

See discussions, stats, and author profiles for this publication at: <https://www.researchgate.net/publication/200034291>

Database Systems: The Complete Book

Chapter · January 2002

CITATIONS

588

READS

31,486

6 authors, including:



Hector Hector

Fundación Universitaria Tecnológico Comfenalco

23 PUBLICATIONS **1,224** CITATIONS

SEE PROFILE

Database Systems: The Complete Book

Hector Garcia-Molina
Jeffrey D. Ullman
Jennifer Widom

*Department of Computer Science
Stanford University*

An Alan R. Apt Book

Prentice
Hall

Prentice Hall
Upper Saddle River, New Jersey 07458

About the Authors

JEFFREY D. ULLMAN is the Stanford W. Ascherman Professor of Computer Science at Stanford University. He is the author or co-author of 16 books, including *Elements of ML Programming* (Prentice Hall 1998). His research interests include data mining, information integration, and electronic education. He is a member of the National Academy of Engineering, and recipient of a Guggenheim Fellowship, the Karl V. Karlstrom Outstanding Educator Award, the SIGMOD Contributions Award, and the Knuth Prize.

JENNIFER WIDOM is Associate Professor of Computer Science and Electrical Engineering at Stanford University. Her research interests include query processing on data streams, data caching and replication, semistructured data and XML, and data warehousing. She is a former Guggenheim Fellow and has served on numerous program committees, advisory boards, and editorial boards.

HECTOR GARCIA-MOLINA is the L. Bosack and S. Lerner Professor of Computer Science and Electrical Engineering, and Chair of the Department of Computer Science at Stanford University. His research interests include digital libraries, information integration, and database application on the Internet. He was a recipient of the SIGMOD Innovations Award and is a member of PITAC (President's Information-Technology Advisory Council).

Table of Contents

1	The Worlds of Database Systems	1
1.1	The Evolution of Database Systems	2
1.1.1	Early Database Management Systems	2
1.1.2	Relational Database Systems	4
1.1.3	Smaller and Smaller Systems	5
1.1.4	Bigger and Bigger Systems	6
1.1.5	Client-Server and Multi-Tier Architectures	7
1.1.6	Multimedia Data	8
1.1.7	Information Integration	8
1.2	Overview of a Database Management System	9
1.2.1	Data-Definition Language Commands	10
1.2.2	Overview of Query Processing	10
1.2.3	Storage and Buffer Management	12
1.2.4	Transaction Processing	13
1.2.5	The Query Processor	14
1.3	Outline of Database-System Studies	15
1.3.1	Database Design	16
1.3.2	Database Programming	17
1.3.3	Database System Implementation	17
1.3.4	Information Integration Overview	19
1.4	Summary of Chapter 1	19
1.5	References for Chapter 1	20
2	The Entity-Relationship Data Model	23
2.1	Elements of the E/R Model	24
2.1.1	Entity Sets	24
2.1.2	Attributes	25
2.1.3	Relationships	25
2.1.4	Entity-Relationship Diagrams	25
2.1.5	Instances of an E/R Diagram	27
2.1.6	Multiplicity of Binary E/R Relationships	27
2.1.7	Multiway Relationships	28
2.1.8	Roles in Relationships	29

2.1.9	Attributes on Relationships	31
2.1.10	Converting Multiway Relationships to Binary	32
2.1.11	Subclasses in the E/R Model	33
2.1.12	Exercises for Section 2.1	36
2.2	Design Principles	39
2.2.1	Faithfulness	39
2.2.2	Avoiding Redundancy	39
2.2.3	Simplicity Counts	40
2.2.4	Choosing the Right Relationships	40
2.2.5	Picking the Right Kind of Element	42
2.2.6	Exercises for Section 2.2	44
2.3	The Modeling of Constraints	47
2.3.1	Classification of Constraints	47
2.3.2	Keys in the E/R Model	48
2.3.3	Representing Keys in the E/R Model	50
2.3.4	Single-Value Constraints	51
2.3.5	Referential Integrity	51
2.3.6	Referential Integrity in E/R Diagrams	52
2.3.7	Other Kinds of Constraints	53
2.3.8	Exercises for Section 2.3	53
2.4	Weak Entity Sets	54
2.4.1	Causes of Weak Entity Sets	54
2.4.2	Requirements for Weak Entity Sets	56
2.4.3	Weak Entity Set Notation	57
2.4.4	Exercises for Section 2.4	58
2.5	Summary of Chapter 2	59
2.6	References for Chapter 2	60
3	The Relational Data Model	61
3.1	Basics of the Relational Model	61
3.1.1	Attributes	62
3.1.2	Schemas	62
3.1.3	Tuples	62
3.1.4	Domains	63
3.1.5	Equivalent Representations of a Relation	63
3.1.6	Relation Instances	64
3.1.7	Exercises for Section 3.1	64
3.2	From E/R Diagrams to Relational Designs	65
3.2.1	From Entity Sets to Relations	66
3.2.2	From E/R Relationships to Relations	67
3.2.3	Combining Relations	70
3.2.4	Handling Weak Entity Sets	71
3.2.5	Exercises for Section 3.2	75
3.3	Converting Subclass Structures to Relations	76
3.3.1	E/R-Style Conversion	77

3.3.2	An Object-Oriented Approach	78
3.3.3	Using Null Values to Combine Relations	79
3.3.4	Comparison of Approaches	79
3.3.5	Exercises for Section 3.3	80
3.4	Functional Dependencies	82
3.4.1	Definition of Functional Dependency	83
3.4.2	Keys of Relations	84
3.4.3	Superkeys	86
3.4.4	Discovering Keys for Relations	87
3.4.5	Exercises for Section 3.4	88
3.5	Rules About Functional Dependencies	90
3.5.1	The Splitting/Combining Rule	90
3.5.2	Trivial Functional Dependencies	92
3.5.3	Computing the Closure of Attributes	92
3.5.4	Why the Closure Algorithm Works	95
3.5.5	The Transitive Rule	96
3.5.6	Closing Sets of Functional Dependencies	98
3.5.7	Projecting Functional Dependencies	98
3.5.8	Exercises for Section 3.5	100
3.6	Design of Relational Database Schemas	102
3.6.1	Anomalies	103
3.6.2	Decomposing Relations	103
3.6.3	Boyce-Codd Normal Form	105
3.6.4	Decomposition into BCNF	107
3.6.5	Recovering Information from a Decomposition	112
3.6.6	Third Normal Form	114
3.6.7	Exercises for Section 3.6	117
3.7	Multivalued Dependencies	118
3.7.1	Attribute Independence and Its Consequent Redundancy	118
3.7.2	Definition of Multivalued Dependencies	119
3.7.3	Reasoning About Multivalued Dependencies	120
3.7.4	Fourth Normal Form	122
3.7.5	Decomposition into Fourth Normal Form	123
3.7.6	Relationships Among Normal Forms	124
3.7.7	Exercises for Section 3.7	126
3.8	Summary of Chapter 3	127
3.9	References for Chapter 3	129
4	Other Data Models	131
4.1	Review of Object-Oriented Concepts	132
4.1.1	The Type System	132
4.1.2	Classes and Objects	133
4.1.3	Object Identity	133
4.1.4	Methods	133
4.1.5	Class Hierarchies	134

