

# Contents

|                                        |     |
|----------------------------------------|-----|
| <b>Preface to Second Edition</b> ..... | vii |
|----------------------------------------|-----|

|                                       |    |
|---------------------------------------|----|
| <b>Preface to First Edition</b> ..... | xi |
|---------------------------------------|----|

---

## Part I Preliminary Concepts

---

|                                                     |    |
|-----------------------------------------------------|----|
| <b>1 Why Queues Rule Performance Analysis</b> ..... | 3  |
| 1.1 Introduction .....                              | 3  |
| 1.2 Buffers Are Queues .....                        | 3  |
| 1.3 Modeling Efficiencies .....                     | 4  |
| 1.4 Bandwidth and Latency Are Related .....         | 8  |
| 1.5 Stretch Factor .....                            | 14 |
| 1.6 How Long Should My Queue Be? .....              | 15 |
| 1.7 A Brief History of Buffers .....                | 18 |
| <b>2 Measurement Tools and Techniques</b> .....     | 23 |
| 2.1 Steady as She Goes .....                        | 23 |
| 2.2 Performance Counters and Objects .....          | 26 |
| 2.3 Java Bytecode Instrumentation .....             | 27 |
| 2.4 Generic Performance Tools .....                 | 27 |
| 2.5 Displaying Performance Metrics .....            | 28 |
| 2.6 Storing Performance Metrics .....               | 30 |
| 2.7 Performance Prediction Tools .....              | 30 |
| 2.8 How Accurate Are Your Data? .....               | 31 |
| 2.9 Are Your Data Poissonian? .....                 | 31 |
| 2.10 Performance Measurement Standards .....        | 34 |
| <b>3 Time—The Zeroth Performance Metric</b> .....   | 37 |
| 3.1 Introduction .....                              | 37 |
| 3.2 What Is Time? .....                             | 38 |

|       |                                          |    |
|-------|------------------------------------------|----|
| 3.2.1 | Physical Time.....                       | 39 |
| 3.2.2 | Synchronization and Causality .....      | 39 |
| 3.2.3 | Discrete and Continuous Time .....       | 40 |
| 3.2.4 | Time Scales.....                         | 40 |
| 3.3   | What Is a Clock?.....                    | 42 |
| 3.3.1 | Physical Clocks .....                    | 42 |
| 3.3.2 | Distributed Physical Clocks.....         | 43 |
| 3.3.3 | Distributed Processing .....             | 43 |
| 3.3.4 | Binary Precedence.....                   | 44 |
| 3.3.5 | Logical Clocks .....                     | 44 |
| 3.3.6 | Clock Ticks .....                        | 46 |
| 3.3.7 | Virtual Clocks .....                     | 47 |
| 3.4   | Representations of Time.....             | 48 |
| 3.4.1 | In the Beginning .....                   | 48 |
| 3.4.2 | Making a Date With Perl.....             | 48 |
| 3.4.3 | High-Resolution Timing .....             | 50 |
| 3.4.4 | Benchmark Timers .....                   | 52 |
| 3.4.5 | Crossing Time Zones.....                 | 53 |
| 3.5   | Time Distributions .....                 | 56 |
| 3.5.1 | Gamma Distribution .....                 | 56 |
| 3.5.2 | Exponential Distribution .....           | 57 |
| 3.5.3 | Poisson Distribution .....               | 59 |
| 3.5.4 | Server Response Time Distribution .....  | 60 |
| 3.5.5 | Network Response Time Distribution ..... | 62 |
| 3.6   | Timing Chains and Bottlenecks .....      | 63 |
| 3.6.1 | Bottlenecks and Queues .....             | 64 |
| 3.6.2 | Distributed Instrumentation .....        | 65 |
| 3.6.3 | Disk Timing Chains .....                 | 65 |
| 3.6.4 | Life and Times of an NFS Operation ..... | 66 |
| 3.7   | Failing Big Time .....                   | 68 |
| 3.7.1 | Hardware Availability .....              | 68 |
| 3.7.2 | Tyranny of the Nines .....               | 69 |
| 3.7.3 | Hardware Reliability .....               | 69 |
| 3.7.4 | Mean Time Between Failures .....         | 71 |
| 3.7.5 | Distributed Hardware .....               | 72 |
| 3.7.6 | Components in Series .....               | 72 |
| 3.7.7 | Components in Parallel .....             | 73 |
| 3.7.8 | Software Reliability .....               | 73 |
| 3.8   | Metastable Lifetimes .....               | 75 |
| 3.8.1 | Microscopic Metastability .....          | 75 |
| 3.8.2 | Macroscopic Metastability .....          | 78 |
| 3.8.3 | Metastability in Networks .....          | 78 |
| 3.8.4 | Quantum-like Phase Transitions .....     | 80 |
| 3.9   | Review.....                              | 80 |
|       | Exercises .....                          | 81 |

