

Contents

Preface.....	xvii
Acknowledgments.....	xxv
CHAPTER 1 Introduction.....	1
1.1 Rationale.....	2
1.1.1 The Traditional Approach to Teaching Computer Science.....	2
1.1.2 The Systems Approach Taken in This Book.....	4
1.2 The Significance of Networking and Distributed Systems in Modern Computing—A Brief Historical Perspective	6
1.3 Introduction to Distributed Systems	9
1.3.1 Benefits and Challenges of Distributed Systems	9
1.3.2 The Nature of Distribution.....	10
1.3.3 Software Architectures for Distributed Applications.....	11
1.3.4 Metrics for Measuring the Quality of Distributed Systems and Applications	11
1.3.5 Introduction to Transparency	12
1.4 Introduction to the Case Studies.....	14
1.4.1 The Main (Distributed Game) Case Study.....	14
1.4.2 The Additional Case Studies.....	16
1.5 Introduction to Supplementary Material and Exercises.....	16
1.5.1 In-Text Activities	17
1.6 The Workbenches Suite of Interactive Teaching and Learning Tools	18
1.6.1 Operating Systems Workbench 3.1 “Systems Programming Edition”	19
1.6.2 The Networking Workbench 3.1 “Systems Programming Edition”	19
1.6.3 Distributed Systems Workbench 3.1 “Systems Programming Edition”	19
1.7 Sample Code and Related Exercises.....	19
1.7.1 Source Code, in C++, C#, and Java	19
1.7.2 Application Development Exercises	20
CHAPTER 2 The Process View	21
2.1 Rationale and Overview.....	22
2.2 Processes.....	22
2.2.1 Basic Concepts.....	22
2.2.2 Creating a Process.....	23
2.3 Process Scheduling	28
2.3.1 Scheduling Concepts.....	32
2.4 Scheduling for Real-Time Systems	58
2.4.1 Limitations of General-Purpose Schedulers for Real-Time Systems	59

2.5	Specific Scheduling Algorithms and Variants, Used in Modern Operating Systems.....	70
2.6	Interprocess Communication.....	70
2.6.1	Introduction to Sockets.....	70
2.7	Threads: An Introduction.....	75
2.7.1	General Concepts.....	75
2.7.2	Thread Implementations.....	76
2.7.3	Thread Scheduling Approaches.....	77
2.7.4	Synchronous (Sequential) Versus Asynchronous (Concurrent) Thread Operation.....	78
2.7.5	Additional Complexity Accompanying Threading.....	83
2.7.6	A Multithreaded IPC Example.....	84
2.8	Other Roles of the Operating System.....	91
2.9	Use of Timers Within Programs.....	91
2.9.1	Use of Timers to Simulate Threadlike Behavior.....	93
2.10	Transparency from the Process Viewpoint.....	94
2.10.1	Concurrency Transparency.....	94
2.10.2	Migration Transparency.....	94
2.11	The Case Study from the Process Perspective.....	95
2.11.1	Scheduling Requirements.....	95
2.11.2	Use of Timers.....	95
2.11.3	Need for Threads.....	96
2.11.4	IPC, Ports, and Sockets.....	96
2.12	End-of-Chapter Exercises.....	97
2.12.1	Questions.....	97
2.12.2	Exercises with the Workbenches.....	98
2.12.3	Programming Exercises.....	103
2.12.4	Answers to End-of-Chapter Questions.....	104
2.12.5	List of In-text Activities.....	105
2.12.6	List of Accompanying Resources.....	105
CHAPTER 3	The Communication View.....	107
3.1	Rationale and Overview.....	108
3.2	The Communication View.....	109
3.2.1	Communication Basics.....	109
3.3	Communication Techniques.....	110
3.3.1	One-Way Communication.....	110
3.3.2	Request-Reply Communication.....	115
3.3.3	Two-Way Data Transfer.....	119
3.3.4	Addressing Methodologies.....	120

