
THE ART OF COMPUTER SYSTEMS PERFORMANCE ANALYSIS

Techniques for
Experimental Design,
Measurement, Simulation,
and Modeling

RAJ JAIN

Digital Equipment Corporation
Littleton, Massachusetts



JOHN WILEY & SONS, INC.

New York / Chichester / Brisbane / Toronto / Singapore

CONTENTS

List of Boxes	xxv
List of Case Studies	xxvii
PART I AN OVERVIEW OF PERFORMANCE EVALUATION	1
1 Introduction	3
1.1 Outline of Topics, 3	
1.2 The Art of Performance Evaluation, 7	
1.3 Professional Organizations, Journals, and Conferences, 8	
1.4 Performance Projects, 11	
Exercise, 12	
2 Common Mistakes and How to Avoid Them	14
2.1 Common Mistakes in Performance Evaluation, 14	
2.2 A Systematic Approach to Performance Evaluation, 22	
Exercises, 28	

3	Selection of Techniques and Metrics	30
3.1	Selecting an Evaluation Technique,	30
3.2	Selecting Performance Metrics,	33
3.3	Commonly Used Performance Metrics,	37
3.4	Utility Classification of Performance Metrics,	40
3.5	Setting Performance Requirements,	41
	Exercises,	43
	Further Reading for Part I	44
	PART II MEASUREMENT TECHNIQUES AND TOOLS	45
4	Types of Workloads	47
4.1	Addition Instruction,	48
4.2	Instruction Mixes,	48
4.3	Kernels,	49
4.4	Synthetic Programs,	50
4.5	Application Benchmarks,	51
4.6	Popular Benchmarks,	52
	Exercises,	59
5	The Art of Workload Selection	60
5.1	Services Exercised,	60
5.2	Level of Detail,	66
5.3	Representativeness,	67
5.4	Timeliness,	68
5.5	Other Considerations in Workload Selection,	69
	Exercises,	69
6	Workload Characterization Techniques	71
6.1	Terminology,	71
6.2	Averaging,	73
6.3	Specifying Dispersion,	73
6.4	Single-Parameter Histograms,	75
6.5	Multiparameter Histograms,	76
6.6	Principal-Component Analysis,	76
6.7	Markov Models,	81

6.8	Clustering, 83	
	Exercises, 91	
7	Monitors	93
7.1	Monitor Terminology, 94	
7.2	Monitor Classification, 94	
7.3	Software Monitors, 95	
7.4	Hardware Monitors, 98	
7.5	Software versus Hardware Monitors, 98	
7.6	Firmware and Hybrid Monitors, 100	
7.7	Distributed-System Monitors, 101	
	Exercises, 109	
8	Program Execution Monitors and Accounting Logs	111
8.1	Program Execution Monitors, 111	
8.2	Techniques for Improving Program Performance, 114	
8.3	Accounting Logs, 114	
8.4	Analysis and Interpretation of Accounting Log Data, 117	
8.5	Using Accounting Logs to Answer Commonly Asked Questions, 119	
	Exercise, 122	
9	Capacity Planning and Benchmarking	123
9.1	Steps in Capacity Planning and Management, 124	
9.2	Problems in Capacity Planning, 125	
9.3	Common Mistakes in Benchmarking, 127	
9.4	Benchmarking Games, 130	
9.5	Load Drivers, 131	
9.6	Remote-Terminal Emulation, 132	
9.7	Components of an RTE, 133	
9.8	Limitations of Current RTEs, 136	
	Exercises, 138	
10	The Art of Data Presentation	139
10.1	Types of Variables, 140	
10.2	Guidelines for Preparing Good Graphic Charts, 141	
10.3	Common Mistakes in Preparing Charts, 144	
10.4	Pictorial Games, 146	

10.5	Gantt Charts, 150	
10.6	Kiviat Graphs, 153	
10.7	Schumacher Charts, 160	
10.8	Decision Maker's Games, 161	
	Exercises, 163	
11	Ratio Games	165
11.1	Choosing an Appropriate Base System, 165	
11.2	Using an Appropriate Ratio Metric, 167	
11.3	Using Relative Performance Enhancement, 168	
11.4	Ratio Games with Percentages, 169	
11.5	Strategies for Winning a Ratio Game, 170	
11.6	Correct Analysis, 174	
	Exercises, 174	
	Further Reading for Part II	175
	PART III PROBABILITY THEORY AND STATISTICS	177
12	Summarizing Measured Data	179
12.1	Basic Probability and Statistics Concepts, 179	
12.2	Summarizing Data by a Single Number, 182	
12.3	Selecting among the Mean, Median, and Mode, 183	
12.4	Common Misuses of Means, 186	
12.5	Geometric Mean, 187	
12.6	Harmonic Mean, 188	
12.7	Mean of a Ratio, 189	
12.8	Summarizing Variability, 192	
12.9	Selecting the Index of Dispersion, 195	
12.10	Determining Distribution of Data, 196	
	Exercises, 200	
13	Comparing Systems Using Sample Data	203
13.1	Sample versus Population, 203	
13.2	Confidence Interval for the Mean, 204	
13.3	Testing for a Zero Mean, 207	
13.4	Comparing Two Alternatives, 208	
13.5	What Confidence Level to Use, 212	