---

**Part II Basic Queueing Theory for PDQ**


---

|          |                                      |           |
|----------|--------------------------------------|-----------|
| <b>4</b> | <b>Getting the Jump on Queueing</b>  | <b>85</b> |
| 4.1      | Introduction                         | 85        |
| 4.2      | What Is a Queue?                     | 86        |
| 4.3      | The Grocery Store—Checking It Out    | 87        |
| 4.3.1    | Queueing Analysis View               | 87        |
| 4.3.2    | Perceptions and Deceptions           | 88        |
| 4.3.3    | The Post Office—Snail Mail           | 89        |
| 4.4      | Fundamental Metric Relationships     | 89        |
| 4.4.1    | Performance Measures                 | 90        |
| 4.4.2    | Arrival Rate                         | 92        |
| 4.4.3    | System Throughput                    | 93        |
| 4.4.4    | Nodal Throughput                     | 94        |
| 4.4.5    | Relative Throughput                  | 94        |
| 4.4.6    | Service Time                         | 96        |
| 4.4.7    | Service Demand                       | 96        |
| 4.4.8    | Utilization                          | 97        |
| 4.4.9    | Residence Time                       | 97        |
| 4.5      | Little's Law Means a Lot             | 98        |
| 4.5.1    | A Little Intuition                   | 99        |
| 4.5.2    | A Visual Proof                       | 100       |
| 4.5.3    | Little's Microscopic Law             | 104       |
| 4.5.4    | Little's Macroscopic Law             | 105       |
| 4.6      | Unlimited Request (Open) Queues      | 106       |
| 4.6.1    | Single Server Queue                  | 106       |
| 4.6.2    | Measured Service Demand              | 107       |
| 4.6.3    | Queueing Delays                      | 107       |
| 4.6.4    | Twin Queueing Facility               | 112       |
| 4.6.5    | Parallel Queues                      | 113       |
| 4.6.6    | Dual Server Queue—Heuristic Analysis | 115       |
| 4.7      | Multiserver Queue                    | 119       |
| 4.7.1    | Erlang's $C$ Formula                 | 120       |
| 4.7.2    | Accuracy of the Heuristic Formula    | 122       |
| 4.7.3    | Erlang's $B$ Formula                 | 122       |
| 4.7.4    | Erlang Algorithms in Perl            | 124       |
| 4.7.5    | Dual Server Queue—Exact Analysis     | 127       |
| 4.8      | Limited Request (Closed) Queues      | 128       |
| 4.8.1    | Closed Queueing Facility             | 128       |
| 4.8.2    | Interactive Response Time Law        | 129       |
| 4.8.3    | Repairman Algorithm in Perl          | 131       |
| 4.8.4    | Response Time Characteristic         | 131       |
| 4.8.5    | Throughput Characteristic            | 133       |
| 4.8.6    | Finite Response Times                | 135       |

