



# Contents

|  |           |
|--|-----------|
| <b>1. Introduction</b>                               | <b>1</b>  |
| 1.1. Objectives and Scope                            | 2         |
| 1.2. Why Go Distributed                              | 3         |
| 1.3. Benefits and Limitations of Distributed Systems | 6         |
| 1.4. Hazards of Distributed Systems                  | 8         |
| 1.5. Key Technical Issues                            | 9         |
| 1.6. Key Management Issues                           | 12        |
| 1.7. Organization of Book                            | 13        |
| <b>2. Distributed Systems Overview</b>               | <b>15</b> |
| 2.1. Definitions and Terminology                     | 16        |
| 2.2. A Distributed Application                       | 18        |
| 2.3. Alternative System Approaches                   | 20        |
| 2.4. Structure of a Node                             | 23        |
| 2.5. Structure of a Distributed System               | 24        |

|  |    |
|--|----|
| 2.6. Dimensions of Distributed Systems                   | 26 |
| 2.7. What to Distribute                                  | 28 |
| 2.8. Application Partitioning                            | 28 |
| 2.9. Requirements  | 30 |
| 2.10. Configurations                                     | 31 |
| 2.11. Summary  | 32 |
| 3. Distributed Data Bases                                | 33 |
| 3.1. Files Versus Data Bases                             | 34 |
| 3.2. User Interface to Data Base Systems                 | 35 |
| 3.2.1. Data Models                                       | 35 |
| 3.2.2. Network, Hierarchical, and Relational Data Models | 37 |
| 3.2.3. Relational Data Models                            | 39 |
| 3.3. Common Data Base Architecture                       | 41 |
| 3.4. Support of Multiple Views of Data                   | 42 |
| 3.5. Centralized Data Base Systems                       | 43 |
| 3.6. Distributed Data Base Systems                       | 44 |
| 3.6.1. Objectives and Requirements                       | 45 |
| 3.6.2. Distributed Data Structures                       | 48 |
| 3.6.3. Data Distribution Alternatives                    | 48 |
| 3.6.4. Directories                                       | 52 |
| 3.6.5. Local Data  | 54 |
| 3.6.6. Distributed Schema                                | 55 |
| 3.6.7. A Generalized Data Distribution Model             | 58 |
| 3.6.8. Dynamic Distribution of Data                      | 59 |
| 3.6.9. Transaction Management                            | 60 |
| 3.7. Other Important Topics                              | 64 |
| 3.8. Summary   | 64 |

|  |    |
|--|----|
| <b>4. Hardware for Distributed Systems</b>       | 65 |
| <b>4.1. Semiconductor Technology</b>             | 66 |
| <b>4.2. Processors</b>                           | 69 |
| <b>4.3. Microprocessors</b>                      | 70 |
| <b>4.4. Minicomputers</b>                        | 70 |
| <b>4.5. Conventional Computers</b>               | 71 |
| <b>4.6. Storage Hierarchy</b>                    | 72 |
| <b>4.6.1. Cache Buffer</b>                       | 72 |
| <b>4.6.2. Main Storage</b>                       | 73 |
| <b>4.6.3. Direct Access Storage</b>              | 74 |
| <b>4.6.4. Solid State Mass Storage</b>           | 75 |
| <b>4.7. Moving Head Disks</b>                    | 76 |
| <b>4.8. Cache Disk</b>                           | 78 |
| <b>4.9. Optical Disk</b>                         | 79 |
| <b>4.10. Floppy Disks</b>                        | 79 |
| <b>4.11. Cartridge Tape</b>                      | 80 |
| <b>4.12. Interconnect</b>                        | 80 |
| <b>4.13. Terminals</b>                           | 81 |
| <b>4.14. Terminal Printers</b>                   | 82 |
| <b>4.15. Allocation of Functions to Hardware</b> | 83 |
| <b>4.16. Summary</b>                             | 85 |
| <b>5. Software For Distributed Systems</b>       | 87 |
| <b>5.1. Operating System Overview</b>            | 88 |

|  |     |
|--|-----|
| 5.2. Centralized Operating Systems                 | 89  |
| 5.3. Distributed Operating System Requirements     | 92  |
| 5.3.1. Data Base Creation, Query, and Update       | 92  |
| 5.3.2. Data Base Transfer Facilities               | 93  |
| 5.3.3. Invocation of Operating System Facilities   | 95  |
| 5.3.4. Transaction Facility                        | 96  |
| 5.3.5. Program Development Facilities              | 96  |
| 5.4. Distributed Operating System Implementation   | 97  |
| 5.5. Heterogeneous Systems                         | 99  |
| 5.6. Distributed Operating System Environments     | 101 |
| 5.7. Case Studies of Distributed Operating Systems | 102 |
| 5.7.1. XNOS  | 102 |
| 5.7.2. RSEEXEC                                     | 104 |
| 5.7.3. National Software Works                     | 106 |
| 5.8. Comparison of Distributed Operating Systems   | 107 |
| 5.9. Summary                                       | 109 |
| 6. Human Interface for Distributed Systems         | 111 |
| 6.1. Historical Perspective                        | 117 |
| 6.2. Stages of Growth                              | 118 |
| 6.2.1. Initiation                                  | 119 |
| 6.2.2. Expansion                                   | 119 |
| 6.2.3. Formalization                               | 120 |
| 6.2.4. Maturity                                    | 121 |
| 6.3. Implications of the Stage Hypothesis          | 121 |
| 6.3.1. Mechanization and Automation                | 121 |
| 6.3.2. Automating Office Procedures                | 122 |
| 6.3.3. Organizational Implications                 | 122 |
| 6.4. The Office Occupational Mix                   | 123 |
| 6.4.1. Activity Distribution                       | 124 |
| 6.4.2. Basic Premises                              | 126 |
| 6.4.3. Base Functions                              | 127 |