4.2	Introduction to ODL	135
4.2.1	Object-Oriented Design	135
4.2.2	Class Declarations	136
4.2.3	Attributes in ODL	136
4.2.4	Relationships in ODL	138
4.2.5	Inverse Relationships	139
4.2.6	Multiplicity of Relationships	140
4.2.7	Methods in ODL	141
4.2.8	Types in ODL	144
4.2.9	Exercises for Section 4.2	146
4.3	Additional ODL Concepts	147
4.3.1	Multiway Relationships in ODL	148
4.3.2	Subclasses in ODL	149
4.3.3	Multiple Inheritance in ODL	150
4.3.4	Extents	151
4.3.5	Declaring Keys in ODL	152
4.3.6	Exercises for Section 4.3	155
4.4	From ODL Designs to Relational Designs	155
4.4.1	From ODL Attributes to Relational Attributes	156
4.4.2	Nonatomic Attributes in Classes	157
4.4.3	Representing Set-Valued Attributes	158
4.4.4	Representing Other Type Constructors	160
4.4.5	Representing ODL Relationships	162
4.4.6	What If There Is No Key?	164
4.4.7	Exercises for Section 4.4	164
4.5	The Object-Relational Model	166
4.5.1	From Relations to Object-Relations	166
4.5.2	Nested Relations	167
4.5.3	References	169
4.5.4	Object-Oriented Versus Object-Relational	170
4.5.5	From ODL Designs to Object-Relational Designs	172
4.5.6	Exercises for Section 4.5	172
4.6	Semistructured Data	173
4.6.1	Motivation for the Semistructured-Data Model	173
4.6.2	Semistructured Data Representation	174
4.6.3	Information Integration Via Semistructured Data	175
4.6.4	Exercises for Section 4.6	177
4.7	XML and Its Data Model	178
4.7.1	Semantic Tags	178
4.7.2	Well-Formed XML	179
4.7.3	Document Type Definitions	180
4.7.4	Using a DTD	182
4.7.5	Attribute Lists	183
4.7.6	Exercises for Section 4.7	185
4.8	Summary of Chapter 4	186

4.9	References for Chapter 4	187
5	Relational Algebra	189
5.1	An Example Database Schema	190
5.2	An Algebra of Relational Operations	191
5.2.1	Basics of Relational Algebra	192
5.2.2	Set Operations on Relations	193
5.2.3	Projection	195
5.2.4	Selection	196
5.2.5	Cartesian Product	197
5.2.6	Natural Joins	198
5.2.7	Theta-Joins	199
5.2.8	Combining Operations to Form Queries	201
5.2.9	Renaming	203
5.2.10	Dependent and Independent Operations	205
5.2.11	A Linear Notation for Algebraic Expressions	206
5.2.12	Exercises for Section 5.2	207
5.3	Relational Operations on Bags	214
5.3.1	Why Bags?	214
5.3.2	Union, Intersection, and Difference of Bags	215
5.3.3	Projection of Bags	216
5.3.4	Selection on Bags	217
5.3.5	Product of Bags	218
5.3.6	Joins of Bags	219
5.3.7	Exercises for Section 5.3	220
5.4	Extended Operators of Relational Algebra	221
5.4.1	Duplicate Elimination	222
5.4.2	Aggregation Operators	222
5.4.3	Grouping	223
5.4.4	The Grouping Operator	224
5.4.5	Extending the Projection Operator	226
5.4.6	The Sorting Operator	227
5.4.7	Outerjoins	228
5.4.8	Exercises for Section 5.4	230
5.5	Constraints on Relations	231
5.5.1	Relational Algebra as a Constraint Language	231
5.5.2	Referential Integrity Constraints	232
5.5.3	Additional Constraint Examples	233
5.5.4	Exercises for Section 5.5	235
5.6	Summary of Chapter 5	236
5.7	References for Chapter 5	237

6 The Database Language SQL	239
6.1 Simple Queries in SQL	240
6.1.1 Projection in SQL	242
6.1.2 Selection in SQL	243
6.1.3 Comparison of Strings	245
6.1.4 Dates and Times	247
6.1.5 Null Values and Comparisons Involving NULL	248
6.1.6 The Truth-Value UNKNOWN	249
6.1.7 Ordering the Output	251
6.1.8 Exercises for Section 6.1	252
6.2 Queries Involving More Than One Relation	254
6.2.1 Products and Joins in SQL	254
6.2.2 Disambiguating Attributes	255
6.2.3 Tuple Variables	256
6.2.4 Interpreting Multirelation Queries	258
6.2.5 Union, Intersection, and Difference of Queries	260
6.2.6 Exercises for Section 6.2	262
6.3 Subqueries	264
6.3.1 Subqueries that Produce Scalar Values	264
6.3.2 Conditions Involving Relations	266
6.3.3 Conditions Involving Tuples	266
6.3.4 Correlated Subqueries	268
6.3.5 Subqueries in FROM Clauses	270
6.3.6 SQL Join Expressions	270
6.3.7 Natural Joins	272
6.3.8 Outerjoins	272
6.3.9 Exercises for Section 6.3	274
6.4 Full-Relation Operations	277
6.4.1 Eliminating Duplicates	277
6.4.2 Duplicates in Unions, Intersections, and Differences	278
6.4.3 Grouping and Aggregation in SQL	279
6.4.4 Aggregation Operators	279
6.4.5 Grouping	280
6.4.6 HAVING Clauses	282
6.4.7 Exercises for Section 6.4	284
6.5 Database Modifications	286
6.5.1 Insertion	286
6.5.2 Deletion	288
6.5.3 Updates	289
6.5.4 Exercises for Section 6.5	290
6.6 Defining a Relation Schema in SQL	292
6.6.1 Data Types	292
6.6.2 Simple Table Declarations	293
6.6.3 Modifying Relation Schemas	294
6.6.4 Default Values	295

6.6.5 Indexes	295
6.6.6 Introduction to Selection of Indexes	297
6.6.7 Exercises for Section 6.6	300
6.7 View Definitions	301
6.7.1 Declaring Views	302
6.7.2 Querying Views	302
6.7.3 Renaming Attributes	304
6.7.4 Modifying Views	305
6.7.5 Interpreting Queries Involving Views	308
6.7.6 Exercises for Section 6.7	310
6.8 Summary of Chapter 6	312
6.9 References for Chapter 6	313
7 Constraints and Triggers	315
7.1 Keys and Foreign Keys	316
7.1.1 Declaring Primary Keys	316
7.1.2 Keys Declared With UNIQUE	317
7.1.3 Enforcing Key Constraints	318
7.1.4 Declaring Foreign-Key Constraints	319
7.1.5 Maintaining Referential Integrity	321
7.1.6 Deferring the Checking of Constraints	323
7.1.7 Exercises for Section 7.1	326
7.2 Constraints on Attributes and Tuples	327
7.2.1 Not-Null Constraints	328
7.2.2 Attribute-Based CHECK Constraints	328
7.2.3 Tuple-Based CHECK Constraints	330
7.2.4 Exercises for Section 7.2	331
7.3 Modification of Constraints	333
7.3.1 Giving Names to Constraints	334
7.3.2 Altering Constraints on Tables	334
7.3.3 Exercises for Section 7.3	335
7.4 Schema-Level Constraints and Triggers	336
7.4.1 Assertions	337
7.4.2 Event-Condition-Action Rules	340
7.4.3 Triggers in SQL	340
7.4.4 Instead-Of Triggers	344
7.4.5 Exercises for Section 7.4	345
7.5 Summary of Chapter 7	347
7.6 References for Chapter 7	348
8 System Aspects of SQL	349
8.1 SQL in a Programming Environment	349
8.1.1 The Impedance Mismatch Problem	350
8.1.2 The SQL/Host Language Interface	352
8.1.3 The DECLARE Section	352

8.1.4	Using Shared Variables	353
8.1.5	Single-Row Select Statements	354
8.1.6	Cursors	355
8.1.7	Modifications by Cursor	358
8.1.8	Protecting Against Concurrent Updates	360
8.1.9	Scrolling Cursors	361
8.1.10	Dynamic SQL	361
8.1.11	Exercises for Section 8.1	363
8.2	Procedures Stored in the Schema	365
8.2.1	Creating PSM Functions and Procedures	365
8.2.2	Some Simple Statement Forms in PSM	366
8.2.3	Branching Statements	368
8.2.4	Queries in PSM	369
8.2.5	Loops in PSM	370
8.2.6	For-Loops	372
8.2.7	Exceptions in PSM	374
8.2.8	Using PSM Functions and Procedures	376
8.2.9	Exercises for Section 8.2	377
8.3	The SQL Environment	379
8.3.1	Environments	379
8.3.2	Schemas	380
8.3.3	Catalogs	381
8.3.4	Clients and Servers in the SQL Environment	382
8.3.5	Connections	382
8.3.6	Sessions	384
8.3.7	Modules	384
8.4	Using a Call-Level Interface	385
8.4.1	Introduction to SQL/CLI	385
8.4.2	Processing Statements	388
8.4.3	Fetching Data From a Query Result	389
8.4.4	Passing Parameters to Queries	392
8.4.5	Exercises for Section 8.4	393
8.5	Java Database Connectivity	393
8.5.1	Introduction to JDBC	393
8.5.2	Creating Statements in JDBC	394
8.5.3	Cursor Operations in JDBC	396
8.5.4	Parameter Passing	396
8.5.5	Exercises for Section 8.5	397
8.6	Transactions in SQL	397
8.6.1	Serializability	397
8.6.2	Atomicity	399
8.6.3	Transactions	401
8.6.4	Read-Only Transactions	403
8.6.5	Dirty Reads	405
8.6.6	Other Isolation Levels	407