|          |                                              |            |
|----------|----------------------------------------------|------------|
| 4.8.7    | Approximating Closed Queues                  | 136        |
| 4.9      | Shorthand for Queues                         | 140        |
| 4.9.1    | Queue Schematics                             | 140        |
| 4.9.2    | Kendall Notation                             | 141        |
| 4.10     | Comparative Performance                      | 142        |
| 4.10.1   | Multiserver Versus Uniserver                 | 143        |
| 4.10.2   | Multiqueue Versus Multiserver                | 143        |
| 4.10.3   | The Envelope Please!                         | 145        |
| 4.11     | Generalized Servers                          | 146        |
| 4.11.1   | Infinite Capacity (IS) Server                | 147        |
| 4.11.2   | Exponential (M) Server                       | 148        |
| 4.11.3   | Deterministic (D) Server                     | 148        |
| 4.11.4   | Uniform (U) Server                           | 149        |
| 4.11.5   | Erlang- $k$ ( $E_k$ ) Server                 | 149        |
| 4.11.6   | Hypoexponential ( <i>Hypo</i> - $k$ ) Server | 150        |
| 4.11.7   | Hyperexponential ( $H_k$ ) Server            | 150        |
| 4.11.8   | Coxian ( <i>Cox</i> - $k$ ) Server           | 151        |
| 4.11.9   | General (G) Server                           | 152        |
| 4.11.10  | Pollaczek–Khintchine Formula                 | 153        |
| 4.11.11  | Polling Systems                              | 155        |
| 4.11.12  | Queues and Scalability                       | 157        |
| 4.12     | Review                                       | 159        |
|          | Exercises                                    | 159        |
| <b>5</b> | <b>Queueing Systems for Computer Systems</b> | <b>161</b> |
| 5.1      | Introduction                                 | 161        |
| 5.2      | Types of Circuits                            | 162        |
| 5.3      | Poisson Properties                           | 164        |
| 5.3.1    | Poisson Merging                              | 164        |
| 5.3.2    | Poisson Branching                            | 165        |
| 5.3.3    | Poisson PASTA                                | 166        |
| 5.4      | Open-Circuit Queues                          | 166        |
| 5.4.1    | Series Circuits                              | 167        |
| 5.4.2    | Feedforward Circuits                         | 167        |
| 5.4.3    | Feedback Circuits                            | 168        |
| 5.5      | Jackson's Theorem                            | 171        |
| 5.5.1    | Jackson Network Traffic                      | 173        |
| 5.5.2    | Jackson Node Traffic                         | 173        |
| 5.5.3    | Routing Requests in PDQ                      | 175        |
| 5.5.4    | Parallel Queues in Series                    | 177        |
| 5.5.5    | Multiple Workloads in Open Circuits          | 180        |
| 5.6      | Closed-Circuit Queues                        | 181        |
| 5.6.1    | Arrival Theorem                              | 182        |
| 5.6.2    | Iterative MVA Algorithm                      | 183        |
| 5.6.3    | Approximate Solution                         | 185        |