|  |            |
|--|------------|
| 6.5. The Graphics Technology Problem                 | 129        |
| 6.6. Organization Structures                         | 130        |
| 6.6.1. Organizations of the Expansion Stage          | 131        |
| 6.6.2. Organizations of the Formalization Stage      | 133        |
| 6.7. Economics of Investment                         | 134        |
| 6.7.1. Management/Technical Department Mechanization | 135        |
| 6.7.2. Support Center Mechanization                  | 137        |
| 6.8. Mechanized Products                             | 139        |
| 6.9. Summary   | 141        |
| <b>7. Communications for Distributed Systems</b>     | <b>145</b> |
| 7.1. Communications Requirements                     | 145        |
| 7.2. Regulation and Standards                        | 147        |
| 7.3. Codes and Alphabets                             | 149        |
| 7.4. Services  | 150        |
| 7.4.1. Local Distribution Service                    | 150        |
| 7.4.2. Interstate Distribution Service               | 154        |
| 7.5. Signaling Procedures                            | 156        |
| 7.6. Interconnection Circuits and Topologies         | 158        |
| 7.6.1. Star  | 160        |
| 7.6.2. Hierarchy                                     | 161        |
| 7.6.3. Ring  | 162        |
| 7.6.4. Linear  | 162        |
| 7.6.5. Fully Connected                               | 163        |
| 7.6.6. Network                                       | 164        |
| 7.6.7. A Mixed System                                | 164        |
| 7.7. Communications Architectures and Protocols      | 165        |
| 7.8. Network Procedures                              | 171        |

|  |     |
|--|-----|
| 7.9. Error Recovery                          | 173 |
| 7.10. Security                               | 173 |
| 7.11. Distributed System Model               | 175 |
| 7.12. The Future                             | 177 |
| 8. Distributed Systems Analysis              | 181 |
| 8.1. Application Analysis                    | 181 |
| 8.2. Categories of Distributed System Models | 183 |
| 8.3. Predictive Models                       | 184 |
| 8.4. A Distributed System Predictive Model   | 185 |
| 8.5. Synthesis Models                        | 188 |
| 8.6. An Example of a Synthesis Model         | 190 |
| 8.7. Correctness Models                      | 191 |
| 8.8. Special Topics in Simulation            | 192 |
| 8.8.1. Macro/Micro Models                    | 192 |
| 8.8.2. Hierarchical Models                   | 192 |
| 8.8.3. Model Verification and Validation     | 192 |
| 8.9. Summary                                 | 193 |
| 9. Distributed Systems Design                | 195 |
| 9.1. General Design Methodology              | 196 |
| 9.2. The Design Phase                        | 198 |
| 9.3. Steps in the Design Process             | 199 |
| 9.4. Establish Specific Requirements         | 200 |
| 9.5. Design System on a Logical Basis        | 203 |
| 9.5.1. Node Location                         | 203 |
| 9.5.2. Node Communications Interconnect      | 203 |

|  |     |
|--|-----|
| 9.5.3. Data Distribution                                       | 205 |
| 9.5.4. Processing Performance                                  | 207 |
| 9.5.5. System Application Organization                         | 208 |
| 9.5.6. Program and Data Movement                               | 208 |
| 9.5.7. Recovery and Reconfiguration                            | 208 |
| 9.6. Map to Real Products                                      | 210 |
| 9.7. Performance Evaluation                                    | 210 |
| 9.8. Determine Feasibility                                     | 211 |
| 9.9. Improvement of Design                                     | 212 |
| 9.10. Case Study   | 213 |
| 9.10.1. Requirements   | 213 |
| 9.10.2. The Design   | 215 |
| 9.11. Summary  | 218 |
| 10. Synchronization of Distributed Data Bases                  | 219 |
| 10.1. Levels of Consistency                                    | 222 |
| 10.2. Requirements   | 223 |
| 10.3. Concurrency Control in Centralized Systems               | 224 |
| 10.4. Timestamps   | 231 |
| 10.5. Alternative Synchronization Methods                      | 231 |
| 10.5.1. Centralized Lock Controller Protocol                   | 232 |
| 10.5.2. Control Token Protocol                                 | 233 |
| 10.5.3. Primary Copy Protocol                                  | 235 |
| 10.5.4. Primary Site Protocol                                  | 236 |
| 10.5.5. Majority Consensus Protocol                            | 237 |
| 10.5.6. A Timestamp Protocol                                   | 239 |
| 10.5.7. A Broadcast Protocol                                   | 240 |
| 10.5.8. A Ticket Protocol                                      | 241 |
| 10.6. Application Characteristics Affecting Protocol Selection | 241 |