8.6.7	Exercises for Section 8.6	409
8.7	Security and User Authorization in SQL	410
8.7.1	Privileges	410
8.7.2	Creating Privileges	412
8.7.3	The Privilege-Checking Process	413
8.7.4	Granting Privileges	414
8.7.5	Grant Diagrams	416
8.7.6	Revoking Privileges	417
8.7.7	Exercises for Section 8.7	421
8.8	Summary of Chapter 8	422
8.9	References for Chapter 8	424
9	Object-Orientation in Query Languages	425
9.1	Introduction to OQL	425
9.1.1	An Object-Oriented Movie Example	426
9.1.2	Path Expressions	426
9.1.3	Select-From-Where Expressions in OQL	428
9.1.4	Modifying the Type of the Result	429
9.1.5	Complex Output Types	431
9.1.6	Subqueries	431
9.1.7	Exercises for Section 9.1	433
9.2	Additional Forms of OQL Expressions	436
9.2.1	Quantifier Expressions	437
9.2.2	Aggregation Expressions	437
9.2.3	Group-By Expressions	438
9.2.4	HAVING Clauses	441
9.2.5	Union, Intersection, and Difference	442
9.2.6	Exercises for Section 9.2	442
9.3	Object Assignment and Creation in OQL	443
9.3.1	Assigning Values to Host-Language Variables	444
9.3.2	Extracting Elements of Collections	444
9.3.3	Obtaining Each Member of a Collection	445
9.3.4	Constants in OQL	446
9.3.5	Creating New Objects	447
9.3.6	Exercises for Section 9.3	448
9.4	User-Defined Types in SQL	449
9.4.1	Defining Types in SQL	449
9.4.2	Methods in User-Defined Types	451
9.4.3	Declaring Relations with a UDT	452
9.4.4	References	452
9.4.5	Exercises for Section 9.4	454
9.5	Operations on Object-Relational Data	455
9.5.1	Following References	455
9.5.2	Accessing Attributes of Tuples with a UDT	456
9.5.3	Generator and Mutator Functions	457

9.5.4	Ordering Relationships on UDT's	458
9.5.5	Exercises for Section 9.5	460
9.6	Summary of Chapter 9	461
9.7	References for Chapter 9	462
10	Logical Query Languages	463
10.1	A Logic for Relations	463
10.1.1	Predicates and Atoms	463
10.1.2	Arithmetic Atoms	464
10.1.3	Datalog Rules and Queries	465
10.1.4	Meaning of Datalog Rules	466
10.1.5	Extensional and Intensional Predicates	469
10.1.6	Datalog Rules Applied to Bags	469
10.1.7	Exercises for Section 10.1	471
10.2	From Relational Algebra to Datalog	471
10.2.1	Intersection	471
10.2.2	Union	472
10.2.3	Difference	472
10.2.4	Projection	473
10.2.5	Selection	473
10.2.6	Product	476
10.2.7	Joins	476
10.2.8	Simulating Multiple Operations with Datalog	477
10.2.9	Exercises for Section 10.2	479
10.3	Recursive Programming in Datalog	480
10.3.1	Recursive Rules	481
10.3.2	Evaluating Recursive Datalog Rules	481
10.3.3	Negation in Recursive Rules	486
10.3.4	Exercises for Section 10.3	490
10.4	Recursion in SQL	492
10.4.1	Defining IDB Relations in SQL	492
10.4.2	Stratified Negation	494
10.4.3	Problematic Expressions in Recursive SQL	496
10.4.4	Exercises for Section 10.4	499
10.5	Summary of Chapter 10	500
10.6	References for Chapter 10	501
11	Data Storage	503
11.1	The "Megatron 2002" Database System	503
11.1.1	Megatron 2002 Implementation Details	504
11.1.2	How Megatron 2002 Executes Queries	505
11.1.3	What's Wrong With Megatron 2002?	506
11.2	The Memory Hierarchy	507
11.2.1	Cache	507
11.2.2	Main Memory	508

11.2.3	Virtual Memory	509
11.2.4	Secondary Storage	510
11.2.5	Tertiary Storage	512
11.2.6	Volatile and Nonvolatile Storage	513
11.2.7	Exercises for Section 11.2	514
11.3	Disks	515
11.3.1	Mechanics of Disks	515
11.3.2	The Disk Controller	516
11.3.3	Disk Storage Characteristics	517
11.3.4	Disk Access Characteristics	519
11.3.5	Writing Blocks	523
11.3.6	Modifying Blocks	523
11.3.7	Exercises for Section 11.3	524
11.4	Using Secondary Storage Effectively	525
11.4.1	The I/O Model of Computation	525
11.4.2	Sorting Data in Secondary Storage	526
11.4.3	Merge-Sort	527
11.4.4	Two-Phase, Multiway Merge-Sort	528
11.4.5	Multiway Merging of Larger Relations	532
11.4.6	Exercises for Section 11.4	532
11.5	Accelerating Access to Secondary Storage	533
11.5.1	Organizing Data by Cylinders	534
11.5.2	Using Multiple Disks	536
11.5.3	Mirroring Disks	537
11.5.4	Disk Scheduling and the Elevator Algorithm	538
11.5.5	Prefetching and Large-Scale Buffering	541
11.5.6	Summary of Strategies and Tradeoffs	543
11.5.7	Exercises for Section 11.5	544
11.6	Disk Failures	546
11.6.1	Intermittent Failures	547
11.6.2	Checksums	547
11.6.3	Stable Storage	548
11.6.4	Error-Handling Capabilities of Stable Storage	549
11.6.5	Exercises for Section 11.6	550
11.7	Recovery from Disk Crashes	550
11.7.1	The Failure Model for Disks	551
11.7.2	Mirroring as a Redundancy Technique	552
11.7.3	Parity Blocks	552
11.7.4	An Improvement: RAID 5	556
11.7.5	Coping With Multiple Disk Crashes	557
11.7.6	Exercises for Section 11.7	561
11.8	Summary of Chapter 11	563
11.9	References for Chapter 11	565

12 Representing Data Elements	567
12.1 Data Elements and Fields	567
12.1.1 Representing Relational Database Elements	568
12.1.2 Representing Objects	569
12.1.3 Representing Data Elements	569
12.2 Records	572
12.2.1 Building Fixed-Length Records	573
12.2.2 Record Headers	575
12.2.3 Packing Fixed-Length Records into Blocks	576
12.2.4 Exercises for Section 12.2	577
12.3 Representing Block and Record Addresses	578
12.3.1 Client-Server Systems	579
12.3.2 Logical and Structured Addresses	580
12.3.3 Pointer Swizzling	581
12.3.4 Returning Blocks to Disk	586
12.3.5 Pinned Records and Blocks	586
12.3.6 Exercises for Section 12.3	587
12.4 Variable-Length Data and Records	589
12.4.1 Records With Variable-Length Fields	590
12.4.2 Records With Repeating Fields	591
12.4.3 Variable-Format Records	593
12.4.4 Records That Do Not Fit in a Block	594
12.4.5 BLOBS	595
12.4.6 Exercises for Section 12.4	596
12.5 Record Modifications	598
12.5.1 Insertion	598
12.5.2 Deletion	599
12.5.3 Update	601
12.5.4 Exercises for Section 12.5	601
12.6 Summary of Chapter 12	602
12.7 References for Chapter 12	603
13 Index Structures	605
13.1 Indexes on Sequential Files	606
13.1.1 Sequential Files	606
13.1.2 Dense Indexes	607
13.1.3 Sparse Indexes	609
13.1.4 Multiple Levels of Index	610
13.1.5 Indexes With Duplicate Search Keys	612
13.1.6 Managing Indexes During Data Modifications	615
13.1.7 Exercises for Section 13.1	620
13.2 Secondary Indexes	622
13.2.1 Design of Secondary Indexes	623
13.2.2 Applications of Secondary Indexes	624
13.2.3 Indirection in Secondary Indexes	625