|          |                                              |            |
|----------|----------------------------------------------|------------|
| 5.7      | Visit Ratios and Routing Probabilities ..... | 189        |
| 5.7.1    | Visit Ratios and Open Circuits .....         | 189        |
| 5.7.2    | Visit Ratios and Closed Circuits .....       | 191        |
| 5.8      | Multiple Workloads in Closed Circuits .....  | 192        |
| 5.8.1    | Workload Classes .....                       | 192        |
| 5.8.2    | Baseline Analysis .....                      | 192        |
| 5.8.3    | Aggregate Analysis .....                     | 194        |
| 5.8.4    | Component Analysis .....                     | 197        |
| 5.9      | Operating Systems and Schedulers .....       | 199        |
| 5.9.1    | Time-Share Scheduler .....                   | 199        |
| 5.9.2    | Fair-Share Scheduler .....                   | 201        |
| 5.9.3    | Priority Scheduling .....                    | 204        |
| 5.9.4    | Thread Scheduler .....                       | 206        |
| 5.10     | Rules for Applying Queueing Models .....     | 207        |
| 5.10.1   | MVA Is a Style of Thinking .....             | 207        |
| 5.10.2   | BCMP Rules .....                             | 208        |
| 5.10.3   | Service Classes .....                        | 209        |
| 5.10.4   | Limitations .....                            | 210        |
| 5.11     | Review .....                                 | 212        |
|          | Exercises .....                              | 213        |
| <b>6</b> | <b>Linux Load Average .....</b>              | <b>215</b> |
| 6.1      | Introduction .....                           | 215        |
| 6.1.1    | Load Average Reporting .....                 | 216        |
| 6.1.2    | What Is an “Average” Load? .....             | 217        |
| 6.2      | A Simple Experiment .....                    | 218        |
| 6.2.1    | Experimental Results .....                   | 219        |
| 6.2.2    | Submerging Into the Kernel .....             | 221        |
| 6.3      | Load Calculation .....                       | 222        |
| 6.3.1    | Fixed-Point Arithmetic .....                 | 223        |
| 6.3.2    | Magic Numbers .....                          | 224        |
| 6.3.3    | Empty Run-Queue .....                        | 226        |
| 6.3.4    | Occupied Run-Queue .....                     | 226        |
| 6.3.5    | Exponential Damping .....                    | 228        |
| 6.4      | Steady-State Averages .....                  | 231        |
| 6.4.1    | Time-Averaged Queue Length .....             | 232        |
| 6.4.2    | Linux Scheduler Model .....                  | 232        |
| 6.5      | Load Averages and Trend Visualization .....  | 235        |
| 6.5.1    | What Is Wrong with Load Averages .....       | 235        |
| 6.5.2    | New Visual Paradigm .....                    | 235        |
| 6.5.3    | Application to Workload Management .....     | 237        |
| 6.6      | Review .....                                 | 237        |
|          | Exercises .....                              | 238        |

|          |                                                 |     |
|----------|-------------------------------------------------|-----|
| <b>7</b> | <b>Performance Bounds and Log Jams</b>          | 239 |
| 7.1      | Introduction                                    | 239 |
| 7.2      | Out of Bounds in Florida                        | 239 |
| 7.2.1    | Load Test Results                               | 240 |
| 7.2.2    | Bottlenecks and Bounds                          | 240 |
| 7.3      | Throughput Bounds                               | 241 |
| 7.3.1    | Saturation Throughput                           | 241 |
| 7.3.2    | Uncontended Throughput                          | 242 |
| 7.3.3    | Optimal Load                                    | 243 |
| 7.4      | Response Time Bounds                            | 244 |
| 7.4.1    | Uncontended Response Time                       | 244 |
| 7.4.2    | Saturation Response Time                        | 244 |
| 7.4.3    | Worst-Case Response Bound                       | 246 |
| 7.5      | Meanwhile, Back in Florida                      | 246 |
| 7.5.1    | Balanced Bounds                                 | 247 |
| 7.5.2    | Balanced Demand                                 | 247 |
| 7.5.3    | Balanced Throughput                             | 248 |
| 7.6      | The X-Files: Encounters with Performance Aliens | 249 |
| 7.6.1    | X Window Architecture                           | 249 |
| 7.6.2    | Production Environment                          | 250 |
| 7.7      | Close Encounters of the Performance Kind        | 251 |
| 7.7.1    | Close Encounters I: Rumors                      | 251 |
| 7.7.2    | Close Encounters II: Measurements               | 251 |
| 7.7.3    | Close Encounters III: Analysis                  | 252 |
| 7.8      | Performance Aliens Revealed                     | 254 |
| 7.8.1    | Out of Sight, Out of Mind                       | 254 |
| 7.8.2    | Log-Jammed Performance                          | 256 |
| 7.8.3    | To Get a Log You Need a Tree                    | 256 |
| 7.9      | X11 Window Scalability                          | 258 |
| 7.9.1    | Measuring Sibling X-Events                      | 258 |
| 7.9.2    | Superlinear Response                            | 259 |
| 7.10     | Review                                          | 260 |
|          | Exercises                                       | 260 |

