

# Contents

Foreword .....	xiii
Preface to the Second Edition .....	xv
Abbreviations .....	xix
<b>CHAPTER 1 Introduction .....</b>	<b>1</b>
1.1 Cloud Computing .....	2
1.2 Network-Centric Computing and Network-Centric Content .....	4
1.3 Cloud Computing, an Old Idea Whose Time Has Come .....	6
1.4 Cloud Delivery Models and Defining Attributes .....	8
1.5 Ethical Issues in Cloud Computing .....	10
1.6 Cloud Vulnerabilities .....	11
<b>CHAPTER 2 Cloud Service Providers and the Cloud Ecosystem .....</b>	<b>13</b>
2.1 The Cloud Ecosystem .....	13
2.2 Cloud Computing Delivery Models and Services .....	15
2.3 Amazon Web Services .....	19
2.4 The Continuing Evolution of AWS .....	26
2.5 Google Clouds .....	30
2.6 Microsoft Windows Azure and Online Services .....	34
2.7 Cloud Storage Diversity and Vendor Lock-In .....	35
2.8 Cloud Computing Interoperability; the Intercloud .....	37
2.9 Service-Level Agreements and Compliance-Level Agreements .....	39
2.10 Responsibility Sharing Between a User and the CSP .....	40
2.11 User Experience .....	42
2.12 Software Licensing .....	44
2.13 Energy Use and Ecological Impact of Cloud Computing .....	45
2.14 Major Challenges Faced by Cloud Computing .....	46
2.15 Further Readings .....	47
2.16 Exercises and Problems .....	48

## SECTION 1

<b>CHAPTER 3 Concurrency in the Cloud .....</b>	<b>53</b>
3.1 Enduring Challenges; Concurrency and Cloud Computing .....	54
3.2 Communication and Concurrency in Computing .....	56
3.3 Computational Models; the BSP Model .....	61
3.4 A Model for Multicore Computing .....	64
3.5 Modeling Concurrency with Petri Nets .....	66
3.6 Process State; Global State of a Process or Thread Group .....	72
3.7 Communication Protocols and Process Coordination .....	76

<b>3.8</b>	Communication, Logical Clocks, and Message Delivery Rules .....	78
<b>3.9</b>	Runs and Cuts; Causal History .....	82
<b>3.10</b>	Threads and Activity Coordination .....	85
<b>3.11</b>	Critical Sections, Locks, Deadlocks, and Atomic Actions .....	93
<b>3.12</b>	Consensus Protocols .....	98
<b>3.13</b>	Load Balancing .....	100
<b>3.14</b>	Multithreading and Concurrency in Java; FlumeJava .....	106
<b>3.15</b>	History Notes and Further Readings .....	108
<b>3.16</b>	Exercises and Problems .....	109
<b>CHAPTER 4</b>	<b>Parallel and Distributed Systems .....</b>	<b>113</b>
<b>4.1</b>	Data, Thread-Level and Task-Level Parallelism .....	114
<b>4.2</b>	Parallel Architectures .....	116
<b>4.3</b>	SIMD Architectures; Vector Processing and Multimedia Extensions .....	120
<b>4.4</b>	Graphics Processing Units .....	122
<b>4.5</b>	Speedup, Amdhal's Law, and Scaled Speedup .....	124
<b>4.6</b>	Multicore Processor Speedup .....	126
<b>4.7</b>	Distributed Systems; System Modularity .....	129
<b>4.8</b>	Soft Modularity versus Enforced Modularity .....	131
<b>4.9</b>	Layering and Hierarchy .....	135
<b>4.10</b>	Virtualization; Layering and Virtualization .....	137
<b>4.11</b>	Peer-to-Peer Systems .....	140
<b>4.12</b>	Large-Scale Systems .....	143
<b>4.13</b>	Composability Bounds and Scalability .....	144
<b>4.14</b>	History Notes and Further Readings .....	146
<b>4.15</b>	Exercises and Problems .....	149