3.3.5 Remote Procedure Call	124
3.3.6 Remote Method Invocation	126
3.4 Layered Models of Communication	128
3.4.1 The OSI Model	131
3.4.2 The TCP/IP Model	132
3.5 The TCP/IP Suite	133
3.5.1 The IP	134
3.5.2 The TCP	136
3.5.3 The TCP Connection	138
3.5.4 The UDP	140
3.5.5 TCP and UDP Compared	141
3.5.6 Choosing Between TCP and UDP	141
3.6 Addresses	144
3.6.1 Flat Versus Hierarchical Addressing	144
3.6.2 Addresses in the Link Layer	145
3.6.3 Addresses in the Network Layer	145
3.6.4 Addresses in the Transport Layer (Ports)	148
3.6.5 Well-Known Ports	149
3.7 Sockets	151
3.7.1 The Socket API: An Overview	152
3.7.2 The Socket API: UDP Primitive Sequence	152
3.7.3 The Socket API: TCP Primitives Sequence	153
3.7.4 Binding (Process to Port)	158
3.8 Blocking and Nonblocking Socket Behaviors	161
3.8.1 Handling Nonblocking Socket Behavior	164
3.8.2 Communication Deadlock	166
3.9 Error Detection and Error Correction	168
3.9.1 A Brief Introduction to Error Detection and Error Correction Codes	168
3.10 Application-Specific Protocols	170
3.11 Integrating Communication with Business Logic	170
3.12 Techniques to Facilitate Components Locating Each Other	172
3.13 Transparency Requirements from the Communication Viewpoint	173
3.13.1 Logical and Physical Views of Systems	174
3.14 The Case Study from the Communication Perspective	174
3.15 End-of-Chapter Exercises	181
3.15.1 Questions	181
3.15.2 Exercises with the Workbenches	184
3.15.3 Programming Exercises	187
3.15.4 Answers to End-of-Chapter Questions	187

3.15.5	Answers/Outcomes of the Workbench Exercises.....	189
3.15.6	List of in-Text Activities	190
3.15.7	List of Accompanying Resources.....	190
Appendix	Socket API Reference.....	191
A1.	Socket.....	191
A2.	Socket Options	193
A3.	Socket Address Formats.....	194
A4.	Setting a Socket to Operate in Blocking or Nonblocking IO Mode	195
A5.	Bind.....	196
A6.	Listen.....	196
A7.	Connect	197
A8.	Accept	197
A9.	Send (Over a TCP Connection)	198
A10.	Recv (Over a TCP Connection)	198
A11.	SendTo (Send a UDP Datagram)	199
A12.	Recvfrom (Receive a UDP Datagram).....	200
A13.	Shutdown	200
A14.	Closesocket	201
CHAPTER 4	The Resource View	203
4.1	Rationale and Overview.....	204
4.2	The CPU as a Resource	204
4.3	Memory as a Resource for Communication	205
4.3.1	Memory Hierarchy.....	210
4.4	Memory Management.....	212
4.4.1	Virtual Memory.....	217
4.5	Resource Management.....	225
4.5.1	Static Versus Dynamic Allocation of Private Memory Resources.....	225
4.5.2	Shared Resources	227
4.5.3	Transactions	228
4.5.4	Locks.....	229
4.5.5	Deadlock	232
4.5.6	Replication of Resources	236
4.6	The Network as a Resource	238
4.6.1	Network Bandwidth.....	238
4.6.2	Data Compression Techniques.....	243
4.6.3	Message Format	246
4.6.4	Serialization	248
4.6.5	The Network as a Series of Links	251
4.6.6	Routers and Routing	254
4.6.7	Overheads of Communication	258
4.6.8	Recovery Mechanisms and Their Interplay with Network Congestion	259

