

---

## Contents

Preface to the Third Edition .....	v
Preface to the Second Edition .....	vii
Preface to the First Edition .....	ix
<b>1 A Wide Range of Applications</b> .....	1
1.1 Basic Concepts.....	1
1.1.1 Stochastic Phenomena .....	1
1.1.2 Distribution Functions .....	3
1.1.3 Hypotheses .....	3
1.2 Applications .....	5
1.3 Testing a Hypothesis.....	7
1.3.1 Five Steps to a Test .....	8
1.3.2 Analyze the Experiment .....	8
1.3.3 Choose a Test Statistic .....	8
1.3.4 Compute the Test Statistic .....	9
1.3.5 Determine the Frequency Distribution of the Test Statistic .....	9
1.3.6 Make a Decision .....	10
1.3.7 Variations on a Theme.....	10
1.4 A Brief History of Statistics in Decision-Making .....	10
1.5 Exercises .....	12
<b>2 Optimal Procedures</b> .....	13
2.1 Defining Optimal .....	13
2.1.1 Trustworthy .....	13
2.1.2 Two Types of Error .....	14
2.1.3 Losses and Risk .....	16
2.1.4 Significance Level and Power .....	17

2.1.4.1	Power and the Magnitude of the Effect . . . . .	18
2.1.4.2	Power and Sample Size . . . . .	18
2.1.4.3	Power and the Alternative . . . . .	20
2.1.5	Exact, Unbiased, Conservative . . . . .	21
2.1.6	Impartial . . . . .	22
2.1.7	Most Stringent Tests . . . . .	23
2.2	Basic Assumptions . . . . .	23
2.2.1	Independent Observations . . . . .	23
2.2.2	Exchangeable Observations . . . . .	24
2.3	Decision Theory . . . . .	25
2.3.1	Bayes' Risk . . . . .	26
2.3.2	Mini-Max . . . . .	27
2.3.3	Generalized Decisions . . . . .	28
2.4	Exercises . . . . .	29
<b>3</b>	<b>Testing Hypotheses . . . . .</b>	<b>33</b>
3.1	Testing a Simple Hypothesis . . . . .	33
3.2	One-Sample Tests for a Location Parameter . . . . .	34
3.2.1	A Permutation Test . . . . .	34
3.2.2	A Parametric Test . . . . .	36
3.2.3	Properties of the Parametric Test . . . . .	37
3.2.4	Student's $t$ . . . . .	38
3.2.5	Properties of the Permutation Test . . . . .	39
3.2.6	Exact Significance Levels: A Digression . . . . .	39
3.3	Confidence Intervals . . . . .	40
3.3.1	Confidence Intervals Based on Permutation Tests . . . . .	41
3.3.2	Confidence Intervals Based on Parametric Tests . . . . .	42
3.3.3	Confidence Intervals Based on the Bootstrap . . . . .	43
3.3.4	Parametric Bootstrap . . . . .	45
3.3.5	Better Confidence Intervals . . . . .	46
3.4	Comparison Among the Test Procedures . . . . .	46
3.5	One-Sample Tests for a Scale Parameter . . . . .	48
3.5.1	Semiparametric Tests . . . . .	48
3.5.2	Parametric Tests: Sufficiency . . . . .	48
3.5.3	Unbiased Tests . . . . .	50
3.5.4	Comparison Among the Test Procedures . . . . .	50
3.6	Comparing the Location Parameters of Two Populations . . . . .	51
3.6.1	A UMPU Parametric Test: Student's $t$ . . . . .	51
3.6.2	A UMPU Semiparametric Procedure . . . . .	51
3.6.3	An Example . . . . .	54
3.6.4	Comparison of the Tests: The Behrens–Fisher Problem . . . . .	54

