on $SE_k$ ( $k \leq n$ ).....	142
5.4.4. Discussion.....	147
5.5. Emulations of the cube network.....	148
5.6. Emulations of the ring and two-dimensional grid network.....	151
5.6.1. Uniform emulations of $R_n$ on $R_{n/2}$ .....	153
5.6.2. Uniform emulations of $GR_n$ on $GR_{n/2}$ .....	154
6. EMULATIONS: FURTHER ANALYSIS.....	160
6.1. Introduction.....	160
6.2. Cross-emulations.....	160
6.3. Defining networks by emulation.....	162
6.3.1. General characterizations.....	163
6.3.2. Characterization of the 4-pin shuffle, the cube, the ring and the grid network by emulation.....	164
6.4. The classification of coverings of processor networks.....	167
6.4.1. Introduction.....	167
6.4.2. Coverings of ring, grid, cube and complete networks.....	171
6.4.2.1. Ring networks.....	171
6.4.2.2. Grid networks.....	172
6.4.2.3. Cube networks.....	172
6.4.2.4. Complete networks.....	173
6.4.3. Coverings of the cube-connected cycles.....	173
6.4.4. Coverings of the 4-pin shuffle.....	178
6.4.5. Coverings of the shuffle-exchange network.....	179
6.5. Emulations of processor networks with buses.....	181
6.5.1. Introduction.....	181
6.5.2. The hypergraph model.....	182
6.5.3. Emulations of hypergraphs.....	184
6.5.4. Emulations of common networks with buses.....	187
6.5.4.1. Emulations of the spanning bus hypercube.....	187
6.5.4.2. Emulations of the dual bus hypercube.....	190

7. EMULATIONS: THE COMPLEXITY OF FINDING UNIFORM EMULATIONS.....	195
7.1. Introduction.....	195
7.2. The complexity of finding uniform emulations for graphs of bounded degree.....	196
7.2.1. Undirected graphs of bounded degree.....	196
7.2.2. Directed graphs of bounded degree.....	203
7.3. The complexity of finding uniform emulations on networks of a certain type.....	207
7.3.1. Uniform emulation on the two-dimensional grid network....	207
7.3.2. Uniform emulation on the cube network.....	211
7.3.3. Uniform emulation on the 4-pin shuffle and the shuffle- exchange network.....	216
7.4. The complexity of finding uniform emulations on paths and ring networks.....	225
7.4.1. Introduction.....	225
7.4.2. NP-completeness for arbitrary undirected graphs.....	226
7.4.3. NP-completeness for trees.....	231
7.4.4. NP-completeness for directed graphs.....	235
7.4.5. Polynomial time algorithms for fixed computation factors..	240
7.4.6. Disconnected graphs.....	246
7.5. The complexity of finding uniform emulations on fixed graphs....	249
7.6. On approximation algorithms for determining minimum cost emulations.....	256
7.6.1. Introduction.....	256
7.6.2. Definitions and notations.....	257
7.6.3. A bound for the best achievable performance ratio on MCE..	258
7.6.4. Relation of MCE with BANDWIDTH.....	260
7.6.5. Relation of MCE with CLIQUE.....	262
7.6.6. Relation of MCE with BALANCED COMPLETE BIPARTITE SUBGRAPH.....	263
7.6.7. Discussion.....	264
7.7. The complexity of finding coverings.....	264
7.8. A note on the complexity of finding uniform emulations of networks with buses .....	267

APPENDIX A. The proof the estimates for  $K_n(2)$  and  $K_n(3)$   
(lemma 2.2.3.2.).....268

APPENDIX B. The proof of the Characterization Theorem for the uniform  
emulations of  $S_n$  on  $S_{n-1}$  (theorem 5.3.2.5.).....272

APPENDIX C. The proof of the topological reduction theorem for uniform  
emulations of  $C_n$  on  $C_{n-1}$  (theorem 5.5.5.).....282

REFERENCES.....288