

CONTENTS

Preface	ix
Acknowledgments	xi
About the Companion Website	xiii
1 Introduction	1
1.1 Measures of System Performance	2
1.2 Characteristics of Queueing Systems	4
1.3 The Experience of Waiting	9
1.4 Little's Law	10
1.5 General Results	19
1.6 Simple Bookkeeping for Queues	22
1.7 Introduction to the QtsPlus Software Problems	26 27
2 Review of Stochastic Processes	35
2.1 The Exponential Distribution	35
2.2 The Poisson Process	39
2.3 Discrete-Time Markov Chains	49
2.4 Continuous-Time Markov Chains Problems	62 69

3	Simple Markovian Queueing Models	73
3.1	Birth-Death Processes	73
3.2	Single-Server Queues ($M/M/1$)	77
3.3	Multiserver Queues ($M/M/c$)	90
3.4	Choosing the Number of Servers	97
3.5	Queues with Truncation ($M/M/c/K$)	100
3.6	Erlang's Loss Formula ($M/M/c/e$)	105
3.7	Queues with Unlimited Service ($M/M/\infty$)	108
3.8	Finite-Source Queues	109
3.9	State-Dependent Service	115
3.10	Queues with Impatience	119
3.11	Transient Behavior	121
3.12	Busy-Period Analysis	126
	Problems	127
4	Advanced Markovian Queueing Models	147
4.1	Bulk Input ($M^{[X]}/M/1$)	147
4.2	Bulk Service ($M/M^{[Y]}/1$)	153
4.3	Erlang Models	158
4.4	Priority Queue Disciplines	172
4.5	Retrial Queues	191
	Problems	204
5	Networks, Series, and Cyclic Queues	213
5.1	Series Queues	215
5.2	Open Jackson Networks	221
5.3	Closed Jackson Networks	229
5.4	Cyclic Queues	243
5.5	Extensions of Jackson Networks	244
5.6	Non-Jackson Networks	246
	Problems	248
6	General Arrival or Service Patterns	255
6.1	General Service, Single Server ($M/G/1$)	255
6.2	General Service, Multiserver ($M/G/c/\cdot, M/G/\infty$)	290
6.3	General Input ($G/M/1, G/M/c$)	295
	Problems	306
7	General Models and Theoretical Topics	313
7.1	$G/E_k/1, G^{[k]}/M/1, \text{ and } G/PH_k/1$	313
7.2	General Input, General Service ($G/G/1$)	320
7.3	Poisson Input, Constant Service, Multiserver ($M/D/c$)	330

7.4	Semi-Markov and Markov Renewal Processes in Queueing	332
7.5	Other Queue Disciplines	337
7.6	Design and Control of Queues	342
7.7	Statistical Inference in Queueing Problems	353
		361
8	Bounds and Approximations	365
8.1	Bounds	366
8.2	Approximations	378
8.3	Deterministic Fluid Queues	392
8.4	Network Approximations Problems	400
		411
9	Numerical Techniques and Simulation	417
9.1	Numerical Techniques	417
9.2	Numerical Inversion of Transforms	433
9.3	Discrete-Event Stochastic Simulation Problems	446
		469
	References	475
	Appendix A: Symbols and Abbreviations	487
	Appendix B: Tables	495
	Appendix C: Transforms and Generating Functions	503
C.1	Laplace Transforms	503
C.2	Generating Functions	510
	Appendix D: Differential and Difference Equations	515
D.1	Ordinary Differential Equations	515
D.2	Difference Equations	531
	Appendix E: QtsPlus Software	537
E.1	Instructions for Downloading	540
	Index	541