13.2.4 Document Retrieval and Inverted Indexes	626
13.2.5 Exercises for Section 13.2	630
13.3 B-Trees	632
13.3.1 The Structure of B-trees	633
13.3.2 Applications of B-trees	636
13.3.3 Lookup in B-Trees	638
13.3.4 Range Queries	638
13.3.5 Insertion Into B-Trees	639
13.3.6 Deletion From B-Trees	642
13.3.7 Efficiency of B-Trees	645
13.3.8 Exercises for Section 13.3	646
13.4 Hash Tables	649
13.4.1 Secondary-Storage Hash Tables	649
13.4.2 Insertion Into a Hash Table	650
13.4.3 Hash-Table Deletion	651
13.4.4 Efficiency of Hash Table Indexes	652
13.4.5 Extensible Hash Tables	652
13.4.6 Insertion Into Extensible Hash Tables	653
13.4.7 Linear Hash Tables	656
13.4.8 Insertion Into Linear Hash Tables	657
13.4.9 Exercises for Section 13.4	660
13.5 Summary of Chapter 13	662
13.6 References for Chapter 13	663
14 Multidimensional and Bitmap Indexes	665
14.1 Applications Needing Multiple Dimensions	666
14.1.1 Geographic Information Systems	666
14.1.2 Data Cubes	668
14.1.3 Multidimensional Queries in SQL	668
14.1.4 Executing Range Queries Using Conventional Indexes	670
14.1.5 Executing Nearest-Neighbor Queries Using Conventional Indexes	671
14.1.6 Other Limitations of Conventional Indexes	673
14.1.7 Overview of Multidimensional Index Structures	673
14.1.8 Exercises for Section 14.1	674
14.2 Hash-Like Structures for Multidimensional Data	675
14.2.1 Grid Files	676
14.2.2 Lookup in a Grid File	676
14.2.3 Insertion Into Grid Files	677
14.2.4 Performance of Grid Files	679
14.2.5 Partitioned Hash Functions	682
14.2.6 Comparison of Grid Files and Partitioned Hashing	683
14.2.7 Exercises for Section 14.2	684
14.3 Tree-Like Structures for Multidimensional Data	687
14.3.1 Multiple-Key Indexes	687

14.3.2	Performance of Multiple-Key Indexes	688
14.3.3	<i>kd</i> -Trees	690
14.3.4	Operations on <i>kd</i> -Trees	691
14.3.5	Adapting <i>kd</i> -Trees to Secondary Storage	693
14.3.6	Quad Trees	695
14.3.7	R-Trees	696
14.3.8	Operations on R-trees	697
14.3.9	Exercises for Section 14.3	699
14.4	Bitmap Indexes	702
14.4.1	Motivation for Bitmap Indexes	702
14.4.2	Compressed Bitmaps	704
14.4.3	Operating on Run-Length-Encoded Bit-Vectors	706
14.4.4	Managing Bitmap Indexes	707
14.4.5	Exercises for Section 14.4	709
14.5	Summary of Chapter 14	710
14.6	References for Chapter 14	711
15	Query Execution	713
15.1	Introduction to Physical-Query-Plan Operators	715
15.1.1	Scanning Tables	716
15.1.2	Sorting While Scanning Tables	716
15.1.3	The Model of Computation for Physical Operators	717
15.1.4	Parameters for Measuring Costs	717
15.1.5	I/O Cost for Scan Operators	719
15.1.6	Iterators for Implementation of Physical Operators	720
15.2	One-Pass Algorithms for Database Operations	722
15.2.1	One-Pass Algorithms for Tuple-at-a-Time Operations	724
15.2.2	One-Pass Algorithms for Unary, Full-Relation Operations	725
15.2.3	One-Pass Algorithms for Binary Operations	728
15.2.4	Exercises for Section 15.2	732
15.3	Nested-Loop Joins	733
15.3.1	Tuple-Based Nested-Loop Join	733
15.3.2	An Iterator for Tuple-Based Nested-Loop Join	733
15.3.3	A Block-Based Nested-Loop Join Algorithm	734
15.3.4	Analysis of Nested-Loop Join	736
15.3.5	Summary of Algorithms so Far	736
15.3.6	Exercises for Section 15.3	736
15.4	Two-Pass Algorithms Based on Sorting	737
15.4.1	Duplicate Elimination Using Sorting	738
15.4.2	Grouping and Aggregation Using Sorting	740
15.4.3	A Sort-Based Union Algorithm	741
15.4.4	Sort-Based Intersection and Difference	742
15.4.5	A Simple Sort-Based Join Algorithm	743
15.4.6	Analysis of Simple Sort-Join	745
15.4.7	A More Efficient Sort-Based Join	746

15.4.8	Summary of Sort-Based Algorithms	747
15.4.9	Exercises for Section 15.4	748
15.5	Two-Pass Algorithms Based on Hashing	749
15.5.1	Partitioning Relations by Hashing	750
15.5.2	A Hash-Based Algorithm for Duplicate Elimination	750
15.5.3	Hash-Based Grouping and Aggregation	751
15.5.4	Hash-Based Union, Intersection, and Difference	751
15.5.5	The Hash-Join Algorithm	752
15.5.6	Saving Some Disk I/O's	753
15.5.7	Summary of Hash-Based Algorithms	755
15.5.8	Exercises for Section 15.5	756
15.6	Index-Based Algorithms	757
15.6.1	Clustering and Nonclustering Indexes	757
15.6.2	Index-Based Selection	758
15.6.3	Joining by Using an Index	760
15.6.4	Joins Using a Sorted Index	761
15.6.5	Exercises for Section 15.6	763
15.7	Buffer Management	765
15.7.1	Buffer Management Architecture	765
15.7.2	Buffer Management Strategies	766
15.7.3	The Relationship Between Physical Operator Selection and Buffer Management	768
15.7.4	Exercises for Section 15.7	770
15.8	Algorithms Using More Than Two Passes	771
15.8.1	Multipass Sort-Based Algorithms	771
15.8.2	Performance of Multipass, Sort-Based Algorithms	772
15.8.3	Multipass Hash-Based Algorithms	773
15.8.4	Performance of Multipass Hash-Based Algorithms	773
15.8.5	Exercises for Section 15.8	774
15.9	Parallel Algorithms for Relational Operations	775
15.9.1	Models of Parallelism	775
15.9.2	Tuple-at-a-Time Operations in Parallel	777
15.9.3	Parallel Algorithms for Full-Relation Operations	779
15.9.4	Performance of Parallel Algorithms	780
15.9.5	Exercises for Section 15.9	782
15.10	Summary of Chapter 15	783
15.11	References for Chapter 15	784
16	The Query Compiler	787
16.1	Parsing	788
16.1.1	Syntax Analysis and Parse Trees	788
16.1.2	A Grammar for a Simple Subset of SQL	789
16.1.3	The Preprocessor	793
16.1.4	Exercises for Section 16.1	794