## SECTION 2

---

<b>CHAPTER 5</b>	<b>Cloud Access and Cloud Interconnection Networks .....</b>	<b>153</b>
<b>5.1</b>	Packet-Switched Networks and the Internet .....	154
<b>5.2</b>	The Transformation of the Internet .....	159
<b>5.3</b>	Web Access and the TCP Congestion Control Window .....	163
<b>5.4</b>	Named Data Networks .....	166
<b>5.5</b>	Software Defined Networks .....	168
<b>5.6</b>	Interconnection Networks for Computer Clouds .....	169
<b>5.7</b>	Multistage Interconnection Networks .....	173
<b>5.8</b>	InfiniBand and Myrinet .....	175
<b>5.9</b>	Storage Area Networks and the Fibre Channel .....	178
<b>5.10</b>	Scalable Data Center Communication Architectures .....	180
<b>5.11</b>	Network Resource Management Algorithms .....	185
<b>5.12</b>	Content Delivery Networks .....	188
<b>5.13</b>	Vehicular Ad Hoc Networks .....	192

<b>5.14 Further Readings . . . . .</b>	193
<b>5.15 Exercises and Problems . . . . .</b>	193
<b>CHAPTER 6 Cloud Data Storage . . . . .</b>	195
<b>6.1 The Evolution of Storage Technologies . . . . .</b>	196
<b>6.2 Storage Models, File Systems, and Databases . . . . .</b>	198
<b>6.3 Distributed File Systems; the Precursors . . . . .</b>	202
<b>6.4 General Parallel File System . . . . .</b>	208
<b>6.5 Google File System . . . . .</b>	211
<b>6.6 Locks; Chubby – a Locking Service . . . . .</b>	213
<b>6.7 NoSQL Databases . . . . .</b>	218
<b>6.8 Data Storage for Online Transaction Processing Systems . . . . .</b>	219
<b>6.9 BigTable . . . . .</b>	220
<b>6.10 Megastore . . . . .</b>	222
<b>6.11 Storage Reliability at Scale . . . . .</b>	224
<b>6.12 Disk Locality versus Data Locality in Computer Clouds . . . . .</b>	228
<b>6.13 Database Provenance . . . . .</b>	229
<b>6.14 History Notes and Further Readings . . . . .</b>	231
<b>6.15 Exercises and Problems . . . . .</b>	233

## **SECTION 3**

---

<b>CHAPTER 7 Cloud Applications . . . . .</b>	237
<b>7.1 Cloud Application Development and Architectural Styles . . . . .</b>	238
<b>7.2 Coordination of Multiple Activities . . . . .</b>	241
<b>7.3 Workflow Patterns . . . . .</b>	245
<b>7.4 Coordination Based on a State Machine Model – the ZooKeeper . . . . .</b>	248
<b>7.5 The MapReduce Programming Model . . . . .</b>	251
<b>7.6 Case Study: the GrepTheWeb Application . . . . .</b>	254
<b>7.7 Hadoop, Yarn, and Tez . . . . .</b>	257
<b>7.8 SQL on Hadoop: Pig, Hive, and Impala . . . . .</b>	262
<b>7.9 Current Cloud Applications and New Opportunities . . . . .</b>	266
<b>7.10 Clouds for Science and Engineering . . . . .</b>	268
<b>7.11 Cloud Computing for Biology Research . . . . .</b>	272
<b>7.12 Social Computing, Digital Content, and Cloud Computing . . . . .</b>	275
<b>7.13 Software Fault Isolation . . . . .</b>	277
<b>7.14 Further Readings . . . . .</b>	278
<b>7.15 Exercises and Problems . . . . .</b>	278
<b>CHAPTER 8 Cloud Hardware and Software . . . . .</b>	281
<b>8.1 Challenges; Virtual Machines and Containers . . . . .</b>	282
<b>8.2 Cloud Hardware; Warehouse-Scale Computers . . . . .</b>	284
<b>8.3 WSC Performance . . . . .</b>	286
<b>8.4 Hypervisors . . . . .</b>	290
<b>8.5 An Engine for Coarse-Grained Data-Parallel Applications . . . . .</b>	290