4.7	Virtual Resources	262
4.7.1	Sockets	262
4.7.2	Ports	262
4.7.3	Network Addresses	263
4.7.4	Resource Names.....	263
4.8	Distributed Application Design Influences on Network Efficiency.....	264
4.9	Transparency from the Resource Viewpoint.....	265
4.9.1	Access Transparency.....	265
4.9.2	Location Transparency.....	265
4.9.3	Replication Transparency.....	265
4.9.4	Concurrency Transparency	265
4.9.5	Scaling Transparency and Performance Transparency	266
4.10	The Case Study from the Resource Perspective	266
4.11	End-of-Chapter Exercises	268
4.11.1	Questions	268
4.11.2	Exercises with the Workbenches	269
4.11.3	Programming Exercises.....	272
4.11.4	Answers to End-of-Chapter Questions.....	273
4.11.5	Answers/Outcomes of the Workbenches Exercises	274
4.11.6	List of In-Text Activities	276
4.11.7	List of Accompanying Resources.....	276
CHAPTER 5	The Architecture View	277
5.1	Rationale and Overview.....	279
5.2	The Architecture View	279
5.2.1	Separation of Concerns	280
5.2.2	Networking and Distribution	281
5.2.3	Complexity in Distributed Systems	282
5.2.4	Layered Architectures.....	283
5.2.5	Hierarchical Architectures	285
5.3	Heterogeneity.....	287
5.3.1	Definitions and Sources of Heterogeneity	287
5.3.2	Performance Heterogeneity	288
5.3.3	Platform Heterogeneity	289
5.3.4	Operating System Heterogeneity	290
5.3.5	Impact of Heterogeneity	290
5.3.6	Porting of Software.....	292
5.4	Hardware and System-Level Architectures	293
5.4.1	Tightly Coupled (Hardware) Systems.....	293
5.4.2	Loosely Coupled (Hardware) Systems	294
5.4.3	Parallel Processing	295

5.5	Software Architectures	296
5.5.1	Coupling Between Software Components	297
5.6	Taxonomy of Software Architecture Classes	302
5.6.1	Single-Tier Applications	302
5.6.2	Two-Tier Applications	302
5.6.3	Three-Tier Applications	304
5.6.4	Multitier Applications	304
5.7	Client-Server	305
5.7.1	Lifetimes of Client and Server	305
5.7.2	Active and Passive Sides of the Connection	306
5.7.3	The CS Architectural Model	306
5.7.4	Variants of the CS Model	308
5.7.5	Stateful Versus Stateless Services	309
5.7.6	Modular and Hierarchical CS Systems	310
5.8	Three-Tier and Multitier Architectures	312
5.9	Peer-to-Peer	323
5.9.1	Characteristics of Peer-to-Peer Applications	323
5.9.2	Complexity of Peer-to-Peer Connectivity	324
5.9.3	Exploring Peer-to-Peer Behavior	325
5.10	Distributed Objects	329
5.11	Middleware: Support for Software Architectures	331
5.11.1	Middleware Operation, an Overview	331
5.12	System Models of Collective Resources and Computation	
	Resource Provision	333
5.12.1	Clusters	334
5.12.2	Grids	334
5.12.3	Data Centers	335
5.12.4	Clouds	335
5.13	Software Libraries	335
5.13.1	Software Library Case Example	338
5.13.2	Static Linking and Dynamic Linking	344
5.13.3	Language-Dependent Feature: The C/C++ Header File	346
5.14	Hardware Virtualization	348
5.14.1	Virtual Machines	349
5.14.2	Java Virtual Machine	350
5.15	Static and Dynamic Configurations	351
5.15.1	Static Configuration	351
5.15.2	Dynamic Configuration	352
5.15.3	Context Awareness	352
5.16	Nonfunctional Requirements of Distributed Applications	353

5.16.1	Replication	355
5.16.2	Semantics of Replication.....	358
5.16.3	An Implementation of Replication	359
5.17	The Relationship Between Distributed Applications and Networks	369
5.18	Transparency from the Architecture Viewpoint.....	371
5.19	The Case Study from the Architectural Perspective	372
5.19.1	Stateful Server Design.....	372
5.19.2	Separation of Concerns for the Game Components	373
5.19.3	Physical and Logical Architectures of the Game Application	374
5.19.4	Transparency Aspects of the Game	375
5.20	End-of-Chapter Exercises	376
5.20.1	Questions.....	376
5.20.2	Programming Exercises.....	377
5.20.3	Answers to end-of-Chapter Questions	378
5.20.4	List of In-Text Activities	380
5.20.5	List of Accompanying Resources.....	381
Appendix	The Peer-to-Peer Application-Level Protocol Message Sequence	382