---

## Part III Practical Application of PDQ

---

|          |                                              |     |
|----------|----------------------------------------------|-----|
| <b>8</b> | <b>Pretty Damn Quick—A Slow Introduction</b> | 263 |
| 8.1      | Introduction                                 | 263 |
| 8.2      | How to Build PDQ Circuits                    | 263 |
| 8.3      | Inputs and Outputs                           | 263 |
| 8.3.1    | Setting Up PDQ                               | 264 |
| 8.3.2    | Some General Guidelines                      | 266 |
| 8.4      | Simple Annotated Example                     | 266 |
| 8.4.1    | Creating the PDQ Model                       | 266 |

|           |                                                    |            |
|-----------|----------------------------------------------------|------------|
| 8.4.2     | Reading the PDQ Report . . . . .                   | 268        |
| 8.4.3     | Validating the PDQ Model . . . . .                 | 268        |
| 8.5       | Classic Queues in PDQ . . . . .                    | 271        |
| 8.5.1     | Delay Node in PDQ . . . . .                        | 271        |
| 8.5.2     | $M/M/1$ in PDQ . . . . .                           | 271        |
| 8.5.3     | $M/M/m$ in PDQ . . . . .                           | 271        |
| 8.5.4     | $M/M/1/N/N$ in PDQ . . . . .                       | 272        |
| 8.5.5     | $M/M/m/N/N$ in PDQ . . . . .                       | 272        |
| 8.5.6     | Feedforward Circuits in PDQ . . . . .              | 272        |
| 8.5.7     | Feedback Circuits in PDQ . . . . .                 | 272        |
| 8.5.8     | Parallel Queues in Series . . . . .                | 276        |
| 8.5.9     | Multiple Workloads in PDQ . . . . .                | 276        |
| 8.5.10    | Priority Queueing in PDQ . . . . .                 | 276        |
| 8.5.11    | Load-Dependent Servers in PDQ . . . . .            | 278        |
| 8.6       | Review . . . . .                                   | 289        |
|           | Exercises . . . . .                                | 289        |
| <b>9</b>  | <b>Multicomputer Analysis with PDQ . . . . .</b>   | <b>291</b> |
| 9.1       | Introduction . . . . .                             | 291        |
| 9.2       | Multiprocessor Architectures . . . . .             | 292        |
| 9.2.1     | Symmetric Multiprocessors . . . . .                | 293        |
| 9.2.2     | Multiprocessor Caches . . . . .                    | 294        |
| 9.2.3     | Cache Bashing . . . . .                            | 295        |
| 9.3       | Multiprocessor Models . . . . .                    | 296        |
| 9.3.1     | Single-Bus Models . . . . .                        | 297        |
| 9.3.2     | Processing Power . . . . .                         | 298        |
| 9.3.3     | Multiple-Bus Models . . . . .                      | 300        |
| 9.3.4     | Cache Protocols . . . . .                          | 302        |
| 9.3.5     | Iron Law of Performance . . . . .                  | 305        |
| 9.4       | Multicomputer Models . . . . .                     | 307        |
| 9.4.1     | Parallel Query Cluster . . . . .                   | 307        |
| 9.4.2     | Query Saturation Method . . . . .                  | 311        |
| 9.5       | Review . . . . .                                   | 316        |
|           | Exercises . . . . .                                | 316        |
| <b>10</b> | <b>How to Scale an Elephant with PDQ . . . . .</b> | <b>317</b> |
| 10.1      | An Elephant Story . . . . .                        | 317        |
| 10.1.1    | What Is Scalability? . . . . .                     | 318        |
| 10.1.2    | SPEC Multiuser Benchmark . . . . .                 | 319        |
| 10.1.3    | Steady-state Measurements . . . . .                | 321        |
| 10.2      | Parts of the Elephant . . . . .                    | 321        |
| 10.2.1    | Service Demand Part . . . . .                      | 322        |
| 10.2.2    | Think Time Part . . . . .                          | 322        |
| 10.2.3    | User Load Part . . . . .                           | 322        |
| 10.3      | PDQ Scalability Model . . . . .                    | 323        |