<b>8.6</b>	<b>Fine-Grained Cluster Resource Sharing .....</b>	<b>292</b>
<b>8.7</b>	<b>Cluster Management with Borg .....</b>	<b>294</b>
<b>8.8</b>	<b>Shared State Cluster Management .....</b>	<b>296</b>
<b>8.9</b>	<b>QoS-Aware Cluster Management .....</b>	<b>298</b>
<b>8.10</b>	<b>Resource Isolation .....</b>	<b>301</b>
<b>8.11</b>	<b>In-Memory Cluster Computing for Big Data .....</b>	<b>306</b>
<b>8.12</b>	<b>Containers; Docker Containers .....</b>	<b>313</b>
<b>8.13</b>	<b>Kubernetes .....</b>	<b>315</b>
<b>8.14</b>	<b>Further Readings .....</b>	<b>317</b>
<b>8.15</b>	<b>Exercises and Problems .....</b>	<b>318</b>
<b>CHAPTER 9</b>	<b>Cloud Resource Management and Scheduling .....</b>	<b>321</b>
<b>9.1</b>	<b>Policies and Mechanisms for Resource Management .....</b>	<b>322</b>
<b>9.2</b>	<b>Cloud Resource Utilization and Energy Efficiency .....</b>	<b>324</b>
<b>9.3</b>	<b>Resource Management and Dynamic Application Scaling .....</b>	<b>327</b>
<b>9.4</b>	<b>Control Theory and Optimal Resource Management .....</b>	<b>328</b>
<b>9.5</b>	<b>Stability of a Two-Level Resource Allocation Architecture .....</b>	<b>332</b>
<b>9.6</b>	<b>Feedback Control Based on Dynamic Thresholds .....</b>	<b>334</b>
<b>9.7</b>	<b>Coordination of Autonomic Performance Managers .....</b>	<b>335</b>
<b>9.8</b>	<b>A Utility Model for Cloud-Based Web Services .....</b>	<b>337</b>
<b>9.9</b>	<b>Scheduling Algorithms for Computer Clouds .....</b>	<b>341</b>
<b>9.10</b>	<b>Delay Scheduling .....</b>	<b>343</b>
<b>9.11</b>	<b>Data-Aware Scheduling .....</b>	<b>348</b>
<b>9.12</b>	<b>Apache Capacity Scheduler .....</b>	<b>351</b>
<b>9.13</b>	<b>Start-Time Fair Queuing .....</b>	<b>352</b>
<b>9.14</b>	<b>Borrowed Virtual Time .....</b>	<b>356</b>
<b>9.15</b>	<b>Further Readings .....</b>	<b>359</b>
<b>9.16</b>	<b>Exercises and Problems .....</b>	<b>362</b>
<b>CHAPTER 10</b>	<b>Cloud Resource Virtualization .....</b>	<b>365</b>
<b>10.1</b>	<b>Performance and Security Isolation in Computer Clouds .....</b>	<b>366</b>
<b>10.2</b>	<b>Virtual Machines .....</b>	<b>367</b>
<b>10.3</b>	<b>Full Virtualization and Paravirtualization .....</b>	<b>370</b>
<b>10.4</b>	<b>Hardware Support for Virtualization .....</b>	<b>372</b>
<b>10.5</b>	<b>Xen – a Hypervisor Based on Paravirtualization .....</b>	<b>375</b>
<b>10.6</b>	<b>Optimization of Network Virtualization in Xen 2.0 .....</b>	<b>380</b>
<b>10.7</b>	<b>Kernel-Based Virtual Machine .....</b>	<b>383</b>
<b>10.8</b>	<b>Nested Virtualization .....</b>	<b>383</b>
<b>10.9</b>	<b>A Trusted Kernel-Based Virtual Machine for ARMv8 .....</b>	<b>388</b>
<b>10.10</b>	<b>Paravirtualization of Itanium Architecture .....</b>	<b>389</b>
<b>10.11</b>	<b>A Performance Comparison of Virtual Machines .....</b>	<b>392</b>
<b>10.12</b>	<b>Open-Source Software Platforms for Private Clouds .....</b>	<b>395</b>
<b>10.13</b>	<b>The Darker Side of Virtualization .....</b>	<b>398</b>
<b>10.14</b>	<b>Virtualization Software .....</b>	<b>399</b>

<b>10.15 History Notes and Further Readings .....</b>	<b>400</b>
<b>10.16 Exercises and Problems .....</b>	<b>401</b>