16.2 Algebraic Laws for Improving Query Plans	795
16.2.1 Commutative and Associative Laws	795
16.2.2 Laws Involving Selection	797
16.2.3 Pushing Selections	800
16.2.4 Laws Involving Projection	802
16.2.5 Laws About Joins and Products	805
16.2.6 Laws Involving Duplicate Elimination	805
16.2.7 Laws Involving Grouping and Aggregation	806
16.2.8 Exercises for Section 16.2	809
16.3 From Parse Trees to Logical Query Plans	810
16.3.1 Conversion to Relational Algebra	811
16.3.2 Removing Subqueries From Conditions	812
16.3.3 Improving the Logical Query Plan	817
16.3.4 Grouping Associative/Commutative Operators	819
16.3.5 Exercises for Section 16.3	820
16.4 Estimating the Cost of Operations	821
16.4.1 Estimating Sizes of Intermediate Relations	822
16.4.2 Estimating the Size of a Projection	823
16.4.3 Estimating the Size of a Selection	823
16.4.4 Estimating the Size of a Join	826
16.4.5 Natural Joins With Multiple Join Attributes	829
16.4.6 Joins of Many Relations	830
16.4.7 Estimating Sizes for Other Operations	832
16.4.8 Exercises for Section 16.4	834
16.5 Introduction to Cost-Based Plan Selection	835
16.5.1 Obtaining Estimates for Size Parameters	836
16.5.2 Computation of Statistics	839
16.5.3 Heuristics for Reducing the Cost of Logical Query Plans	840
16.5.4 Approaches to Enumerating Physical Plans	842
16.5.5 Exercises for Section 16.5	845
16.6 Choosing an Order for Joins	847
16.6.1 Significance of Left and Right Join Arguments	847
16.6.2 Join Trees	848
16.6.3 Left-Deep Join Trees	848
16.6.4 Dynamic Programming to Select a Join Order and Grouping	852
16.6.5 Dynamic Programming With More Detailed Cost Functions	856
16.6.6 A Greedy Algorithm for Selecting a Join Order	857
16.6.7 Exercises for Section 16.6	858
16.7 Completing the Physical-Query-Plan	859
16.7.1 Choosing a Selection Method	860
16.7.2 Choosing a Join Method	862
16.7.3 Pipelining Versus Materialization	863
16.7.4 Pipelining Unary Operations	864
16.7.5 Pipelining Binary Operations	864
16.7.6 Notation for Physical Query Plans	867

16.7.7 Ordering of Physical Operations	870
16.7.8 Exercises for Section 16.7	871
16.8 Summary of Chapter 16	872
16.9 References for Chapter 16	874
17 Coping With System Failures	875
17.1 Issues and Models for Resilient Operation	875
17.1.1 Failure Modes	876
17.1.2 More About Transactions	877
17.1.3 Correct Execution of Transactions	879
17.1.4 The Primitive Operations of Transactions	880
17.1.5 Exercises for Section 17.1	883
17.2 Undo Logging	884
17.2.1 Log Records	884
17.2.2 The Undo-Logging Rules	885
17.2.3 Recovery Using Undo Logging	889
17.2.4 Checkpointing	890
17.2.5 Nonquiescent Checkpointing	892
17.2.6 Exercises for Section 17.2	895
17.3 Redo Logging	897
17.3.1 The Redo-Logging Rule	897
17.3.2 Recovery With Redo Logging	898
17.3.3 Checkpointing a Redo Log	900
17.3.4 Recovery With a Checkpointed Redo Log	901
17.3.5 Exercises for Section 17.3	902
17.4 Undo/Redo Logging	903
17.4.1 The Undo/Redo Rules	903
17.4.2 Recovery With Undo/Redo Logging	904
17.4.3 Checkpointing an Undo/Redo Log	905
17.4.4 Exercises for Section 17.4	908
17.5 Protecting Against Media Failures	909
17.5.1 The Archive	909
17.5.2 Nonquiescent Archiving	910
17.5.3 Recovery Using an Archive and Log	913
17.5.4 Exercises for Section 17.5	914
17.6 Summary of Chapter 17	914
17.7 References for Chapter 17	915
18 Concurrency Control	917
18.1 Serial and Serializable Schedules	918
18.1.1 Schedules	918
18.1.2 Serial Schedules	919
18.1.3 Serializable Schedules	920

18.1.4	The Effect of Transaction Semantics	921
18.1.5	A Notation for Transactions and Schedules	923
18.1.6	Exercises for Section 18.1	924
18.2	Conflict-Serializability	925
18.2.1	Conflicts	925
18.2.2	Precedence Graphs and a Test for Conflict-Serializability	926
18.2.3	Why the Precedence-Graph Test Works	929
18.2.4	Exercises for Section 18.2	930
18.3	Enforcing Serializability by Locks	932
18.3.1	Locks	933
18.3.2	The Locking Scheduler	934
18.3.3	Two-Phase Locking	936
18.3.4	Why Two-Phase Locking Works	937
18.3.5	Exercises for Section 18.3	938
18.4	Locking Systems With Several Lock Modes	940
18.4.1	Shared and Exclusive Locks	941
18.4.2	Compatibility Matrices	943
18.4.3	Upgrading Locks	943
18.4.4	Update Locks	945
18.4.5	Increment Locks	946
18.4.6	Exercises for Section 18.4	949
18.5	An Architecture for a Locking Scheduler	951
18.5.1	A Scheduler That Inserts Lock Actions	951
18.5.2	The Lock Table	954
18.5.3	Exercises for Section 18.5	957
18.6	Managing Hierarchies of Database Elements	957
18.6.1	Locks With Multiple Granularity	957
18.6.2	Warning Locks	958
18.6.3	Phantoms and Handling Insertions Correctly	961
18.6.4	Exercises for Section 18.6	963
18.7	The Tree Protocol	963
18.7.1	Motivation for Tree-Based Locking	963
18.7.2	Rules for Access to Tree-Structured Data	964
18.7.3	Why the Tree Protocol Works	965
18.7.4	Exercises for Section 18.7	968
18.8	Concurrency Control by Timestamps	969
18.8.1	Timestamps	970
18.8.2	Physically Unrealizable Behaviors	971
18.8.3	Problems With Dirty Data	972
18.8.4	The Rules for Timestamp-Based Scheduling	973
18.8.5	Multiversion Timestamps	975
18.8.6	Timestamps and Locking	978
18.8.7	Exercises for Section 18.8	978

18.9	Concurrency Control by Validation	979
18.9.1	Architecture of a Validation-Based Scheduler	979
18.9.2	The Validation Rules	980
18.9.3	Comparison of Three Concurrency-Control Mechanisms	983
18.9.4	Exercises for Section 18.9	984
18.10	Summary of Chapter 18	985
18.11	References for Chapter 18	987
19	More About Transaction Management	989
19.1	Serializability and Recoverability	989
19.1.1	The Dirty-Data Problem	990
19.1.2	Cascading Rollback	992
19.1.3	Recoverable Schedules	992
19.1.4	Schedules That Avoid Cascading Rollback	993
19.1.5	Managing Rollbacks Using Locking	994
19.1.6	Group Commit	996
19.1.7	Logical Logging	997
19.1.8	Recovery From Logical Logs	1000
19.1.9	Exercises for Section 19.1	1001
19.2	View Serializability	1003
19.2.1	View Equivalence	1003
19.2.2	Polygraphs and the Test for View-Serializability	1004
19.2.3	Testing for View-Serializability	1007
19.2.4	Exercises for Section 19.2	1008
19.3	Resolving Deadlocks	1009
19.3.1	Deadlock Detection by Timeout	1009
19.3.2	The Waits-For Graph	1010
19.3.3	Deadlock Prevention by Ordering Elements	1012
19.3.4	Detecting Deadlocks by Timestamps	1014
19.3.5	Comparison of Deadlock-Management Methods	1016
19.3.6	Exercises for Section 19.3	1017
19.4	Distributed Databases	1018
19.4.1	Distribution of Data	1019
19.4.2	Distributed Transactions	1020
19.4.3	Data Replication	1021
19.4.4	Distributed Query Optimization	1022
19.4.5	Exercises for Section 19.4	1022
19.5	Distributed Commit	1023
19.5.1	Supporting Distributed Atomicity	1023
19.5.2	Two-Phase Commit	1024
19.5.3	Recovery of Distributed Transactions	1026
19.5.4	Exercises for Section 19.5	1028

