Table of Contents

Pref	ace	xiii
Part	t I. Foundations of Data Systems	
1.	Reliable, Scalable, and Maintainable Applications	
	Thinking About Data Systems	4
	Reliability	6
	Hardware Faults	6 7
	Software Errors	8
	Human Errors	9
	How Important Is Reliability?	10
	Scalability	10
	Describing Load	11
	Describing Performance	13
	Approaches for Coping with Load	17
	Maintainability	18
	Operability: Making Life Easy for Operations	19
	Simplicity: Managing Complexity	20
	Evolvability: Making Change Easy	21
	Summary	22
2.	Data Models and Query Languages	27
	Relational Model Versus Document Model	28
	The Birth of NoSQL	29
	The Object-Relational Mismatch	29
	Many-to-One and Many-to-Many Relationships	33
	Are Document Databases Repeating History?	36

	Relational Versus Document Databases Today	38
	Query Languages for Data	42
	Declarative Queries on the Web	44
	MapReduce Querying	46
	Graph-Like Data Models	49
	Property Graphs	50
	The Cypher Query Language	52
	Graph Queries in SQL	53
	Triple-Stores and SPARQL	55
	The Foundation: Datalog	60
	Summary	63
3.	Storage and Retrieval	. 69
	Data Structures That Power Your Database	70
	Hash Indexes	72
	SSTables and LSM-Trees	76
	B-Trees	79
	Comparing B-Trees and LSM-Trees	83
	Other Indexing Structures	85
	Transaction Processing or Analytics?	90
	Data Warehousing	91
	Stars and Snowflakes: Schemas for Analytics	93
	Column-Oriented Storage	95
	Column Compression	97
	Sort Order in Column Storage	99
	Writing to Column-Oriented Storage	101
	Aggregation: Data Cubes and Materialized Views	101
	Summary	103
4.	Encoding and Evolution	111
	Formats for Encoding Data	112
	Language-Specific Formats	113
	JSON, XML, and Binary Variants	114
	Thrift and Protocol Buffers	117
	Avro	122
	The Merits of Schemas	127
	Modes of Dataflow	128
	Dataflow Through Databases	129
	Dataflow Through Services: REST and RPC	131
	Message-Passing Dataflow	136
	Summary	139

Part II. **Distributed Data**

5.	Replication	151
	Leaders and Followers	152
	Synchronous Versus Asynchronous Replication	153
	Setting Up New Followers	155
	Handling Node Outages	156
	Implementation of Replication Logs	158
	Problems with Replication Lag	161
	Reading Your Own Writes	162
	Monotonic Reads	164
	Consistent Prefix Reads	165
	Solutions for Replication Lag	167
	Multi-Leader Replication	168
	Use Cases for Multi-Leader Replication	168
	Handling Write Conflicts	171
	Multi-Leader Replication Topologies	175
	Leaderless Replication	177
	Writing to the Database When a Node Is Down	177
	Limitations of Quorum Consistency	181
	Sloppy Quorums and Hinted Handoff	183
	Detecting Concurrent Writes	184
	2 etecting concurrent virtees	
	Summary	192
6.	Summary	
6.	Summary Partitioning	192 199
6.	Partitioning and Replication	192
6.	Partitioning	192 199 200
6.	Partitioning	192 199 200 201
6.	Partitioning	192 199 200 201 202
6.	Partitioning. Partitioning and Replication Partitioning of Key-Value Data Partitioning by Key Range Partitioning by Hash of Key	192 199 200 201 202 203
6.	Partitioning. Partitioning and Replication Partitioning of Key-Value Data Partitioning by Key Range Partitioning by Hash of Key Skewed Workloads and Relieving Hot Spots	192 199 200 201 202 203 205
6.	Partitioning	192 199 200 201 202 203 205 206
6.	Partitioning. Partitioning and Replication Partitioning of Key-Value Data Partitioning by Key Range Partitioning by Hash of Key Skewed Workloads and Relieving Hot Spots Partitioning and Secondary Indexes Partitioning Secondary Indexes by Document	192 199 200 201 202 203 205 206 206
6.	Partitioning. Partitioning and Replication Partitioning of Key-Value Data Partitioning by Key Range Partitioning by Hash of Key Skewed Workloads and Relieving Hot Spots Partitioning and Secondary Indexes Partitioning Secondary Indexes by Document Partitioning Secondary Indexes by Term	192 199 200 201 202 203 205 206 206 208
6.	Partitioning Partitioning and Replication Partitioning of Key-Value Data Partitioning by Key Range Partitioning by Hash of Key Skewed Workloads and Relieving Hot Spots Partitioning and Secondary Indexes Partitioning Secondary Indexes by Document Partitioning Secondary Indexes by Term Rebalancing Partitions	192 199 200 201 202 203 205 206 206 208 209
6.	Partitioning Partitioning and Replication Partitioning of Key-Value Data Partitioning by Key Range Partitioning by Hash of Key Skewed Workloads and Relieving Hot Spots Partitioning and Secondary Indexes Partitioning Secondary Indexes by Document Partitioning Secondary Indexes by Term Rebalancing Partitions Strategies for Rebalancing Operations: Automatic or Manual Rebalancing Request Routing	192 199 200 201 202 203 205 206 206 208 209 210
6.	Partitioning. Partitioning and Replication Partitioning of Key-Value Data Partitioning by Key Range Partitioning by Hash of Key Skewed Workloads and Relieving Hot Spots Partitioning and Secondary Indexes Partitioning Secondary Indexes by Document Partitioning Secondary Indexes by Term Rebalancing Partitions Strategies for Rebalancing Operations: Automatic or Manual Rebalancing	192 199 200 201 202 203 205 206 206 208 209 210 213
6.	Partitioning Partitioning and Replication Partitioning of Key-Value Data Partitioning by Key Range Partitioning by Hash of Key Skewed Workloads and Relieving Hot Spots Partitioning and Secondary Indexes Partitioning Secondary Indexes by Document Partitioning Secondary Indexes by Term Rebalancing Partitions Strategies for Rebalancing Operations: Automatic or Manual Rebalancing Request Routing	192 199 200 201 202 203 205 206 206 208 209 210 213 214
	Partitioning Partitioning and Replication Partitioning of Key-Value Data Partitioning by Key Range Partitioning by Hash of Key Skewed Workloads and Relieving Hot Spots Partitioning and Secondary Indexes Partitioning Secondary Indexes by Document Partitioning Secondary Indexes by Term Rebalancing Partitions Strategies for Rebalancing Operations: Automatic or Manual Rebalancing Request Routing Parallel Query Execution	192 199 200 201 202 203 205 206 208 209 210 213 214 216