3.7	Comparing the Dispersions of Two Populations .....	57
3.7.1	The Parametric Approach.....	57
3.7.2	The Permutation Approach.....	58
3.7.3	The Bootstrap Approach .....	61
3.8	Bivariate Correlation .....	62
3.9	Which Test? .....	63
3.10	Exercises .....	63
<b>4</b>	<b>Distributions .....</b>	<b>67</b>
4.1	Properties of Independent Observations .....	67
4.2	Binomial Distribution .....	67
4.3	Poisson: Events Rare in Time and Space .....	68
4.3.1	Applying the Poisson .....	69
4.3.2	A Poisson Distribution of Poisson Distributions .....	70
4.3.3	Comparing Two Poissons.....	70
4.4	Time Between Events .....	71
4.5	The Uniform Distribution .....	71
4.6	The Exponential Family of Distributions .....	72
4.6.1	Proofs of the Properties.....	73
4.6.2	Normal Distribution .....	74
4.7	Which Distribution? .....	75
4.8	Exercises .....	75
<b>5</b>	<b>Multiple Tests .....</b>	<b>79</b>
5.1	Controlling the Overall Error Rate .....	79
5.1.1	Standardized Statistics.....	80
5.1.2	Paired Sample Tests .....	81
5.2	Combination of Independent Tests.....	81
5.2.1	Omnibus Statistics .....	82
5.2.2	Binomial Random Variables .....	82
5.2.3	Bayes' Factor .....	83
5.3	Exercises .....	84
<b>6</b>	<b>Experimental Designs .....</b>	<b>85</b>
6.1	Invariance .....	85
6.1.1	Some Examples .....	86
6.2	<i>k</i> -Sample Comparisons—Least-Squares Loss Function .....	87
6.2.1	Linear Hypotheses .....	87
6.2.2	Large and Small Sample Properties of the <i>F</i> -ratio Test .....	89
6.2.3	Discrete Data and Time-to-Event Data .....	90
6.3	<i>k</i> -Sample Comparisons—Other Loss Functions .....	91
6.3.1	<i>F</i> -ratio .....	91
6.3.2	Pitman Correlation.....	92

6.3.3	Effect of Ties . . . . .	95
6.3.4	Cochran–Armitage Test . . . . .	96
6.3.5	Linear Estimation . . . . .	96
6.3.6	A Unifying Theory . . . . .	97
6.4	Four Ways to Control Variation . . . . .	97
6.4.1	Control the Environment . . . . .	98
6.4.2	Block the Experiment . . . . .	98
6.4.2.1	Using Ranks . . . . .	99
6.4.2.2	Matched Pairs . . . . .	100
6.4.3	Measure Factors That Cannot Be Controlled . . . . .	101
6.4.3.1	Eliminate the Functional Relationship . . . . .	101
6.4.3.2	Selecting Variables . . . . .	102
6.4.3.3	Restricted Randomization . . . . .	102
6.4.4	Randomize . . . . .	103
6.5	Latin Square . . . . .	104
6.6	Very Large Samples . . . . .	106
6.7	Sequential Analysis . . . . .	107
6.7.1	A Vaccine Trial . . . . .	107
6.7.2	Determining the Boundary Values . . . . .	110
6.7.3	Power of a Sequential Analysis . . . . .	110
6.7.4	Expected Sample Size . . . . .	111
6.7.5	Curtailed Inspection . . . . .	112
6.7.6	Restricted Sequential Sampling Schemes . . . . .	112
6.8	Sequentially Adaptive Treatment Allocation . . . . .	113
6.8.1	Group Sequential Trials . . . . .	113
6.8.2	Determining the Sampling Ratio . . . . .	113
6.8.3	Exact Random Allocation Tests . . . . .	114
6.9	Exercises . . . . .	115
7	<b>Multifactor Designs . . . . .</b>	119
7.1	Multifactor Models . . . . .	119
7.2	Analysis of Variance . . . . .	120
7.3	Permutation Methods: Main Effects . . . . .	124
7.3.1	An Example . . . . .	125
7.4	Permutation Methods: Interactions . . . . .	126
7.5	Synchronized Rearrangements . . . . .	127
7.5.1	Exchangeable and Weakly Exchangeable Variables . . . . .	128
7.5.2	Two Factors . . . . .	129
7.5.3	Three or More Factors . . . . .	132
7.5.4	Similarities . . . . .	133
7.5.5	Test for Interaction . . . . .	135
7.6	Unbalanced Designs . . . . .	137
7.6.1	Missing Combinations . . . . .	138
7.6.2	The Boot-Perm Test . . . . .	139