19.6 Distributed Locking	1029
19.6.1 Centralized Lock Systems	1030
19.6.2 A Cost Model for Distributed Locking Algorithms	1030
19.6.3 Locking Replicated Elements	1031
19.6.4 Primary-Copy Locking	1032
19.6.5 Global Locks From Local Locks	1033
19.6.6 Exercises for Section 19.6	1034
19.7 Long-Duration Transactions	1035
19.7.1 Problems of Long Transactions	1035
19.7.2 Sagas	1037
19.7.3 Compensating Transactions	1038
19.7.4 Why Compensating Transactions Work	1040
19.7.5 Exercises for Section 19.7	1041
19.8 Summary of Chapter 19	1041
19.9 References for Chapter 19	1044
20 Information Integration	1047
20.1 Modes of Information Integration	1047
20.1.1 Problems of Information Integration	1048
20.1.2 Federated Database Systems	1049
20.1.3 Data Warehouses	1051
20.1.4 Mediators	1053
20.1.5 Exercises for Section 20.1	1056
20.2 Wrappers in Mediator-Based Systems	1057
20.2.1 Templates for Query Patterns	1058
20.2.2 Wrapper Generators	1059
20.2.3 Filters	1060
20.2.4 Other Operations at the Wrapper	1062
20.2.5 Exercises for Section 20.2	1063
20.3 Capability-Based Optimization in Mediators	1064
20.3.1 The Problem of Limited Source Capabilities	1065
20.3.2 A Notation for Describing Source Capabilities	1066
20.3.3 Capability-Based Query-Plan Selection	1067
20.3.4 Adding Cost-Based Optimization	1069
20.3.5 Exercises for Section 20.3	1069
20.4 On-Line Analytic Processing	1070
20.4.1 OLAP Applications	1071
20.4.2 A Multidimensional View of OLAP Data	1072
20.4.3 Star Schemas	1073
20.4.4 Slicing and Dicing	1076
20.4.5 Exercises for Section 20.4	1078
20.5 Data Cubes	1079
20.5.1 The Cube Operator	1079
20.5.2 Cube Implementation by Materialized Views	1082
20.5.3 The Lattice of Views	1085

20.5.4 Exercises for Section 20.5	1087
20.6 Data Mining	1088
20.6.1 Data-Mining Applications	1088
20.6.2 Finding Frequent Sets of Items	1092
20.6.3 The A-Priori Algorithm	1093
20.6.4 Exercises for Section 20.6	1096
20.7 Summary of Chapter 20	1097
20.8 References for Chapter 20	1098
Index	1101

Chapter 1

The Worlds of Database Systems

Databases today are essential to every business. They are used to maintain internal records, to present data to customers and clients on the World-Wide-Web, and to support many other commercial processes. Databases are likewise found at the core of many scientific investigations. They represent the data gathered by astronomers, by investigators of the human genome, and by biochemists exploring the medicinal properties of proteins, along with many other scientists.

The power of databases comes from a body of knowledge and technology that has developed over several decades and is embodied in specialized software called a *database management system*, or *DBMS*, or more colloquially a "database system." A DBMS is a powerful tool for creating and managing large amounts of data efficiently and allowing it to persist over long periods of time, safely. These systems are among the most complex types of software available. The capabilities that a DBMS provides the user are:

1. *Persistent storage.* Like a file system, a DBMS supports the storage of very large amounts of data that exists independently of any processes that are using the data. However, the DBMS goes far beyond the file system in providing flexibility, such as data structures that support efficient access to very large amounts of data.
2. *Programming interface.* A DBMS allows the user or an application program to access and modify data through a powerful query language. Again, the advantage of a DBMS over a file system is the flexibility to manipulate stored data in much more complex ways than the reading and writing of files.
3. *Transaction management.* A DBMS supports concurrent access to data, i.e., simultaneous access by many distinct processes (called "transac-

tions") at once. To avoid some of the undesirable consequences of simultaneous access, the DBMS supports *isolation*, the appearance that transactions execute one-at-a-time, and *atomicity*, the requirement that transactions execute either completely or not at all. A DBMS also supports *durability*, the ability to recover from failures or errors of many types.

1.1 The Evolution of Database Systems

What is a database? In essence a database is nothing more than a collection of information that exists over a long period of time, often many years. In common parlance, the term *database* refers to a collection of data that is managed by a DBMS. The DBMS is expected to:

1. Allow users to create new databases and specify their *schema* (logical structure of the data), using a specialized language called a *data-definition language*.
2. Give users the ability to *query* the data (a "query" is database lingo for a question about the data) and modify the data, using an appropriate language, often called a *query language* or *data-manipulation language*.
3. Support the storage of very large amounts of data — many gigabytes or more — over a long period of time, keeping it secure from accident or unauthorized use and allowing efficient access to the data for queries and database modifications.
4. Control access to data from many users at once, without allowing the actions of one user to affect other users and without allowing simultaneous accesses to corrupt the data accidentally.

1.1.1 Early Database Management Systems

The first commercial database management systems appeared in the late 1960's. These systems evolved from file systems, which provide some of item (3) above; file systems store data over a long period of time, and they allow the storage of large amounts of data. However, file systems do not generally guarantee that data cannot be lost if it is not backed up, and they don't support efficient access to data items whose location in a particular file is not known.

Further, file systems do not directly support item (2), a query language for the data in files. Their support for (1) — a schema for the data — is limited to the creation of directory structures for files. Finally, file systems do not satisfy (4). When they allow concurrent access to files by several users or processes, a file system generally will not prevent situations such as two users modifying the same file at about the same time, so the changes made by one user fail to appear in the file.

The first important applications of DBMS's were ones where data was composed of many small items, and many queries or modifications were made. Here are some of these applications.

Airline Reservations Systems

In this type of system, the items of data include:

1. Reservations by a single customer on a single flight, including such information as assigned seat or meal preference.
2. Information about flights — the airports they fly from and to, their departure and arrival times, or the aircraft flown, for example.
3. Information about ticket prices, requirements, and availability.

Typical queries ask for flights leaving around a certain time from one given city to another, what seats are available, and at what prices. Typical data modifications include the booking of a flight for a customer, assigning a seat, or indicating a meal preference. Many agents will be accessing parts of the data at any given time. The DBMS must allow such concurrent accesses, prevent problems such as two agents assigning the same seat simultaneously, and protect against loss of records if the system suddenly fails.

Banking Systems

Data items include names and addresses of customers, accounts, loans, and their balances, and the connection between customers and their accounts and loans, e.g., who has signature authority over which accounts. Queries for account balances are common, but far more common are modifications representing a single payment from, or deposit to, an account.

As with the airline reservation system, we expect that many tellers and customers (through ATM machines or the Web) will be querying and modifying the bank's data at once. It is vital that simultaneous accesses to an account not cause the effect of a transaction to be lost. Failures cannot be tolerated. For example, once the money has been ejected from an ATM machine, the bank must record the debit, even if the power immediately fails. On the other hand, it is not permissible for the bank to record the debit and then not deliver the money if the power fails. The proper way to handle this operation is far from obvious and can be regarded as one of the significant achievements in DBMS architecture.

Corporate Records

Many early applications concerned corporate records, such as a record of each sale, information about accounts payable and receivable, or information about employees — their names, addresses, salary, benefit options, tax status, and

Offset 572-573
 Offset table 580-581, 598
 OID
 See Object identifier
 OLAP 1047, 1070-1089
 See also MOLAP, ROLAP
 OLD ROW/TABLE 341-344
 Olken, F. 785
 OLTP 1070
 ON 271
 On-demand swizzling 585
 O'Neil, E. 424
 O'Neil, P. 424, 712
 One-one relationship 28-29, 140-141
 One-pass algorithm 722-733, 850, 862
 On-line analytic processing
 See OLAP
 On-line transaction processing
 See OLTP
 Open 720
 Operand 192
 Operator 192
 Optical disk 512-513
 Optimistic concurrency control
 See Timestamp, Validation
 Optimization
 See Query optimization
 OQL 425-449, 570
 ORDER BY 251-252, 284
 Ordering relationship, for UDT 458-460
 Outerjoin 222, 228-230, 272-274
 Output action 881, 918
 Output attribute 802
 Overflow block 599, 616-617, 619, 649, 656
 Overloaded method 142
 Ozsü, M. T. 1045

P

Pad character 570
 Page 509
 See also Disk block
 Palermo, F. P. 874

Papadimitriou, C. H. 987, 1044
 Papakonstantinou, Y. 188, 1099
 Parallel computing 6-7, 775-782, 983
 Parameter 392, 396-397
 Parity bit 548, 552-553
 Parse tree 788-789, 810
 Parser 713-715, 788-795
 Partial-match query 667, 681, 684, 688-689, 692
 Partition attribute 438
 Partitioned hash function 666, 682-684
 Pascal 350
 Path expression 426, 428
 Paton, N. W. 348
 Pattern 791
 Patterson, D. A. 566
 PCDATA 180
 Pelagatti, G. 1044
 Pelzer, T. 314
 Percentiles
 See Equal-height histogram
 Persistence 1, 301
 Persistent stored modules
 See PSM
 Peterson, W. W. 664
 Phantom 961-962
 Physical address 579, 582
 Physical query plan 714-715, 787, 821, 842-845, 859-872
 Piatetsky-Shapiro, G. 1099
 Pinned block 586-587, 768, 995
 Pipelining 859, 863-867
 See also Iterator
 Pippenger, N. 663
 Pirahesh, H. 348, 502, 916, 1044, 1099
 Plan selection 1022
 See also Algorithm selection. Capability-based plan selection. Cost-based enumeration. Cost-based plan selection. Heuristic plan selection. Physical query plan. Top-down plan selection