13.6	Hypothesis Testing versus Confidence Intervals, 213	
13.7	One-Sided Confidence Intervals, 214	
13.8	Confidence Intervals for Proportions, 215	
13.9	Determining Sample Size, 216	
	Exercises, 218	
14	Simple Linear Regression Models	221
14.1	Definition of a Good Model, 222	
14.2	Estimation of Model Parameters, 223	
14.3	Allocation of Variation, 226	
14.4	Standard Deviation of Errors, 228	
14.5	Confidence Intervals for Regression Parameters, 229	
14.6	Confidence Intervals for Predictions, 232	
14.7	Visual Tests for Verifying the Regression Assumptions, 234	
	Exercises, 241	
15	Other Regression Models	244
15.1	Multiple Linear Regression Models, 245	
15.2	Regression with Categorical Predictors, 254	
15.3	Curvilinear Regression, 257	
15.4	Transformations, 259	
15.5	Outliers, 265	
15.6	Common Mistakes in Regression, 266	
	Exercises, 270	
	Further Reading for Part III	272
	PART IV EXPERIMENTAL DESIGN AND ANALYSIS	273
16	Introduction to Experimental Design	275
16.1	Terminology, 275	
16.2	Common Mistakes in Experimentation, 278	
16.3	Types of Experimental Designs, 279	
	Exercise, 282	

17	2^k Factorial Designs	283
17.1	2^2 Factorial Designs, 284	
17.2	Computation of Effects, 285	
17.3	Sign Table Method for Calculating Effects, 286	
17.4	Allocation of Variation, 286	
17.5	General 2^k Factorial Designs, 291	
	Exercise, 292	
18	2^{k-r} Factorial Designs with Replications	293
18.1	2^{2-r} Factorial Designs, 293	
18.2	Computation of Effects, 294	
18.3	Estimation of Experimental Errors, 294	
18.4	Allocation of Variation, 295	
18.5	Confidence Intervals for Effects, 298	
18.6	Confidence Intervals for Predicted Responses, 299	
18.7	Visual Tests for Verifying the Assumptions, 302	
18.8	Multiplicative Models for 2^{2-r} Experiments, 303	
18.9	General 2^{k-r} Factorial Design, 308	
	Exercise, 313	
19	2^{k-p} Fractional Factorial Designs	314
19.1	Preparing the Sign Table for a 2^{k-p} Design, 316	
19.2	Confounding, 318	
19.3	Algebra of Confounding, 320	
19.4	Design Resolution, 321	
	Exercises, 326	
20	One-Factor Experiments	327
20.1	Model, 327	
20.2	Computation of Effects, 328	
20.3	Estimating Experimental Errors, 330	
20.4	Allocation of Variation, 331	
20.5	Analysis of Variance, 332	
20.6	Visual Diagnostic Tests, 334	
20.7	Confidence Intervals for Effects, 335	
20.8	Unequal Sample Sizes, 337	
	Exercise, 342	

21	Two-Factor Full Factorial Design without Replications	343
21.1	Model, 344	
21.2	Computation of Effects, 344	
21.3	Estimating Experimental Errors, 346	
21.4	Allocation of Variation, 347	
21.5	Analysis of Variance, 348	
21.6	Confidence Intervals for Effects, 351	
21.7	Multiplicative Models for Two-Factor Experiments, 353	
21.8	Missing Observations, 360	
	Exercises, 367	
22	Two-Factor Full Factorial Design with Replications	368
22.1	Model, 368	
22.2	Computation of Effects, 369	
22.3	Computation of Errors, 372	
22.4	Allocation of Variation, 372	
22.5	Analysis of Variance, 374	
22.6	Confidence Intervals for Effects, 374	
	Exercise, 379	
23	General Full Factorial Designs with k Factors	381
23.1	Model, 381	
23.2	Analysis of a General Design, 382	
23.3	Informal Methods, 386	
	Exercises, 389	
	Further Reading for Part IV	390
	PART V SIMULATION	391
24	Introduction to Simulation	393
24.1	Common Mistakes in Simulation, 394	
24.2	Other Causes of Simulation Analysis Failure, 395	
24.3	Terminology, 398	
24.4	Selecting a Language for Simulation, 401	
24.5	Types of Simulations, 403	
24.6	Event-Set Algorithms, 408	
	Exercises, 411	