7.7	Which Test Should You Use? . . . . .	140
7.8	Exercises . . . . .	140
<b>8</b>	<b>Categorical Data . . . . .</b>	<b>143</b>
8.1	Fisher's Exact Test . . . . .	143
8.1.1	Hypergeometric Distribution . . . . .	145
8.1.2	One-Tailed and Two-Tailed Tests . . . . .	145
8.1.3	The Two-Tailed Test . . . . .	146
8.1.4	Determining the <i>p</i> -Value . . . . .	146
8.1.5	What is the Alternative? . . . . .	148
8.1.6	Increasing the Power . . . . .	148
8.1.7	Ongoing Controversy . . . . .	149
8.2	Odds Ratio . . . . .	150
8.2.1	Stratified $2 \times 2$ 's . . . . .	151
8.3	Exact Significance Levels . . . . .	152
8.4	Unordered $r \times c$ Contingency Tables . . . . .	154
8.4.1	Agreement Between Observers . . . . .	156
8.4.2	What Should We Randomize? . . . . .	157
8.4.3	Underlying Assumptions . . . . .	158
8.4.4	Symmetric Contingency Tables . . . . .	158
8.5	Ordered Contingency Tables . . . . .	160
8.5.1	Ordered $2 \times c$ Tables . . . . .	160
8.5.1.1	Alternative Hypotheses . . . . .	161
8.5.1.2	Back-up Statistics . . . . .	162
8.5.1.3	Directed Chi-Square . . . . .	162
8.5.2	More Than Two Rows and Two Columns . . . . .	163
8.5.2.1	Singly Ordered Tables . . . . .	163
8.5.2.2	Doubly Ordered Tables . . . . .	163
8.6	Covariates . . . . .	164
8.6.1	Bross' Method . . . . .	164
8.6.2	Blocking . . . . .	165
8.7	Exercises . . . . .	166
<b>9</b>	<b>Multivariate Analysis . . . . .</b>	<b>169</b>
9.1	Nonparametric Combination of Univariate Tests . . . . .	169
9.2	Parametric Approach . . . . .	171
9.2.1	Canonical Form . . . . .	171
9.2.2	Hotelling's $T^2$ . . . . .	172
9.2.3	Multivariate Analysis of Variance (MANOVA) . . . . .	173
9.3	Permutation Methods . . . . .	173
9.3.1	Which Test—Parametric or Permutation? . . . . .	175
9.3.2	Interpreting the Results . . . . .	176

9.4	Alternative Statistics .....	177
9.4.1	Maximum- <i>t</i> .....	177
9.4.2	Block Effects .....	177
9.4.3	Runs Test .....	178
9.4.4	Which Statistic? .....	180
9.5	Repeated Measures .....	181
9.5.1	An Example .....	181
9.5.2	Matched Pairs .....	182
9.5.3	Response Profiles .....	183
9.5.4	Missing Data .....	183
9.5.5	Bioequivalence .....	184
9.6	Exercises .....	185
<b>10</b>	<b>Clustering in Time and Space .....</b>	<b>189</b>
10.1	The Generalized Quadratic Form .....	189
10.1.1	Mantel's <i>U</i> .....	189
10.1.2	An Example .....	189
10.2	Applications .....	190
10.2.1	The MRPP Statistic .....	190
10.2.2	The BW Statistic of Cliff and Ord [1973] .....	191
10.2.3	Equivalances .....	192
10.2.4	Extensions .....	192
10.2.5	Another Dimension .....	192
10.3	Alternate Approaches .....	193
10.3.1	Quadrant Density .....	193
10.3.2	Nearest-Neighbor Analysis .....	193
10.3.3	Comparing Two Spatial Distributions .....	193
10.4	Exercises .....	194
<b>11</b>	<b>Coping with Disaster .....</b>	<b>195</b>
11.1	Missing Data .....	195
11.2	Covariates After the Fact .....	197
11.2.1	Observational Studies .....	197
11.3	Outliers .....	198
11.3.1	Original Data .....	199
11.3.2	Ranks .....	199
11.3.3	Scores .....	200
11.3.4	Robust Transformations .....	201
11.3.5	Use an $L_1$ Test .....	201
11.3.6	Censoring .....	201
11.3.7	Discarding .....	202
11.4	Censored Data .....	202
11.4.1	GAMP Tests .....	202
11.4.2	Fishery and Animal Counts .....	204

