# Preface xiii

# 1. Introduction

- 1.1. Advantages of Nonparametric Methods 1
- 1.2. The Distribution-Free Property
- 1.3. Some Real-World Applications 3
- 1.4. Format and Organization 6
- 1.5. Computing with R 8
- 1.6. Historical Background 9

# 2. The Dichotomous Data Problem

Introduction 11

- 2.1. A Binomial Test 11
- 2.2. An Estimator for the Probability of Success 22
- 2.3. A Confidence Interval for the Probability of Success (Wilson) 24

2

2.4. Bayes Estimators for the Probability of Success 33

### 3. The One-Sample Location Problem

	Introduction 39				
	Paired Replicates Analyses by Way of Signed Ranks 39				
3.1.	A Distribution-Free Signed Rank Test (Wilcoxon) 40				
3.2.	An Estimator Associated with Wilcoxon's Signed Rank Statistic				
	(Hodges-Lehmann) 56				
3.3.	A Distribution-Free Confidence Interval Based on Wilcoxon's Signed Rank Test				
	(Tukey) 59				
	Paired Replicates Analyses by Way of Signs 63				
3.4.	A Distribution-Free Sign Test (Fisher) 63				
3.5.	An Estimator Associated with the Sign Statistic (Hodges-Lehmann) 76				
3.6.	A Distribution-Free Confidence Interval Based on the Sign Test (Thompson,				
	Savur) 80				
	One-Sample Data 84				
3.7.	Procedures Based on the Signed Rank Statistic 84				
3.8.	Procedures Based on the Sign Statistic 90				
3.9.	An Asymptotically Distribution-Free Test of Symmetry				
	(Randles-Fligner-Policello-Wolfe, Davis-Quade) 94				
	Bivariate Data 102				
3.10.	A Distribution-Free Test for Bivariate Symmetry (Hollander) 102				
3.11.	Efficiencies of Paired Replicates and One-Sample Location Procedures 112				

1

11

39

# 4. The Two-Sample Location Problem

Introduction 115	Introd	luction	115
------------------	--------	---------	-----

- 4.1. A Distribution-Free Rank Sum Test (Wilcoxon, Mann and Whitney) 115
- 4.2. An Estimator Associated with Wilcoxon's Rank Sum Statistic (Hodges-Lehmann) 136
- (Hodges-Lehmann) 136
  4.3. A Distribution-Free Confidence Interval Based on Wilcoxon's Rank Sum Test (Moses) 142
- 4.4. A Robust Rank Test for the Behrens-Fisher Problem (Fligner-Policello) 145
- 4.5. Efficiencies of Two-Sample Location Procedures 149

#### 5. The Two-Sample Dispersion Problem and Other Two-Sample Problems 151

Introduction 151

- 5.1. A Distribution-Free Rank Test for Dispersion-Medians Equal (Ansari-Bradley) 152
- 5.2. An Asymptotically Distribution-Free Test for Dispersion Based on the Jackknife-Medians Not Necessarily Equal (Miller) 169
- 5.3. A Distribution-Free Rank Test for Either Location or Dispersion (Lepage) 181
- 5.4. A Distribution-Free Test for General Differences in Two Populations (Kolmogorov-Smirnov) 190
- 5.5. Efficiencies of Two-Sample Dispersion and Broad Alternatives Procedures 200

### 6. The One-Way Layout

# Introduction 202

- 6.1. A Distribution-Free Test for General Alternatives (Kruskal-Wallis) 204
- 6.2. A Distribution-Free Test for Ordered Alternatives (Jonckheere-Terpstra) 215
- 6.3. Distribution-Free Tests for Umbrella Alternatives (Mack-Wolfe) 225
- 6.3A. A Distribution-Free Test for Umbrella Alternatives, Peak Known (Mack-Wolfe) 226
- 6.3B. A Distribution-Free Test for Umbrella Alternatives, Peak Unknown (Mack-Wolfe) 241
  - 6.4. A Distribution-Free Test for Treatments Versus a Control (Fligner–Wolfe) 249 Rationale For Multiple Comparison Procedures 255
  - 6.5. Distribution-Free Two-Sided All-Treatments Multiple Comparisons Based on Pairwise Rankings-General Configuration (Dwass, Steel, and Critchlow-Fligner) 256
  - 6.6. Distribution-Free One-Sided All-Treatments Multiple Comparisons Based on Pairwise Rankings-Ordered Treatment Effects (Hayter-Stone) 265
- 6.7. Distribution-Free One-Sided Treatments-Versus-Control Multiple Comparisons Based on Joint Rankings (Nemenyi, Damico-Wolfe) 271
- 6.8. Contrast Estimation Based on Hodges-Lehmann Two-Sample Estimators (Spjøtvoll) 278
- 6.9. Simultaneous Confidence Intervals for All Simple Contrasts (Critchlow-Fligner) 282
- 6.10. Efficiencies of One-Way Layout Procedures 287