25	Analysis of Simulation Results	413
25.1	Model Verification Techniques, 413	
25.2	Model Validation Techniques, 420	
25.3	Transient Removal, 423	
25.4	Terminating Simulations, 428	
25.5	Stopping Criteria: Variance Estimation, 430	
25.6	Variance Reduction, 436	
	Exercises, 436	
26	Random-Number Generation	437
26.1	Desired Properties of a Good Generator, 437	
26.2	Linear-Congruential Generators, 439	
26.3	Tausworthe Generators, 444	
26.4	Extended Fibonacci Generators, 450	
26.5	Combined Generators, 450	
26.6	A Survey of Random-Number Generators, 452	
26.7	Seed Selection, 453	
26.8	Myths about Random-Number Generation, 455	
	Exercises, 458	
27	Testing Random-Number Generators	460
27.1	Chi-Square Test, 461	
27.2	Kolmogorov-Smirnov Test, 462	
27.3	Serial-Correlation Test, 465	
27.4	Two-Level Tests, 466	
27.5	k -Dimensional Uniformity or k -Distributivity, 467	
27.6	Serial Test, 468	
27.7	Spectral Test, 470	
	Exercises, 473	
28	Random-Variate Generation	474
28.1	Inverse Transformation, 474	
28.2	Rejection, 476	
28.3	Composition, 478	
28.4	Convolution, 479	
28.5	Characterization, 480	
	Exercise, 482	

29	Commonly Used Distributions	483
29.1	Bernoulli Distribution, 483	
29.2	Beta Distribution, 484	
29.3	Binomial Distribution, 485	
29.4	Chi-Square Distribution, 486	
29.5	Erlang Distribution, 487	
29.6	Exponential Distribution, 488	
29.7	<i>F</i> Distribution, 489	
29.8	Gamma Distribution, 490	
29.9	Geometric Distribution, 491	
29.10	Lognormal Distribution, 492	
29.11	Negative Binomial Distribution, 492	
29.12	Normal Distribution, 493	
29.13	Pareto Distribution, 495	
29.14	Pascal Distribution, 495	
29.15	Poisson Distribution, 496	
29.16	Student's <i>t</i> Distribution, 497	
29.17	Uniform Distribution (Continuous), 497	
29.18	Uniform Distribution (Discrete), 498	
29.19	Weibull Distribution, 499	
29.20	Relationships among Distributions, 499	
	Exercises, 501	
	Further Reading for Part V	502
	Current Areas of Research in Simulation, 503	
PART VI	QUEUEING MODELS	505
30	Introduction to Queueing Theory	507
30.1	Queueing Notation, 507	
30.2	Rules for All Queues, 510	
30.3	Little's Law, 513	
30.4	Types of Stochastic Processes, 515	
	Exercises, 518	

31	Analysis of a Single Queue	519
31.1	Birth-Death Processes, 519	
31.2	M/M/1 Queue, 522	
31.3	M/M/m Queue, 527	
31.4	M/M/m/B Queue with Finite Buffers, 534	
31.5	Results for Other Queueing Systems, 540 Exercises, 545	
32	Queueing Networks	547
32.1	Open and Closed Queueing Networks, 547	
32.2	Product Form Networks, 548	
32.3	Queueing Network Models of Computer Systems, 552 Exercise, 554	
33	Operational Laws	555
33.1	Utilization Law, 556	
33.2	Forced Flow Law, 557	
33.3	Little's Law, 560	
33.4	General Response Time Law, 561	
33.5	Interactive Response Time Law, 563	
33.6	Bottleneck Analysis, 563 Exercises, 568	
34	Mean-Value Analysis and Related Techniques	570
34.1	Analysis of Open Queueing Networks, 570	
34.2	Mean-Value Analysis, 575	
34.3	Approximate MVA, 579	
34.4	Balanced Job Bounds, 585 Exercises, 591	
35	Convolution Algorithm	593
35.1	Distribution of Jobs in a System, 593	
35.2	Convolution Algorithm for Computing $G(N)$, 595	
35.3	Computing Performance Using $G(N)$, 598	
35.4	Timesharing Systems, 602 Exercises, 607	

36 Hierarchical Decomposition of Large Queueing Networks	608
36.1 Load-dependent Service Centers, 608	
36.2 Hierarchical Decomposition, 613	
36.3 Limitations of Queueing Theory, 620 Exercises, 622	
Further Reading for Part VI	624
Symbols Frequently Used in Queueing Analysis, 624	
Appendix A Statistical Tables	627
A.1 Area of the Unit Normal Distribution, 628	
A.2 Quantiles of the Unit Normal Distribution, 629	
A.3 Commonly Used Normal Quantiles, 630	
A.4 Quantiles of the t Distribution, 631	
A.5 Quantiles of the Chi-Square Distribution, 632	
A.6 90-Percentiles of the $F(n, m)$ Distribution, 634	
A.7 95-Percentiles of the $F(n, m)$ Distribution, 635	
A.8 99-Percentiles of the $F(n, m)$ Distribution, 636	
A.9 Quantiles of the K-S Distribution, 637	
A.10 Approximation Formulas for Statistical Tables, 638	
Solutions to Selected Exercises	639
References	651
Author Index	661
Subject Index	665