|           |                                                |            |
|-----------|------------------------------------------------|------------|
| 10.3.1    | Interpretation .....                           | 324        |
| 10.3.2    | Amdahl's Law .....                             | 326        |
| 10.3.3    | The Elephant's Dimensions .....                | 328        |
| 10.4      | Review .....                                   | 329        |
|           | Exercises .....                                | 330        |
| <b>11</b> | <b>Client/Server Analysis with PDQ .....</b>   | <b>331</b> |
| 11.1      | Introduction .....                             | 331        |
| 11.2      | Client/Server Architectures .....              | 332        |
| 11.2.1    | Multitier Environments .....                   | 333        |
| 11.2.2    | Three-Tier Options .....                       | 333        |
| 11.3      | Benchmark Environment .....                    | 335        |
| 11.3.1    | Performance Scenarios .....                    | 335        |
| 11.3.2    | Workload Characterization .....                | 337        |
| 11.3.3    | Distributed Workflow .....                     | 339        |
| 11.4      | Scalability Analysis with PDQ .....            | 340        |
| 11.4.1    | Benchmark Baseline .....                       | 341        |
| 11.4.2    | Client Scaleup .....                           | 346        |
| 11.4.3    | Load Balancer Bottleneck .....                 | 349        |
| 11.4.4    | Database Server Bottleneck .....               | 349        |
| 11.4.5    | Production Client Load .....                   | 349        |
| 11.4.6    | Saturation Client Load .....                   | 350        |
| 11.4.7    | Per-Process Analysis .....                     | 350        |
| 11.5      | Review .....                                   | 353        |
|           | Exercises .....                                | 354        |
| <b>12</b> | <b>Web Application Analysis with PDQ .....</b> | <b>355</b> |
| 12.1      | Introduction .....                             | 355        |
| 12.2      | HTTP Protocol .....                            | 355        |
| 12.2.1    | HTTP Performance .....                         | 360        |
| 12.2.2    | HTTP Analysis Using PDQ .....                  | 361        |
| 12.2.3    | Fork-on-Demand Analysis .....                  | 361        |
| 12.2.4    | Prefork Analysis .....                         | 363        |
| 12.3      | Two-Tier PDQ Model .....                       | 369        |
| 12.3.1    | Data and Information Are Not the Same .....    | 369        |
| 12.3.2    | HTTPd Performance Measurements .....           | 369        |
| 12.3.3    | Java Performance Measurements .....            | 369        |
| 12.4      | Middleware Analysis Using PDQ .....            | 372        |
| 12.4.1    | Active Client Threads .....                    | 372        |
| 12.4.2    | Load Test Results .....                        | 374        |
| 12.4.3    | Derived Service Demands .....                  | 375        |
| 12.4.4    | Preliminary PDQ Model .....                    | 375        |
| 12.4.5    | Adding Hidden Latencies in PDQ .....           | 379        |
| 12.4.6    | Adding Overdriven Throughput in PDQ .....      | 381        |
| 12.5      | Review .....                                   | 384        |