	The Meaning of ACID	223
	Single-Object and Multi-Object Operations	228
	Weak Isolation Levels	233
	Read Committed	234
	Snapshot Isolation and Repeatable Read	237
	Preventing Lost Updates	242
	Write Skew and Phantoms	246
	Serializability	251
	Actual Serial Execution	252
	Two-Phase Locking (2PL)	257
	Serializable Snapshot Isolation (SSI)	261
	Summary	266
8.	The Trouble with Distributed Systems	273
	Faults and Partial Failures	274
	Cloud Computing and Supercomputing	275
	Unreliable Networks	277
	Network Faults in Practice	279
	Detecting Faults	280
	Timeouts and Unbounded Delays	281
	Synchronous Versus Asynchronous Networks	284
	Unreliable Clocks	287
	Monotonic Versus Time-of-Day Clocks	288
	Clock Synchronization and Accuracy	289
	Relying on Synchronized Clocks	291
	Process Pauses	295
	Knowledge, Truth, and Lies	300
	The Truth Is Defined by the Majority	300
	Byzantine Faults	304
	System Model and Reality	306
	Summary	310
9.	Consistency and Consensus	321
	Consistency Guarantees	322
	Linearizability	324
	What Makes a System Linearizable?	325
	Relying on Linearizability	330
	Implementing Linearizable Systems	332
	The Cost of Linearizability	335
	Ordering Guarantees	339
	Ordering and Causality	339
	Sequence Number Ordering	343

Total Order Broadcast Distributed Transactions and Consensus	348
	352
Atomic Commit and Two-Phase Commit (2P	C) 354
Distributed Transactions in Practice	360
Fault-Tolerant Consensus	364
Membership and Coordination Services	370
Summary	373
Part III. Derived Data	
10. Batch Processing	389
Batch Processing with Unix Tools	391
Simple Log Analysis	391
The Unix Philosophy	394
MapReduce and Distributed Filesystems	397
MapReduce Job Execution	399
Reduce-Side Joins and Grouping	403
Map-Side Joins	408
The Output of Batch Workflows	411
Comparing Hadoop to Distributed Databases	414
Beyond MapReduce	419
Materialization of Intermediate State	419
Graphs and Iterative Processing	424
High-Level APIs and Languages	426
Summary	429
11. Stream Processing	439
Transmitting Event Streams	440
Messaging Systems	441
Partitioned Logs	446
Databases and Streams	451
Keeping Systems in Sync	452
Change Data Capture	454
Event Sourcing	457
State, Streams, and Immutability	459
Processing Streams	464
Uses of Stream Processing	465
Reasoning About Time	468
Stream Joins	472
Fault Tolerance	476
Summary	479

12.	The Future of Data Systems	489
	Data Integration	490
	Combining Specialized Tools by Deriving Data	490
	Batch and Stream Processing	494
	Unbundling Databases	499
	Composing Data Storage Technologies	499
	Designing Applications Around Dataflow	504
	Observing Derived State	509
	Aiming for Correctness	515
	The End-to-End Argument for Databases	516
	Enforcing Constraints	521
	Timeliness and Integrity	524
	Trust, but Verify	528
	Doing the Right Thing	533
	Predictive Analytics	533
	Privacy and Tracking	536
	Summary	543
Glos	sary	553
Inde		559