



# QUEUEING SYSTEMS, VOLUME 2 : COMPUTER APPLICATIONS

## LEONARD KLEINROCK

### SUMMARY

This book presents and develops methods from queuing theory in sufficient depth so that students and professionals may apply these methods to many modern engineering problems, as well as conduct creative research in the field.

It provides a long-needed alternative both to highly mathematical texts and to those which are simplistic or limited in approach. Written in mathematical language, it avoids the "theorem-proof" technique: instead, it guides the reader through a step-by-step, intuitively motivated yet precise development leading to a natural discovery of results. Queuing Systems, Volume 1 covers material ranging from a refresher of transform and probability theory through the treatment of advanced queuing systems. It is divided into four sections: 1) preliminaries; 2) elementary queuing theory; 3) intermediate queuing theory and 4) advanced material!

Important features of Queuing Systems, Volume 1: Theory include:

- techniques of duality, collective marks
- queuing networks
- complete appendix on z-transforms and Laplace transforms
- an entire appendix on probability theory, providing the notation and main results

needed throughout the text

- definition and use of a new and convenient graphical notation for describing the arrival and departure of customers to a queuing system
- a Venn diagram classification of many common stochastic processes

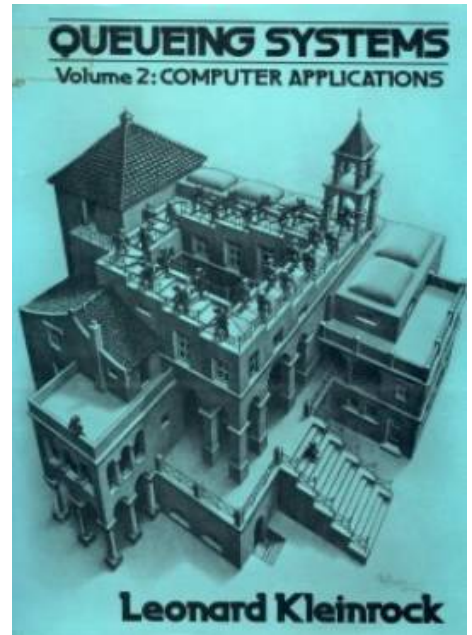
1975 (0 471-49110-1) 417 pp.

**FUNDAMENTALS OF QUEUEING THEORY** . Second Edition

Donald Gross and Carl M. Harris

This graduated, meticulous look at queuing fundamentals developed from the authors lecture notes presents all aspects of the methodology - including Simple Markovian birth-death queuing models; advanced Markovian models; networks, series, and cyclic queues; models with general arrival or service patterns; bounds, approximations, and numerical techniques; and simulation - in a style suitable to courses of study of widely varying depth and duration. This Second Edition features new expansions and abridgements which enhance pedagogical use: new material on numerical solution techniques for both steady-state and transient solutions; changes in simulation language and new results in statistical analysis; and more. Complete with a solutions manual, here is a comprehensive, rigorous introduction to the basics of the discipline.

1985 (0471-83143-3) 220 pp.



## TABLE OF CONTENTS

### VOLUME II

<b>Chapter 1</b>	<b>A Queuing Theory Primer</b>	<b>1</b>
1.1.	Notation	2
1.2.	General Results	5
1.3.	Markov, Birth-Death, and Poisson Processes	7
1.4.	The M/M/1 Queue	10
1.5.	The M/M/m Queuing System	13
1.6.	Markovian Queuing Networks	14
1.7.	The M/G/1 Queue	15
1.8.	The G/M/1 Queue	20
1.9.	The G/M/m Queue	20
1.10.	The G/G/1 Queue	22
<b>Chapter 2</b>	<b>Rounds, Inequalities and Approximations</b>	<b>27</b>
2.1.	The Heavy- Traffic Approximation	29
2.2.	An Upper Bound for the Average Wait	32
2.3.	Lower Bounds for the Average Wait	34
2.4.	Bounds on the Tail of the Waiting Time Distribution	44
2.5.	Some Remarks for G/G/m	46
2.6.	A Discrete Approximation	51
2.7.	The Fluid Approximation for Queues	56
2.8.	Diffusion Processes	62
2.9.	Diffusion Approximation for M/G/1	79
2.10.	The Rush-Hour Approximation	87