Platter; 515 517
 PL/I 350
 Pointer swizzling
 See Swizzling
 Polygraph 1004-1008
 Precedence graph 926-930
 Precommitted transaction 1025
 Predicate 463-464
 Prefetching
 See Double-buffering
 PREPARE 362, 392
 Prepared statement 394-395
 Preprocessor 793-794
 Preservation, of FD's 115-116, 125
 Preservation of value sets 827
 Price, T. G. 874
 Primary index 622
 See also Dense index, Sparse index
 Primary key 48, 316-317, 319, 576, 606
 Primary-copy locking 1032-1033
 PRIOR 361
 Privilege 410-421
 Probe relation 847, 850
 Procedure 365, 376-377
 Product 192-193, 197-198, 218, 254-255, 476, 730, 737, 796, 798-799, 803, 805, 832
 Projection 112-113, 192-193, 195, 205, 216-217, 242, 245, 473, 724-725, 737, 802-805, 823, 832, 864
 See also Extended projection, Pushing projections
 Projection, of FD's 98-100
 Prolog 501
 Pseudotransitivity 101
 PSM 349, 365-378
 PUBLIC 410
 Pushing projections 802-804, 818
 Pushing selections 797, 800-801, 818
 Putzolo, F. 566, 988

Q

Quad tree 666, 695-696
 Quantifier
 See ALL, ANY, EXISTS
 Quass, D. 187, 237, 712, 785, 1099
 Query 297, 466, 504-505
 See also Decision-support query, Lookup, Nearest-neighbor query, Partial-match query, Range query, Where-am-I query
 Query compiler 10, 14-15, 713-715, 787
 See also Query optimization
 Query execution 713, 870-871
 Query language 2, 10
 See also Datalog, OQL, Relational algebra, SQL
 Query optimization 15, 714-715
 See also Plan selection
 Query plan 10, 14
 See also Logical query plan, Physical query plan, Plan selection
 Query processing 17-18, 506
 See also Execution engine, Query compiler
 Query processor
 See Query compiler, Query execution
 Query rewriting 714-715, 788, 810-821
 See also Algebraic law
 Quicksort 527
 Quotient 213

R

RAID 551-563, 876-877
 Rajaraman, A. 1099
 RAM disk 514
 Ramakrishnan, R. 502
 Random-access memory 508
 Range query 638-639, 652, 667, 673, 681, 689, 692-693

- Raw-data cube 1072
 - See also Data cube, Fact table
- Read action 881, 918
- READ COMMITTED 407-408
- Read lock
 - See Shared lock
- Read set 979
- Read time 970
- READ UNCOMMITTED 407-408
- Read-locks-one-write-locks-all 1034
- Read-only transaction 403-404, 958
- Real number 293, 569
- Record 567, 572-577, 598-601
 - See also Sliding records, Spanned record, Tagged field, Variable-format record, Variable-length record
- Record address
 - See Database address
- Record fragment 595
- Record header 575-576
- Record structure
 - See Struct
- Recoverable schedule 992-994
- Recovery 12, 875, 889-890, 898-902, 904-905, 913, 990, 1000-1001, 1026-1028
- Recovery manager 879
- Recursion 463, 480-500
- Redo logging 887, 897-903
- Redundancy 39-40, 103, 118-119, 125
- Redundant arrays of independent disks
 - See RAID
- Redundant disk 552
- Reference 133, 167, 169-171, 452, 455-456
- Reference column 452-454
- REFERENCES 320, 410
- REFERENCING 341
- Referential integrity 47, 51-53, 232
 - See also Foreign key
- Reflexivity 99
- Relation 61, 303, 463, 791, 793-794
 - See also Build relation, Dimension table, Fact table, Probe relation, Table, View
- Relation schema 62, 66, 73, 194, 292-301
- Relational algebra 189-237, 259-260, 463, 471-480, 795-808, 811
- Relational atom 464
- Relational database schema 24, 62, 190-191, 379-381, 383
- Relational model 4-5, 61-130, 155-164, 173
 - See also Nested relation, Object-relational model
- Relational OLAP
 - See ROLAP
- Relationship 25, 31-32, 40-44, 67-70, 138-141, 162-163
 - See also Binary relationship, Is a relationship, Many-many relationship, Many-one relationship, Multiway relationship, One-one relationship, Supporting relationship
- Relationship set 27
- RELATIVE 361
- Renaming 193, 203-205, 304-305
- REPEAT 373
- REPEATABLE READ 407-408
- Repeating field 590-593
- Replicated data 1021, 1031-1032
- Resilience 875
- RETURN 367
- Reuter, A. 916, 988
- Revoking privileges 417-421
- Right outerjoin 228, 273
- Right-deep join tree 848
- Right-recursion 484
- Rivest, R. L. 712
- Robinson, J. T. 712, 988
- ROLAP 1073
- Role 29-31
- Rollback 402, 404-405
 - See also Abort, Cascading rollback
- Roll-up 1079

- Root 174, 633
 - Root tag 179
 - Rosenkrantz, D. J. 1045
 - Rotation, of disk 517
 - Rotational latency 520, 540
 - See also Latency
 - Rothnie, J. B. Jr. 712, 987
 - Roussopoulos, N. 712
 - Row-level trigger 342
 - R-tree 666, 696-699
 - Rule 465-468
 - Run-length encoding 704-707
- S**
- Safe rule 467, 482
 - Saga 1037-1040
 - Sagiv, Y. 1099
 - Salem, K. 566, 1044
 - Salton, G. 664
 - Schedule 918, 923-924
 - See also Serial schedule, Serializable schedule
 - Scheduler 917, 932, 934-936, 951-957, 969, 973-975, 979-980
 - Schema 49, 85, 167, 173, 504, 572, 575
 - See also Database schema, Global schema, Relation schema, Relational database schema, Star schema
 - Schneider, R. 711
 - Schwarz, P. 916, 1044
 - Scope, of names 269
 - Scrolling cursor 361
 - Search key 605-606, 612, 614, 623, 665
 - See also Hash key
 - Second normal form 116
 - Secondary index 622-625
 - See also Inverted index
 - Secondary storage 6, 510-513
 - See also Disk, Optical disk
 - Second-chance algorithm
 - See Clock algorithm
 - Sector 516, 518
 - Seeger, B. 711
 - Seek time 519-520, 535, 540
 - SELECT 240-243, 284, 410, 428, 431-432, 789-790
 - See also Single-row select
 - Selection 192-193, 196, 205, 217-218, 221, 241, 243, 245-246, 473-475, 724-725, 737, 758-760, 777-779, 797-801, 805, 818, 823-826, 844, 860-862, 864, 868
 - See also Filter, Pushing selections, Two-argument selection
 - Selectivity, of a join 858
 - Self-describing data 175
 - Selinger, P. G. 874
 - See also Griffiths, P. P.
 - Selinger-style optimization 845, 857
 - Sellis, T. K. 712
 - Semantic analysis
 - See Preprocessor
 - Semijoin 213
 - Semistructured data 16, 131, 173-178
 - Sequential file 606-607
 - Serial schedule 919-920
 - Serializability 397-400, 407, 918, 921-923, 927, 989-990
 - See also Conflict-serializability, View-serializability
 - Serializable schedule 920-921, 994
 - Server 7, 382
 - See also Client-server system
 - Session 384, 413
 - SET 289, 325, 367-368, 381, 383-384, 404, 729, 797-798, 803
 - Set type 144-145, 158-160, 166-167, 217, 446
 - Sethi, R. 789
 - Set-null policy 322
 - Sevcik, K. 712
 - Shapiro, L. D. 785
 - Shared disk 776, 778
 - Shared lock 940-942, 956

