Contents

Preface xiii

I Preliminaries 1

1 Data Structures and Algorithms 3
  1.1 A Philosophy of Data Structures 4
    1.1.1 The Need for Data Structures 4
    1.1.2 Costs and Benefits 6
  1.2 Abstract Data Types and Data Structures 8
  1.3 Design Patterns 12
    1.3.1 Flyweight 13
    1.3.2 Visitor 14
    1.3.3 Composite 15
    1.3.4 Strategy 16
  1.4 Problems, Algorithms, and Programs 17
  1.5 Further Reading 19
  1.6 Exercises 21

2 Mathematical Preliminaries 25
  2.1 Sets and Relations 25
  2.2 Miscellaneous Notation 29
  2.3 Logarithms 31
  2.4 Summations and Recurrences 33
## Contents

2.5 Recursion 36
2.6 Mathematical Proof Techniques 39
  2.6.1 Direct Proof 40
  2.6.2 Proof by Contradiction 40
  2.6.3 Proof by Mathematical Induction 41
2.7 Estimating 47
2.8 Further Reading 49
2.9 Exercises 50

3 Algorithm Analysis 57
  3.1 Introduction 57
  3.2 Best, Worst, and Average Cases 63
  3.3 A Faster Computer, or a Faster Algorithm? 65
  3.4 Asymptotic Analysis 67
    3.4.1 Upper Bounds 68
    3.4.2 Lower Bounds 70
    3.4.3 $\Theta$ Notation 71
    3.4.4 Simplifying Rules 72
    3.4.5 Classifying Functions 73
  3.5 Calculating the Running Time for a Program 74
  3.6 Analyzing Problems 79
  3.7 Common Misunderstandings 81
  3.8 Multiple Parameters 83
  3.9 Space Bounds 84
  3.10 Speeding Up Your Programs 86
  3.11 Empirical Analysis 89
  3.12 Further Reading 90
  3.13 Exercises 91
  3.14 Projects 95

II Fundamental Data Structures 97

4 Lists, Stacks, and Queues 99
### 5.6.2 Assigning and Using Huffman Codes

<table>
<thead>
<tr>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.6.2 Assigning and Using Huffman Codes</td>
</tr>
</tbody>
</table>

### 5.7 Further Reading

<table>
<thead>
<tr>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.7 Further Reading</td>
</tr>
</tbody>
</table>

### 5.8 Exercises

<table>
<thead>
<tr>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.8 Exercises</td>
</tr>
</tbody>
</table>

### 5.9 Projects

<table>
<thead>
<tr>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.9 Projects</td>
</tr>
</tbody>
</table>

### 6 Non-Binary Trees

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1 General Tree Definitions and Terminology</td>
<td>205</td>
</tr>
<tr>
<td>6.2 The Parent Pointer Implementation</td>
<td>208</td>
</tr>
<tr>
<td>6.3 General Tree Implementations</td>
<td>216</td>
</tr>
<tr>
<td>6.4 $K$-ary Trees</td>
<td>221</td>
</tr>
<tr>
<td>6.5 Sequential Tree Implementations</td>
<td>223</td>
</tr>
<tr>
<td>6.6 Further Reading</td>
<td>226</td>
</tr>
<tr>
<td>6.7 Exercises</td>
<td>226</td>
</tr>
<tr>
<td>6.8 Projects</td>
<td>230</td>
</tr>
</tbody>
</table>

### III Sorting and Searching

#### 7 Internal Sorting

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.1 Sorting Terminology and Notation</td>
<td>235</td>
</tr>
<tr>
<td>7.2 Three $\Theta(n^2)$ Sorting Algorithms</td>
<td>236</td>
</tr>
<tr>
<td>7.3 Shellsort</td>
<td>237</td>
</tr>
<tr>
<td>7.4 Mergesort</td>
<td>238</td>
</tr>
<tr>
<td>7.5 Quicksort</td>
<td>239</td>
</tr>
</tbody>
</table>
viii

Contents

9.5 Further Reading 351
9.6 Exercises 352
9.7 Projects 355

10 Indexing 357
  10.1 Linear Indexing 359
  10.2 ISAM 361
  10.3 Tree-based Indexing 364
  10.4 2-3 Trees 366
  10.5 B-Trees 372
    10.5.1 B+-Trees 375
    10.5.2 B-Tree Analysis 381
  10.6 Further Reading 382
  10.7 Exercises 382
  10.8 Projects 385

IV Advanced Data Structures 387

11 Graphs 389
  11.1 Terminology and Representations 390
  11.2 Graph Implementations 394
  11.3 Graph Traversals 397
    11.3.1 Depth-First Search 400
    11.3.2 Breadth-First Search 401
    11.3.3 Topological Sort 405
  11.4 Shortest-Paths Problems 407
    11.4.1 Single-Source Shortest Paths 407
  11.5 Minimum-Cost Spanning Trees 411
    11.5.1 Prim’s Algorithm 412
    11.5.2 Kruskal’s Algorithm 415
  11.6 Further Reading 416
  11.7 Exercises 416
  11.8 Projects 420
12 Lists and Arrays Revisited 423
  12.1 Multilists 423
  12.2 Matrix Representations 427
  12.3 Memory Management 430
    12.3.1 Dynamic Storage Allocation 431
    12.3.2 Failure Policies and Garbage Collection 438
  12.4 Further Reading 443
  12.5 Exercises 444
  12.6 Projects 445

13 Advanced Tree Structures 447
  13.1 Tries 447
  13.2 Balanced Trees 452
    13.2.1 The AVL Tree 453
    13.2.2 The Splay Tree 455
  13.3 Spatial Data Structures 459
    13.3.1 The K-D Tree 461
    13.3.2 The PR quadtree 466
    13.3.3 Other Point Data Structures 471
    13.3.4 Other Spatial Data Structures 471
  13.4 Further Reading 473
  13.5 Exercises 473
  13.6 Projects 475

V Theory of Algorithms 479

14 Analysis Techniques 481
  14.1 Summation Techniques 482
  14.2 Recurrence Relations 487
    14.2.1 Estimating Upper and Lower Bounds 487
    14.2.2 Expanding Recurrences 491
    14.2.3 Divide and Conquer Recurrences 492
    14.2.4 Average-Case Analysis of Quicksort 495
Contents

16.6 Exercises 551
16.7 Projects 552

17 Limits to Computation 553
17.1 Reductions 554
17.2 Hard Problems 559
  17.2.1 The Theory of $\mathcal{NP}$-Completeness 560
  17.2.2 $\mathcal{NP}$-Completeness Proofs 565
  17.2.3 Coping with $\mathcal{NP}$-Complete Problems 569
17.3 Impossible Problems 573
  17.3.1 Uncountability 574
  17.3.2 The Halting Problem Is Unsolvable 577
17.4 Further Reading 581
17.5 Exercises 581
17.6 Projects 584

Bibliography 585

Index 591