xi

Part I Basic Concepts 1

Hardware and Applications; Synchronization; Program Properties

Chapter 1 Sequential Programming 7

Dhaing Philes phars, Readers and Writes

4.2 Basic Uses and Programming Technicas

1.1 Language Notation 7 Declarations; Statements; Procedures

1.2 Logic, Propositions, and Predicates 14 Formal Logical Systems; Propositions; Predicates

1.3 A Programming Logic 23 Axioms; Inference Rules

1.4 Proofs in Programming Logic 31 Proof Outlines; Equivalence and Simulation

1.5 Program Derivation 36

Weakest Preconditions; Weakest Preconditions of Statements; Linear Search Revisited; Sorting

Historical Notes and References 47 Exercises 49

Chapter 2 Concurrency and Synchronization 57

2.1 Specifying Concurrent Execution 57

2.2 Atomic Actions and Synchronization 59 Fine-Grained Atomicity; Specifying Synchronization

2.3 Semantics of Concurrent Execution 64

xii

2.4 Techniques for Avoiding Interference 67 Disjoint Variables; Weakened Assertions; Global Invariants; Synchronization

2.5 Auxiliary Variables 78

2.6 Safety and Liveness Properties 81 Proving Safety Properties; Scheduling Policies and Fairness

Historical Notes and References 86 Exercises 89

Part II Shared Variables 95

Chapter 3 Fine-Grained Synchronization 97

- 3.1 The Critical Section Problem 98 A Coarse-Grained Solution; Spin Locks: A Fine-Grained Solution; Implementing Await Statements
- **3.2 Critical Sections: Tie-Breaker Algorithm 107** A Coarse-Grained Solution; A Fine-Grained Solution; An N-Process Solution
- **3.3 Critical Sections: Ticket Algorithm 112** Coarse-Grained Solution; Fine-Grained Solutions
- **3.4 Critical Sections: Bakery Algorithm 115** Coarse-Grained Solution; A Fine-Grained Solution
- **3.5 Barrier Synchronization 120** Shared Counter; Flags and Coordinators; Symmetric Barriers

3.6 Data Parallel Algorithms 127 Parallel Prefix Computations; Operations on Linked Lists; Grid Computations; Synchronous Multiprocessors

3.7 On-The-Fly Garbage Collection 134 Problem Specification; Solution Outline; A Coarse-Grained Solution; A Fine-Grained Solution

3.8 Implementing Processes 146 A Single-Processor Kernel; A Multiprocessor Kernel

Historical Notes and References 155 Exercises 159

Chapter 4 Semaphores 171

- 4.1 Notation and Semantics 172
- 4.2 Basic Uses and Programming Techniques 175 Critical Sections: Changing Variables; Barriers: Signaling Events; Producers and Consumers: Split Binary Semaphores; Bounded Buffers: Resource Counting
- 4.3 Selective Mutual Exclusion 189 Dining Philosophers; Readers and Writers
- 4.4 General Condition Synchronization 197 Readers and Writers Revisited; The Technique of Passing the Baton;



Readers and Writers Solution; Alternative Scheduling Policies

4.5 Resource Allocation 204

Problem Definition and General Solution Pattern; Shortest-Job-Next Allocation

4.6 Implementation 210

Historical Notes and References 212 Exercises 214

Chapter 5 Conditional Critical Regions 225

5.1 Notation and Semantics 226 Examples; Inference Rules; Safety and Liveness Properties

- 5.2 Dining Philosophers Revisited 232
- 5.3 Readers/Writers Revisited 235

Readers' Preference Solution; Writers' Preference Solution

5.4 Interprocess Communication 238 Bounded Buffer With Exclusive Access; Bounded Buffer With Concurrent Access

5.5 Scheduling and Resource Allocation 242

5.6 Implementations 245

Using Busy Waiting; Using Semaphores with Passing the Baton; Using Semaphores with Rem's Algorithm; Using a Kernel

Historical Notes and References 254 Exercises 255

xiv

Chapter 6 Monitors 263

- 6.1 Programming Notation 264 Synchronization in Monitors; Additional Operations on Condition Variables
- 6.2 Formal Semantics and Program Proofs 271 Axioms and Proof Obligations; A Procedure Call Inference Rule; Safety and Liveness Properties; An Example: Readers and Writers

6.3 Synchronization Techniques 283

Interval Timer: Covering Conditions and Priority Wait; A Fair Semaphore: Passing the Condition; The Sleeping Barber Problem: Rendezvous