#### 7. The Two-Way Layout

#### Introduction 289

 7.1. A Distribution-Free Test for General Alternatives in a Randomized Complete Block Design (Friedman, Kendall-Babington Smith) 292

202

289

- 7.2. A Distribution-Free Test for Ordered Alternatives in a Randomized Complete Block Design (Page) 304
   Patient J. for M. Silver, Design (Page) 304
  - Rationale for Multiple Comparison Procedures 315
- 7.3. Distribution-Free Two-Sided All-Treatments Multiple Comparisons Based on Friedman Rank Sums-General Configuration (Wilcoxon, Nemenyi, McDonald-Thompson) 316
- 7.4. Distribution-Free One-Sided Treatments Versus Control Multiple Comparisons Based on Friedman Rank Sums (Nemenyi, Wilcoxon-Wilcox, Miller) 322
- 7.5. Contrast Estimation Based on One-Sample Median Estimators (Doksum) 328 Incomplete Block Data-Two-Way Layout with Zero or One Observation Per Treatment-Block Combination 331
- 7.6. A Distribution-Free Test for General Alternatives in a Randomized Balanced Incomplete Block Design (BIBD) (Durbin-Skillings-Mack) 332
- 7.7. Asymptotically Distribution-Free Two-Sided All-Treatments Multiple Comparisons for Balanced Incomplete Block Designs (Skillings-Mack) 341
- 7.8. A Distribution-Free Test for General Alternatives for Data From an Arbitrary Incomplete Block Design (Skillings-Mack) 343
   Replications-Two-Way Layout with at Least One Observation for Every Treatment-Block Combination 354
- 7.9. A Distribution-Free Test for General Alternatives in a Randomized Block Design with an Equal Number c(>1) of Replications Per Treatment-Block Combination (Mack-Skillings) 354
- 7.10. Asymptotically Distribution-Free Two-Sided All-Treatments Multiple Comparisons for a Two-Way Layout with an Equal Number of Replications in Each Treatment-Block Combination (Mack-Skillings) 367 Analyses Associated with Signed Ranks 370
- 7.11. A Test Based on Wilcoxon Signed Ranks for General Alternatives in a Randomized Complete Block Design (Doksum) 370
- 7.12. A Test Based on Wilcoxon Signed Ranks for Ordered Alternatives in a Randomized Complete Block Design (Hollander) 376
- 7.13. Approximate Two-Sided All-Treatments Multiple Comparisons Based on Signed Ranks (Nemenyi) 379
- 7.14. Approximate One-Sided Treatments-Versus-Control Multiple Comparisons Based on Signed Ranks (Hollander) 382
- 7.15. Contrast Estimation Based on the One-Sample Hodges-Lehmann Estimators (Lehmann) 386
- 7.16. Efficiencies of Two-Way Layout Procedures 390

# 8. The Independence Problem

### Introduction 393

- 8.1. A Distribution-Free Test for Independence Based on Signs (Kendall) 393
- 8.2. An Estimator Associated with the Kendall Statistic (Kendall) 413
- An Asymptotically Distribution-Free Confidence Interval Based on the Kendall Statistic (Samara-Randles, Fligner-Rust, Noether) 415
- 8.4. An Asymptotically Distribution-Free Confidence Interval Based on Efron's Bootstrap 420
- 8.5. A Distribution-Free Test for Independence Based on Ranks (Spearman) 427
- 8.6. A Distribution-Free Test for Independence Against Broad Alternatives (Hoeffding) 442
- 8.7. Efficiencies of Independence Procedures 450