|                                                   |            |
|---------------------------------------------------|------------|
| Exercises .....                                   | 384        |
| <b>13 Virtual Machine Analysis with PDQ .....</b> | <b>387</b> |
| 13.1 Introduction .....                           | 387        |
| 13.2 The Virtual Machine Spectrum .....           | 388        |
| 13.3 Micro-VMM Scale: Hyperthreading .....        | 390        |
| 13.3.1 Controlled Measurements .....              | 392        |
| 13.3.2 PDQ Model of Micro-VMM .....               | 395        |
| 13.4 Meso-VMM Scale: Hypervisors .....            | 397        |
| 13.4.1 Performance Monitoring Tools .....         | 404        |
| 13.4.2 Controlled Measurements .....              | 405        |
| 13.5 Macro-VMM Scale: Clouds and P2P .....        | 407        |
| 13.5.1 Macro-VM Polling .....                     | 408        |
| 13.5.2 Scalability Analysis Using PDQ .....       | 409        |
| 13.6 Cloud Computing Models .....                 | 411        |
| 13.6.1 Fixed-Size Bounds .....                    | 413        |
| 13.6.2 Harmonic Bounds .....                      | 416        |
| 13.6.3 Scaled-Size Bounds .....                   | 417        |
| 13.6.4 Erlang Model .....                         | 418        |
| 13.6.5 LogP Model .....                           | 419        |
| 13.7 Summary .....                                | 421        |

---

## Part IV Appendices

---

|                                                 |            |
|-------------------------------------------------|------------|
| <b>A Thanks for No Memories .....</b>           | <b>425</b> |
| A.1 Life in the Markov Lane .....               | 425        |
| A.2 Exponential Invariance .....                | 426        |
| A.3 Shape Preservation .....                    | 428        |
| A.4 A Counterexample .....                      | 428        |
| <b>B Compendium of Queueing Equations .....</b> | <b>431</b> |
| B.1 Fundamental Metrics .....                   | 431        |
| B.2 Queueing Delays .....                       | 432        |
| <b>C Units and Abbreviations .....</b>          | <b>433</b> |
| C.1 SI Prefixes .....                           | 433        |
| C.2 Time Suffixes .....                         | 433        |
| C.3 Capacity Suffixes .....                     | 433        |
| <b>D Perl PDQ Manual .....</b>                  | <b>435</b> |
| D.1 Introduction .....                          | 435        |
| D.2 Perl PDQ Module .....                       | 435        |
| D.2.1 PDQ Data Types .....                      | 435        |
| D.2.2 PDQ Global Variables .....                | 436        |

|          |                                              |            |
|----------|----------------------------------------------|------------|
| D.2.3    | PDQ Functions .....                          | 437        |
| D.3      | Function Synopses .....                      | 437        |
| D.3.1    | pdq::CreateClosed .....                      | 437        |
| D.3.2    | pdq::CreateMultiNode .....                   | 438        |
| D.3.3    | pdq::CreateNode .....                        | 438        |
| D.3.4    | pdq::CreateOpen .....                        | 439        |
| D.3.5    | pdq::CreateSingleNode .....                  | 439        |
| D.3.6    | pdq::GetLoadOpt.....                         | 440        |
| D.3.7    | pdq::GetQueueLength.....                     | 441        |
| D.3.8    | pdq::GetResidenceTime .....                  | 441        |
| D.3.9    | pdq::GetResponse .....                       | 442        |
| D.3.10   | pdq::GetThruMax .....                        | 443        |
| D.3.11   | pdq::GetThruput .....                        | 443        |
| D.3.12   | pdq::GetUtilization .....                    | 444        |
| D.3.13   | pdq::Init .....                              | 444        |
| D.3.14   | pdq::Report .....                            | 445        |
| D.3.15   | pdq::SetDebug .....                          | 446        |
| D.3.16   | pdq::SetDemand .....                         | 447        |
| D.3.17   | pdq::SetTUnit .....                          | 448        |
| D.3.18   | pdq::SetVisits .....                         | 448        |
| D.3.19   | pdq::SetWUnit .....                          | 449        |
| D.3.20   | pdq::Solve .....                             | 449        |
| D.4      | Perl Scripts .....                           | 450        |
| D.5      | PDQ Scripts .....                            | 451        |
| D.6      | Installing the PDQ Module .....              | 451        |
| <b>E</b> | <b>Solutions to Selected Exercises .....</b> | <b>453</b> |
|          | <b>Bibliography.....</b>                     | <b>457</b> |
|          | <b>Index.....</b>                            | <b>465</b> |