Chapter 3	Priority Queuing	106
3.1.	The Model	106
3.2.	An Approach for Calculating Average Waiting Times	106
3.3.	The Delay Cycle, Generalized Busy Periods, and Waiting Time Distributions	110
3.4.	Conservation Laws	113
3.5.	The Last-Come-First-Serve Queuing Discipline	118
3.6.	Head-of-the-Line Priorities	119
3.7.	Time-Dependent Priorities	126
3.8.	Optimal Bribing for Queue Position	135
3.9.	Service- Time-Dependent Disciplines	144
Chapter 4	Computer Time-Sharing and Multiaccess Systems	156
4.1.	Definitions and Models	159
4.2.	Distribution of Attained Service	162
4.3.	The Batch Processing Algorithm	164
4.4.	The Round-Robin Scheduling Algorithm	166
4.5.	The Last-Come-First-Serve Scheduling Algorithm	170
4.6.	The FB Scheduling Algorithm	172
4.7.	The Multilevel Processor Sharing Scheduling Algorithm	177
4.8.	Selfish Scheduling Algorithms	188
4.9.	A Conservation Law for Time-Shared Systems	197
4.10.	Tight Bounds on the Mean Response Time	199
4.11.	Finite Population Models	206
4.12.	Multiple-Resource Models	212
4.13.	Models for Multiprogramming	230
4.14.	Remote Terminal Access to Computers	236
Chapter 5	Computer-Communication Networks: Analysis and Design	270
5.1.	Resource Sharing	272
5.2.	Some Contrasts and Trade-Offs	290
5.3.	Network Structures and Packet Switching	292
5.4.	The ARPANET-An Operational Description of an Existing Network	304
5.5.	Definitions, Model, and Problem Statements	314
5.6.	Delay Analysis	320
5.7.	The Capacity Assignment Problem	329
5.8.	The Traffic Flow Assignment Problem	340
5.9.	The Capacity and Flow Assignment Problem	348
5.10.	Some Topological Considerations-Applications to the ARPANET	351
5.11.	Satellite Packet Switching	360
5.12.	Ground Radio Packet Switching	393
Chapter 6	Computer-Communication Networks: Measurement, Flow Control, and ARP ANET Traps	422
6.1.	Simulation and Routing	423
6.2.	Early ARP ANET Measurements	429
6.3.	Flow Control	438
6.4.	Lockups, Degradations, and Traps	446
6.5.	Network Throughput	451
6.6.	One Week of ARPANET Data	458
6.7.	Line Overhead in the ARPANET	484
6.8.	Recent Changes to the Flow Control Procedure	501
6.9.	The Challenge of the Future	508
Glossary of Notation		516
Summary of Important Results		523
Index		537
VOLUME I		
PART I : PRELIMINARIES		
Chapter 1	Queuing Systems	3
1.1.	Systems of Flow	3
1.2.	The Specification and Measure of Queuing Systems	8
Chapter 2	Some Important Random Processes	10
2.1.	Notation and Structure for Basic Queuing Systems	10
2.2.	Definition and Classification of Stochastic Processes	19
2.3.	Discrete- Time Markov Chains	26
2.4.	Continuous- Time Markov Chains	44
2.5.	Birth-Death Processes	53
PART II : ELEMENTARY QUEUEING THEORY		

Chapter 3	Birth-Death Queuing Systems in Equilibrium	89
3.1.	General Equilibrium Solution	90
3.2.	M/M/1: The Classical Queuing System	94
3.3.	Discouraged Arrivals	99
3.4.	M/M/∞: Responsive Servers (Infinite Number of Servers)	101
3.5.	M/M/m: The m-Server Case	102
3.6.	M/M/1/K: Finite Storage	103
3.7.	M/M/m/m: m-Server Loss Systems	105
3.8.	M/M/1/M: Finite Customer Population-Single Server	106
3.9.	M/M/∞/M: Finite Customer Population-"Infinite" Number of Servers	107
3.10.	M/M/m/K/M: Finite Population, m-Server Case, Finite Storage	108
Chapter 4	Markovian Queues in Equilibrium	115
4.1.	The Equilibrium Equations	115
4.2.	The Method of Stages-Erlangian Distribution Er	119
4.3.	The Queue M/Er,1	126
4.4.	The Queue Er,M/1	130
4.5.	Bulk Arrival Systems	134
4.6.	Bulk Service Systems	137
4.7.	Series-Parallel Stages: Generalizations	139
4.8.	Networks of Markovian Queues	147
PART III : INTERMEDIATE QUEUEING THEORY		
Chapter 5	The Queue M/G/I	167
5.1.	The M/G/I System	168
5.2.	The Paradox of Residual Life: A Bit of Renewal Theory	169
5.3.	The Imbedded Markov Chain	174
5.4.	The Transition Probabilities	177
5.5.	The Mean Queue Length	180
5.6.	Distribution of Number in System	191
5.7.	Distribution of Waiting Time	196
5.8.	The Busy Period and Its Duration	206
5.9.	The Number Served in a Busy Period	216
5.10.	From Busy Periods to Waiting Times	219
5.11.	Combinatorial Methods	223
5.12.	The Takacs Integro differential Equation	226
Chapter 6	The Queue G/M/m	241
6.1.	Transition Probabilities for the Imbedded Markov Chain (G/M/m)	241
6.2.	Condition al Distribution of Queue Size	246
6.3.	Condition al Distribution of Waiting Time	250
6.4.	The Queue G/M/1	251
6.5.	The Queue G/M/m	253
6.6.	The Queue G/M/2	256
Chapter 7	The Method of Collective Marks	261
7.1.	The Marking of Customers	261
7.2.	The Catastrophe Process	267
PART IV : ADVANCED MATERIAL		
Chapter 8	The Queue G/G/I	275
8.1.	Lindley's Integral Equation	275
8.2.	Spectral Solution to Lindley's Integral Equation	283
8.3.	Kingman's Algebra for Queues	299
8.4.	The Idle Time and Duality	304
Epilogue		319
Appendix I:	Transform Theory Refresher: z- Transform and Laplace Transform	
1.1.	Why Transforms?	321
1.2.	The z- Transform	327
1.3.	The Laplace Transform	338
1.4.	Use of Transforms in the Solution of Difference and Differential Equations	355
Appendix II:	Probablity Theory Refresher	
11.1.	Rules of the Game	363
11.2.	Random Variables	368
11.3.	Expectation	377
11.4.	Transforms, Generating Functions, and Characteristic Functions	381
11.5.	Inequalities and Limit Theorems	388

11.6. Stochastic Processes	393
Glossary of Notation	396
Summary of Important Results	400
Index	411
<a href="#">TOP</a>	