# 9. Regression Problems

		Introduction 451		
		One Regression Line 452		
	9.1.	A Distribution-Free fest for the Stope of the Regression Enne (1997)		
	9.2.	A Slope Estimator Associated with the Then State to the the Theil Test		
	9.3.			
	0.4	(Theil) 460 An Intercept Estimator Associated with the Theil Statistic and Use of the Estim	ated	
	9.4.	Linear Relationship for Prediction (Hettmansperger–McKean–Sheather) 463	3	
		k(>2) Regression Lines 466		
	9.5.		ion	
	9.5.	Lines (Sen, Adichie) 466		
		General Multiple Linear Regression 475		
	9.6.	Asymptotically Distribution-Free Rank-Based Tests for General Multiple Linear		
	2.0.	Regression (Jaeckel, Hettmansperger–McKean) 475		
		Nonparametric Regression Analysis 490		
	9.7.			
		Analysis 490		
	9.8.	Efficiencies of Regression Procedures 494		
10.	Com	paring Two Success Probabilities	495	
		Introduction 495		
	10.1.	Approximate Tests and Confidence Intervals for the Difference between Two Sur	cess	
		Probabilities (Pearson) 496		
	10.2.	An Exact Test for the Difference between Two Success Probabilities (Fisher)	511	
	10.3.			
	10.4.	Inference for k Strata of $2 \times 2$ Tables (Mantel and Haenszel) 522		
	10.5.	Efficiencies 534		
11	Life	Distributions and Survival Analysis		
<u> </u>		Distributions and Survival Analysis	535	
		Introduction 535		
	11.1.	A Test of Exponentiality Versus IFR Alternatives (Epstein) 536		
	11.2.	A Test of Exponentiality Versus NBU Alternatives (Hollander-Proschan) 545		
	11,3.	A Trank of The state of the sta	55	
	11.4.	A Test of Exponentiality Versus a Trend Change in Mean Residual Life	22	
		(Guess-Hollander-Proschan) 563		
	11.5.	A Confidence Band for the Distribution Function (Kolmogorov) 568		
	11.6.	An Estimator of the Distribution Function When the Data are Censored (Kaplan–Meier) 578		
	11.7.	A Two-Sample Test for Censored Data (Mantel) 594		
	11.8.	Efficiencies 605		
12	Done	the Frains deale		
1 <i>#</i> ••	Dens	ity Estimation	609	

# 12. Density Estimation

Introduction 609

- 12.1. Density Functions and Histograms 609
- 12.2. Kernel Density Estimation 617
- 12.3. Bandwidth Selection 624
- 12.4. Other Methods 628

#### 13. Wavelets

#### 14. Smooth ιg

	Introduction	656	
14.1.	Local Averagii	ng (Friedman)	657
14.2.	Local Regress	ion (Cleveland)	662

- Kernel Smoothing 14.3. 667
- Other Methods of Smoothing 14.4. 675

#### 15. Ranked Set Sampling

676 Introduction

- Rationale and Historical Development 15.1. 676
- Collecting a Ranked Set Sample 15.2. 677
- Ranked Set Sampling Estimation of a Population Mean 15.3. 685
- Ranked Set Sample Analogs of the Mann-Whitney-Wilcoxon Two-Sample 15.4. Procedures (Bohn-Wolfe) 717
- Other Important Issues for Ranked Set Sampling 737 15.5.
- 15.6. Extensions and Related Approaches 742

#### 16. An Introduction to Bayesian Nonparametric Statistics via the Dirichlet 744 Process

Introduction 744 16.1. Ferguson's Dirichlet Process 745 16.2. A Bayes Estimator of the Distribution Function (Ferguson) 749 752 16.3. Rank Order Estimation (Campbell and Hollander) 16.4. A Bayes Estimator of the Distribution When the Data are Right-Censored (Susarla and Van Ryzin) 755 759 16.5. Other Bayesian Approaches **Bibliography** 763 **R** Program Index 791 **Author Index** 799

Subject Index 809 629

656

676