11.5	Censored Match Pairs.....	204
11.5.1	GAMP Test for Matched Pairs.....	205
11.5.2	Ranks .....	206
11.5.3	One-Sample: Bootstrap Estimates .....	206
11.6	Adaptive Tests .....	207
11.7	Exercises .....	208
<b>12</b>	<b>Solving the Unsolved and the Insolvable .....</b>	<b>209</b>
12.1	Key Criteria .....	209
12.1.1	Sufficient Statistics .....	209
12.1.2	Three Stratagems .....	210
12.1.3	Restrict the Alternatives .....	210
12.1.4	Consider the Loss Function .....	212
12.1.5	Impartiality .....	213
12.2	The Permutation Distribution.....	213
12.2.1	Ensuring Exchangeability .....	213
12.2.1.1	Test for Parallelism .....	214
12.2.1.2	Linear Transforms That Preserve Exchangeability .....	215
12.3	New Statistics .....	216
12.3.1	Nonresponders .....	216
12.3.1.1	Extension to $K$ -samples .....	217
12.3.2	Animal Movement.....	217
12.3.3	The Building Blocks of Life.....	217
12.3.4	Structured Exploratory Data Analysis .....	218
12.3.5	Comparing Multiple Methods of Assessment .....	219
12.4	Model Validation .....	221
12.4.1	Regression Models.....	221
12.4.1.1	Via the Bootstrap .....	221
12.4.1.2	Via Permutation Tests .....	221
12.4.2	Models With a Metric .....	222
12.5	Bootstrap Confidence Intervals .....	223
12.5.1	Hall–Wilson Criteria.....	224
12.5.2	Bias-Corrected Percentile .....	225
12.6	Exercises .....	226
<b>13</b>	<b>Publishing Your Results .....</b>	<b>229</b>
13.1	Design Methodology .....	229
13.1.1	Randomization in Assignment .....	229
13.1.2	Choosing the Experimental Unit .....	230
13.1.3	Determining Sample Size.....	231
13.1.4	Power Comparisons .....	231
13.2	Preparing Manuscripts for Publication .....	231
13.2.1	Reportable Elements .....	232
13.2.2	Details of the Analysis .....	232

<b>14 Increasing Computational Efficiency . . . . .</b>	233
14.1 Seven Techniques . . . . .	233
14.2 Monte Carlo . . . . .	233
14.2.1 Stopping Rules . . . . .	234
14.2.2 Variance of the Result . . . . .	235
14.2.3 Cutting the Computation Time . . . . .	235
14.3 Rapid Enumeration and Selection Algorithms . . . . .	236
14.3.1 Matched Pairs . . . . .	236
14.4 Recursive Relationships . . . . .	236
14.5 Focus on the Tails . . . . .	237
14.5.1 Contingency Tables . . . . .	239
14.5.1.1 Network Representation . . . . .	239
14.5.1.2 The Network Algorithm . . . . .	241
14.5.2 Play the Winner Allocation . . . . .	242
14.5.3 Directed Vertex Peeling . . . . .	242
14.6 Gibbs Sampling . . . . .	243
14.6.1 Metropolis–Hastings Sampling Methods . . . . .	244
14.7 Characteristic Functions . . . . .	245
14.8 Asymptotic Approximations . . . . .	246
14.8.1 A Central Limit Theorem . . . . .	246
14.8.2 Edgeworth Expansions . . . . .	246
14.8.3 Generalized Correlation . . . . .	247
14.9 Confidence Intervals . . . . .	247
14.10 Sample Size and Power . . . . .	248
14.10.1 Simulations . . . . .	248
14.10.2 Network Algorithms . . . . .	249
14.11 Some Conclusions . . . . .	250
14.12 Software . . . . .	251
14.12.1 Do-It-Yourself . . . . .	251
14.12.2 Complete Packages . . . . .	252
14.12.2.1 Freeware . . . . .	252
14.12.2.2 Shareware . . . . .	252
14.12.2.3 \$\$\$ . . . . .	252
14.13 Exercises . . . . .	253
<b>Appendix: Theory of Testing Hypotheses . . . . .</b>	255
A.1 Probability . . . . .	255
A.2 The Fundamental Lemma . . . . .	257
A.3 Two-Sided Tests . . . . .	258
A.3.1 One-Parameter Exponential Families . . . . .	259
A.4 Tests for Multiparameter Families . . . . .	262
A.4.1 Basu’s Theorem . . . . .	262
A.4.2 Conditional Probability and Expectation . . . . .	263
A.4.3 Multiparameter Exponential Families . . . . .	263

A.5	Exchangeable Observations . . . . .	268
A.5.1	Order Statistics . . . . .	269
A.5.2	Transformably Exchangeable . . . . .	270
A.5.3	Exchangeability-Preserving Transforms . . . . .	271
A.6	Confidence Intervals . . . . .	272
A.7	Asymptotic Behavior . . . . .	273
A.7.1	A Theorem on Linear Forms . . . . .	273
A.7.2	Monte Carlo . . . . .	274
A.7.3	Asymptotic Efficiency . . . . .	274
A.7.4	Exchangeability . . . . .	275
A.7.5	Improved Bootstrap Confidence Intervals . . . . .	276
A.8	Exercises . . . . .	276
	<b>Bibliography</b> . . . . .	279
	<b>Author Index</b> . . . . .	303
	<b>Subject Index</b> . . . . .	309