- Shared memory 775-776, 778
- Shared variable 352-354
- Shared-nothing machine 776-777
- Shaw, D. E. 785
- Sheth, A. 1099
- Signature 141-142
- Silberschatz, A. 988
- Silo 512
- Simon, A. R. 314
- Simple projection 802
- Simplicity 40
- Single-row select 354, 370
- Single-value constraint 47, 51
 - See also Functional dependency, Many-one relationship
- Size estimation 822-834, 836-839
- Size, of a relation 717, 822, 840, 842
- Skeen, D. 1045
- Slicing 1076-1078
- Sliding records 616
- Smalltalk 132
- Smith, J. M. 874
- Smyth, P. 1099
- Snodgrass, R. T. 712
- Sort join 743-747, 844, 862-863
- Sort key 526, 606, 636
- Sorted file
 - See Sequential file
- Sorted sublist 529, 738, 770
- Sorting 222, 227-228, 526-532, 737-749, 755-756, 771-773, 845
 - See also ORDER BY, Ordering relationship, for UDT
- Sort-scan 716-717, 719, 721-722, 868
- Source 1047
- Spanned record 594-595
- Sparse index 609-612, 622, 636
- Splitting law 797-798
- Splitting nodes 640-642, 645, 698-699
- Splitting rule 90-91
- SQL 4-5, 131, 189, 239-424, 449-461, 492-500, 789-793
- SQL agent 385
- SQLSTATE 352-353, 356, 374
- Srikant, R. 1099
- Stable storage 548-550
- Star schema 1073-1075
- Start action 884
- START TRANSACTION 402
- Start-checkpoint action 893
- Start-dump action 911
- Starvation 1016-1017
- State, of a database 879, 1039
- Statement record 386-388
- Statement-level trigger 342
- Statistics 13, 836, 839-840
 - See also Histogram
- Stearns, R. E. 1045
- Stemming 629
- Stern, R. C. 210
- Stonebraker, M. 21, 785, 1045
- Stop word 629
- Storage manager 12, 17-18
 - See also Buffer
- Stratified negation 486-490, 494-496
- Strict locking 994
- String 245-247, 292
 - See also Bit string
- Stripe 676
- Striping 596
- Strong, H. R. 663
- Struct 132-133, 137-138, 144-145, 157, 166-167, 431, 446, 568
- Structured address 580-581
- Sturgis, H. 566, 1044
- Subclass 33-36, 76-80, 149-151
- Subgoal 465
- Subquery 264-276, 431-432, 812-819
 - See also Correlated subquery
- Subrahmanian, V. S. 712
- Suciu, D. 187-188, 1099
- Sum 223, 279, 437
- Superkey 86, 105
- Support 1093
- Supporting relationship 56, 72, 74-75
- Swami, A. 1099
- Swizzling 581-586

- Syntactic category 788-789
- Syntax analysis
 - See Parser
- System failure 876-877
- System R 21, 314, 874
- T**
- Table 293, 301, 303
 - See also Relation
- Table-scan 716, 719, 721, 861-862, 867-868
- Tag 178
- Tagged field 593
- Tanaka, H. 785
- Tape 512
- Template 1058-1059
- Tertiary memory 512-513
- Tertiary storage 6
- Thalheim, B. 60
- THEN 368
- Theta-join 199-201, 205, 220, 477, 731, 796-799, 802, 805, 819-820, 826-827
- Theta-outerjoin 229
- Third normal form
 - See 3NF
- Thomas, R. H. 1045
- Thomasian, A. 988
- Thrashing 766
- 3NF 114-116, 124-125
- Three-valued logic 249-251
- Thuraisingham, B. 988
- TIME 247-248, 293, 571-572
- Timeout 1009-1010
- TIMESTAMP 248, 575, 577, 969-979, 984, 1014-1017
- Tombstone 581, 600
- Top-down plan selection 843
- TPMMS
 - See Two-phase, multiway merge-sort
- Track 515-517, 579
- Traiger, I. L. 987-988
- Training set 1091

- Transaction 1-2, 12, 17-19, 397-409, 877-883, 923-924, 1020-1021
 - See also Incomplete transaction, Long-duration transaction
- Transaction component 1020
- Transaction manager 878, 917
- Transaction processing
 - See Concurrency, Deadlock, Locking, Logging, Scheduling
- Transfer time 520, 535
- Transitive rule 96-97, 121
- Translation table 582-583
- Tree
 - See B-tree, Bushy tree, Decision tree, Expression tree, Join tree, *kd*-tree, Left-deep join tree, Parse tree, Quad tree, Right-deep join tree, R-tree
- Tree protocol 963-969
- Trigger 315, 336, 340-345, 410-411, 876, 879
- Trivial FD 92, 105
- Trivial MVD 120-122, 127
- Tuple 62-63, 170
 - See also Dangling tuple
- Tuple variable 256-257
- Tuple-based check 327, 330-331, 339
- Turing-complete language 189
- Two-argument selection 812-817
- Two-pass algorithm 737-757
- Two-phase commit 1024-1028
- Two-phase locking 936-938
- Two-phase, multiway merge-sort 0, 528-532, 536-537
- Type 794, 1049
- Type constructor 132
- Type system 132-133, 144-146, 171
- U**
- UDT 449-452
- Ullman, J. D. 21, 130, 474, 502, 530, 726, 789, 852, 1099-1100
- UNDER 410-411
- UNDO 375

Undo logging 884-896
 Undo/redo logging 887, 903-909
 Union 192-194, 215-217, 260-262,
 278, 442, 472, 722-723, 728-
 729, 741, 747, 751-752, 755,
 779, 796-798, 803, 833
 Union rule 127
 UNIQUE 316-319
 UNKNOWN 249-251
 Unknown value 248
 Unstratified negation
 See Stratified negation
 Unswizzling 586
 Updatable view 305-307
 Update 289-290, 410, 601, 615-616,
 709, 1052
 See also Modification
 Update anomaly 103
 Update lock 945-946
 Update record 885-886, 897, 903
 Upgrading locks 943-945, 957
 See also Update lock
 USAGE 410
 User-defined type
 See UDT
 Uthurusamy, R. 1099

V

Valduries, P. 1045
 Valid XML 178-179
 Validation 969, 979-985
 Value count 719, 822, 840
 VALUES 286
 Van Gelder, A. 502
 VARCHAR 292
 Variable-format record 590, 593-594
 Variable-length record 570-571, 589-
 594, 998-999
 Vassalos, V. 1099
 Vertical decomposition 1020
 Vianu, V. 21
 View 301-312, 345, 1053
 See also Materialized view
 View-serializability 1003-1009
 Virtual memory 509-510, 578

Vitter, J. S. 566
 Volatile storage 513-514

W

Wade, B. W. 424
 Wait-die 1014-1017
 Waiting bit 955
 Waits-for graph 1010-1012
 Walker, A. 502
 Warehouse 1048, 1051-1053, 1071
 Warning protocol 958-961
 Weak entity set 54-59, 71-75, 154
 Weiner, J. L. 187
 Well-formed XML 178-180
 Westwood, J. N. 210
 WHEN 340, 342
 WHERE 240-241, 243-244, 264, 284,
 288, 428-429, 789
 Where-am-I query 667, 697
 WHILE 373
 White, S. 424
 Widom, J. 187-188, 348, 1099
 Wiederhold, G. 604, 1100
 WITH 492-493
 Wong, E. 21, 874
 Wood, D. 785
 Workflow 1036
 World-Wide-Web consortium 187
 Wound-wait 1014-1017
 Wrapper 1048, 1057-1064
 Wrapper generator 1059-1060
 Write action 881, 918
 Write failure 546, 550
 See also System failure
 Write lock
 See Exclusive lock
 Write set 979
 Write time 970
 Write-ahead logging rule 897
 See also Redo logging
 Write-through cache 508

X

XML 16, 131-132, 173, 178-186, 629

Y

Yerneni, R. 1100
 Youssefi, K. 874

Z

Zaniolo, C. 130, 712
 Zicari, R. 712
 Zig-zag join 762-763
 Zip disk 513
 Zipfian distribution 632, 825