6.4 Disk Scheduling: Program Structures 295 Scheduler as a Separate Monitor; Scheduler as an Intermediary

6.5 Alternative Approaches to Synchronization 305 Alternative Signaling Disciplines; Equivalence of the Signaling Disciplines; Differences Between the Signaling Disciplines; Alternatives to Mutual Exclusion; Path Expressions

6.6 Implementations 319 Using Semaphores; Using a Kernel

Historical Notes and References 325 Exercises 329

Part III Message Passing 339

Chapter 7 Asynchronous Message Passing 343

7.1 Programming Notation 344

7.2 Formal Semantics 346 Axioms and Satisfaction Proofs; Auxiliary Variables and Non-Interference; An Example; Safety and Liveness Properties

7.3 Filters: A Sorting Network 355

7.4 Clients and Servers 359 Active Monitors; A Self-Scheduling Disk Driver;

File Servers: Conversational Continuity

7.5 Heartbeat Algorithms 370

Network Topology: Shared-Variable Solution; Network Topology: Distributed Solution

7.6 Probe/Echo Algorithms 376 Broadcast in a Network; Network Topology Revisited

7.7 Broadcast Algorithms 383

Logical Clocks and Event Ordering; Distributed Semaphores

7.8 Token-Passing Algorithms 388 Distributed Mutual Exclusion; Termination Detection in a Ring; **Termination Detection in a Graph**

- 7.9 Replicated Servers 396 **Replicated Files; Replicated Workers: Adaptive Quadrature**
- 7.10 Implementations 402 Shared-Memory Kernel; Distributed Kernel

Historical Notes and References 410 Exercises 415

Chapter 8 Synchronous Message Passing 423

8.1 Programming Notation 424 **Communication Statements; Guarded Communication**

8.2 Formal Semantics 429

Axioms, Inference Rules, and Satisfaction Proofs; Auxiliary Variables and Non-Interference; An Example; Safety and Liveness Properties

8.3 Networks of Filters 439

Prime Number Generation: The Sieve of Eratosthenes; Matrix/Vector Multiplication

8.4 Interacting Parallel Processes 443

Parallel Sorting: A Heartbeat Algorithm; **Parallel Prefix Computations;** Matrix Multiplication: Broadcast Algorithm; Matrix Multiplication: Heartbeat Algorithm

xvi

8.5 Clients and Servers 453

Resource Allocation; File Servers and Conversational Continuity; Centralized Dining Philosophers; Decentralized Dining Philosophers

8.6 Implementations 460

Centralized Clearing House; Decentralized Implementations

Historical Notes and References 472 Exercises 474

Chapter 9 RPC and Rendezvous 483

9.1 Remote Procedure Call 484

Synchronization in Modules; A Time Server; Caches in a Distributed File System; A Sorting Network of Merge Filters; Formal Semantics

9.2 Rendezvous 494

Client/Server Examples; A Sorting Network of Merge Filters; Formal Semantics; An Example Proof; Safety and Liveness Properties

9.3 A Multiple Primitives Notation 509 Invoking and Servicing Operations; Examples; Formal Semantics

9.4 Clients and Servers 515

Readers/Writers Revisited: Encapsulated Access; Replicated Files; Network Topology Using Probe/Echo Algorithms

9.5 Parallel Algorithms 522

Region Labeling: A Heartbeat Algorithm;

The Traveling Salesman Problem: Replicated Workers

9.6 Implementations 529

RPC in a Kernel; Rendezvous Using Asynchronous Message Passing; Multiple Primitives in a Kernel

Matrix Vector Multiplication

8.4 Interesting Parallel Processes 448

Historical Notes and References 540 Exercises 543

xvii

Part IV Practice 551

Chapter 10 Language Overviews 553

10.1 Turing Plus: Monitors 555 Program Structure; Process Interaction; Example: File Difference Checker

10.2 Occam: Synchronous Message Passing 561 Program Structure; Sequential and Parallel Constructors; Communication and Synchronization; **Example:** Prime Number Sieve

10.3 Ada: Rendezvous 567

Program Components; Communication and Synchronization; **Example: The Dining Philosophers**

10.4 SR: Multiple Primitives 575

Program Components; Communication and Synchronization; **Example: The Traveling Salesman Problem**

Maszy different language menhautens have been proceed for eneritying

10.5 Linda: Distributed Data Structures 581 Tuple Space and Process Interaction; Example: Prime Numbers with Replicated Workers

10.6 Comparison and Performance 588 Performance Experiments; Interpretation of Results

Historical Notes and References 593 Exercises 598

Glossary 603

Bibliography 607

Index 627