## SECTION 4

<b>CHAPTER 11 Cloud Security .....</b>	<b>405</b>
11.1 Security, the Top Concern for Cloud Users .....	406
11.2 Cloud Security Risks .....	407
11.3 Privacy and Privacy Impact Assessment .....	411
11.4 Trust .....	413
11.5 Cloud Data Encryption .....	415
11.6 Security of Database Services .....	417
11.7 Operating System Security .....	419
11.8 Virtual Machine Security .....	420
11.9 Security of Virtualization .....	422
11.10 Security Risks Posed by Shared Images .....	425
11.11 Security Risks Posed by a Management OS .....	428
11.12 Xoar – Breaking the Monolithic Design of the TCB .....	431
11.13 A Trusted Hypervisor .....	434
11.14 Mobile Devices and Cloud Security .....	435
11.15 Further Readings .....	436
11.16 Exercises and Problems .....	437
<b>CHAPTER 12 Big Data, Data Streaming, and the Mobile Cloud .....</b>	<b>439</b>
12.1 Big Data .....	440
12.2 Data Warehouses and Google Databases for Big Data .....	442
12.3 Bootstrapping Techniques for Data Analytics .....	450
12.4 Approximate Query Processing .....	453
12.5 Dynamic Data-Driven Applications .....	457
12.6 Data Streaming .....	460
12.7 A Dataflow Model for Data Streaming .....	463
12.8 Joining Multiple Data Streams .....	467
12.9 System Availability at Scale .....	469
12.10 The Scale and the Latency .....	471
12.11 Mobile Computing and Applications .....	476
12.12 Energy Efficiency of Mobile Computing .....	478
12.13 Alternative Mobile Cloud Computing Models .....	480
12.14 Mobile Edge Cloud and Markov Decision Processes .....	482
12.15 Further Readings .....	485
12.16 Exercises and Problems .....	486
<b>CHAPTER 13 Advanced Topics .....</b>	<b>489</b>
13.1 A Glimpse at the Future .....	489
13.2 Cloud Scheduling Subject to Deadlines .....	491
13.3 Scheduling MapReduce Applications Subject to Deadlines .....	496

13.4	Emergence and Self-Organization . . . . .	497
13.5	Resource Bundling; Combinatorial Auctions for Cloud Resources . . . . .	500
13.6	Cloud Interoperability and Super Clouds . . . . .	503
13.7	In Search for Blooms Amid a Flurry of Challenges . . . . .	505
<b>APPENDIX A</b>	<b>Cloud Application Development (online appendix)</b> . . . . .	<b>507</b>
<b>APPENDIX B</b>	<b>Cloud Projects (online appendix)</b> . . . . .	<b>509</b>
Literature . . . . .		511
Glossary . . . . .		533
Index . . . . .		549

## ONLINE APPENDICES

---

<b>APPENDIX A</b>	<b>Cloud Application Development</b> . . . . .	<b>e1</b>
A.1	AWS EC2 Instances . . . . .	e2
A.2	Connecting Clients to Cloud Instances through Firewalls . . . . .	e3
A.3	Security Rules for Application- and Transport-Layer Protocols in EC2 . . . . .	e7
A.4	How to Launch an EC2 Linux Instance and Connect to It . . . . .	e8
A.5	How to Use S3 in Java . . . . .	e12
A.6	How to Manage AWS SQS Services in C# . . . . .	e14
A.7	How to Install SNS on Ubuntu 10.04 . . . . .	e15
A.8	How to Create an EC2 Placement Group and use MPI . . . . .	e17
A.9	StarCluster – A Cluster Computing Toolkit for EC2 . . . . .	e19
A.10	An Alternative Setting of an MPI Virtual Cluster . . . . .	e19
A.11	How to Install Hadoop on Eclipse on a Windows System . . . . .	e21
A.12	Exercises and Problems . . . . .	e24
<b>APPENDIX B</b>	<b>Cloud Projects</b> . . . . .	<b>e27</b>
B.1	Cloud-Based Simulation of a Distributed Trust Algorithm . . . . .	e27
B.2	Simulation of Traffic Management in a Smart City . . . . .	e31
B.3	A Cloud Trust Management Service . . . . .	e37
B.4	A Cloud Service for Adaptive Data Streaming . . . . .	e45
B.5	Cloud-Based Optimal FPGA Synthesis . . . . .	e49
B.6	Tensor Network Contraction on AWS . . . . .	e51