CHAPTER 6	Distributed Systems	383
6.1	Rationale and Overview.....	385
6.2	Transparency.....	385
6.2.1	Access Transparency	387
6.2.2	Location Transparency	388
6.2.3	Replication Transparency.....	389
6.2.4	Concurrency Transparency.....	393
6.2.5	Migration Transparency	398
6.2.6	Failure Transparency	398
6.2.7	Scaling Transparency	400
6.2.8	Performance Transparency	403
6.2.9	Distribution Transparency	404
6.2.10	Implementation Transparency	404
6.3	Common Services.....	404
6.4	Name Services	405
6.4.1	Name Service Operation.....	406
6.4.2	Directory Service	407
6.4.3	Challenges of Name Service Design and Implementation	413
6.5	Domain Name System (DNS)	414
6.5.1	Domain Namespace	415
6.5.2	DNS Implementation	417
6.5.3	DNS Name Servers: Authority and Delegation	420

6.5.4	Replication	421
6.5.5	Name Resolution in More Detail	422
6.5.6	Caching in DNS	423
6.5.7	Exploring Address Resolution	423
6.5.8	Reverse DNS Lookup	426
6.6	Time Services	427
6.6.1	Time Services.....	427
6.6.2	Physical Clock Synchronization	428
6.6.3	Logical Clocks and Synchronization	433
6.7	Election Algorithms.....	436
6.7.1	Operation Overview.....	437
6.7.2	The Bully Election Algorithm	439
6.7.3	The Ring Election Algorithm.....	440
6.7.4	Leader Preelection	440
6.7.5	Exploration with an Election Algorithm.....	441
6.8	Group Communications.....	448
6.8.1	Transparency Aspects of Group Communication.....	450
6.9	Notification Services.....	450
6.9.1	Publish-Subscribe Services.....	451
6.10	Middleware: Mechanism and Operation.....	452
6.11	Middleware Examples and Support Technologies.....	454
6.11.1	The Common Object Request Broker Architecture (CORBA)	454
6.11.2	Interface Definition Language (IDL)	462
6.11.3	Extensible Markup Language.....	464
6.11.4	JavaScript Object Notation (JSON).....	465
6.11.5	Web Services and REST.....	466
6.11.6	The Simple Object Access Protocol (SOAP)	467
6.12	Deterministic and Nondeterministic Aspects of Distributed Systems.....	468
6.13	End of Chapter Exercises.....	470
6.13.1	Questions.....	470
6.13.2	Programming Exercises.....	470
6.13.3	Answers to End of Chapter Questions	472
6.13.4	List of In-Text Activities	473
6.13.5	List of Accompanying Resources.....	473
CHAPTER 7	Case Studies: Putting It All Together	475
7.1	Rationale and Overview.....	476
7.2	Introduction to the Use Cases.....	476
7.3	Case Study #1: Time Service Client (with Library)	477
7.3.1	Learning Outcomes Associated with the Case Study.....	477
7.3.2	Requirements Analysis.....	477

7.3.3	Architecture and Code Structure	478
7.3.4	Separation of Concerns	483
7.3.5	Coupling and Binding Between Components	484
7.3.6	Communication Aspects of the Design	484
7.3.7	Implementation	488
7.3.8	Testing	488
7.3.9	Transparency Aspects of the Use Case	489
7.3.10	Case Study Resources	491
7.4	Case Study #2: Event Notification Service	492
7.4.1	Learning Outcomes Associated with the Case Study	492
7.4.2	Requirements Analysis	493
7.4.3	Architecture and Code Structure	494
7.4.4	Separation of Concerns	495
7.4.5	Coupling and Binding Between Components	495
7.4.6	Communication Aspects of the Design	496
7.4.7	An Application Use Scenario to Illustrate the Use of the ENS	501
7.4.8	Testing	503
7.4.9	Transparency Aspects of the ENS	503
7.4.10	Case Study Resources	508
7.5	Good Design Practice for Distributed Applications	508
7.5.1	Requirements Analysis	509
7.5.2	Architectural Aspects	509
7.5.3	Communication Aspects	510
7.5.4	Reuse Code When Opportunities Arise	510
7.5.5	Create Libraries of Tested and Trusted Code	511
7.5.6	Testing Aspects	511
7.6	End of Chapter Programming Exercises	512
7.7	List of Accompanying Resources	513
	Index	515