|  |            |
|--|------------|
| <b>10.7. Summary</b>                                       | <b>242</b> |
| <b>11. Deadlock in Distributed Systems</b>                 | <b>243</b> |
| <b>11.1. Deadlock</b>                                      | <b>244</b> |
| <b>11.2. General Strategies in Coping with Deadlock</b>    | <b>246</b> |
| <b>11.3. Alternative Approaches</b>                        | <b>250</b> |
| <b>11.4. Distributed Deadlock Control Procedures</b>       | <b>252</b> |
| <b>11.5. Deadlock-Free Procedures</b>                      | <b>255</b> |
| <b>11.6. Summary</b>                                       | <b>256</b> |
| <b>12. Security in Distributed Systems</b>                 | <b>257</b> |
| <b>12.1. Computer Fraud</b>                                | <b>258</b> |
| <b>12.2. Typical Security Controls</b>                     | <b>259</b> |
| <b>12.3. Design Alternatives</b>                           | <b>260</b> |
| <b>12.3.1. Passwords</b>                                   | <b>261</b> |
| <b>12.3.2. Objects</b>                                     | <b>262</b> |
| <b>12.3.3. Personal Characteristics</b>                    | <b>262</b> |
| <b>12.3.4. Computer Dialog</b>                             | <b>263</b> |
| <b>12.4. Access Control</b>                                | <b>263</b> |
| <b>12.5. Maintaining Desired Level Of Security</b>         | <b>265</b> |
| <b>12.6. Communications and Encryption</b>                 | <b>265</b> |
| <b>12.7. The Placement Of Controls</b>                     | <b>267</b> |
| <b>12.7.1. Distributed Control</b>                         | <b>267</b> |
| <b>12.7.2. Centralized Control</b>                         | <b>269</b> |
| <b>12.8. Systems Analysis for Enhancements of Security</b> | <b>272</b> |
| <b>12.9. Summary</b>                                       | <b>273</b> |

|   |            |
|---|------------|
| <b>13. Reliability and Recovery</b>                   | <b>275</b> |
| 13.1. Error Detection                                 | 277        |
| 13.2. Types of Failures                               | 278        |
| 13.3. Reliability in Nonredundant Distributed Systems | 278        |
| 13.4. Recovery in Nonredundant Distributed Systems    | 280        |
| 13.5. Reliability in Redundant Distributed Systems    | 282        |
| 13.6. Recovery in Redundant Distributed Systems       | 282        |
| 13.7. Optimizing Recovery Procedures                  | 283        |
| 13.8. Summary   | 285        |
| <b>14. Case Studies of Distributed Systems</b>        | <b>287</b> |
| 14.1. Aeroquip Corporation                            | 287        |
| 14.2. Bank of America                                 | 288        |
| 14.3. Celanese  | 289        |
| 14.4. David Jones                                     | 290        |
| 14.5. General Mills                                   | 293        |
| 14.6. GTE Automatic Electric                          | 296        |
| 14.7. KUIPNET   | 297        |
| 14.8. Lowes, Inc.                                     | 297        |
| 14.9. SITA  | 299        |
| 14.10. SSD-1  | 299        |

|   |     |
|---|-----|
| 14.11. Texas Instruments                                  | 301 |
| 14.12. Summary  | 302 |
| 15. Management of Distributed Systems                     | 303 |
| 15.1. Technical and Organizational Environment            | 304 |
| 15.2. A Framework for Analysis of Decentralization        | 305 |
| 15.3. The Role of Management                              | 306 |
| 15.4. Management Alternatives for a Distributed System    | 308 |
| 15.4.1. Planning  | 311 |
| 15.4.2. Standards   | 313 |
| 15.4.3. System Design and Program Management              | 313 |
| 15.4.4. System Implementation                             | 314 |
| 15.4.5. Operation   | 314 |
| 15.4.6. Maintenance                                       | 314 |
| 15.4.7. Equipment Procurement                             | 315 |
| 15.4.8. Applications Development                          | 315 |
| 15.4.9. Selection of Systems Approach                     | 316 |
| 15.5. Management Tools for Distributed System Development | 318 |
| 15.6. Central Staff Responsibilities                      | 319 |
| 15.7. Efficiency vs. Effectiveness                        | 321 |
| 15.8. Impact on the Organization                          | 322 |
| 15.9. Summary   | 323 |
| 16. Conclusion  | 325 |
| Glossary  | 329 |
| Bibliography  | 341 |
| Index   | 371 |

