

Contents

1	Introduction	13
1.1	Why this textbook?	13
1.2	Types of data	16
1.3	Data and models	16
1.4	Sequence of topics	17
1.5	References	19
2	Review of Mathematics	21
2.1	Exponents	21
2.2	Inequalities	23
2.3	Functions	24
2.3.1	Functions in Statistics	25
2.3.2	Plotting functions using SAS - SAS demo	26
2.4	Solving linear equations	35
2.5	Roots of equations	36
2.6	Calculus	37
2.6.1	Derivatives	37
2.6.2	Function plot with derivative - SAS demo	39
2.6.3	Integrals	44
2.7	References	46
2.8	Problems	47
3	Populations and Statistics	49
3.1	Statistical populations	49
3.2	Descriptive statistics and frequency	50
3.2.1	Sample mean	51
3.2.2	Median	52
3.2.3	Sample variance	53

3.2.4	Standard deviation	53
3.2.5	Coefficient of variation	53
3.2.6	Range	54
3.2.7	Frequency distributions - SAS demo	54
3.2.8	Mode	62
3.2.9	Skewness	62
3.2.10	Kurtosis	65
3.2.11	Development time - SAS demo	68
3.2.12	Frequency distributions for categorical data - SAS demo	73
3.3	References	77
3.4	Problems	78
4	Probability Theory	79
4.1	Probability theory	79
4.1.1	Events	79
4.1.2	Union, intersection, and complement of events	80
4.1.3	Probability distributions	84
4.1.4	Probability spaces	86
4.1.5	Independence of events	86
4.1.6	Conditional probability	87
4.1.7	A biological probability distribution	88
4.1.8	Bayes theorem	91
4.2	References	95
4.3	Problems	96
5	Discrete Random Variables	97
5.1	Binomial distribution	98
5.1.1	Binomial distribution - SAS demo	100
5.2	Poisson distribution	104
5.2.1	Poisson distribution - SAS demo	105
5.3	Negative binomial distribution	108
5.3.1	Negative binomial distribution - SAS demo	108
5.4	Expected values for discrete distributions	112
5.4.1	Variance for discrete distributions	114
5.5	Discrete random variables and samples	116
5.5.1	Parasitic wasps - SAS demo	116
5.5.2	Corn borers - SAS demo	124
5.6	Classifying spatial or temporal patterns	133

CONTENTS	5
-----------------	----------

5.7 References	136
5.8 Problems	137
6 Continuous Random Variables	139
6.1 Uniform distribution	140
6.1.1 Random sampling coordinates - SAS demo	143
6.2 Normal distribution	149
6.2.1 Normal distribution - SAS demo	151
6.2.2 Sample calculations - standard normal distribution . .	153
6.2.3 Sample calculations - other normal distributions . . .	158
6.3 Expected values and variance for continuous distributions . .	161
6.4 Continuous random variables and samples	162
6.4.1 Elytra lengths - SAS demo	165
6.4.2 Development time - SAS demo	170
6.5 References	175
6.6 Problems	176
7 Expected Value, Variance, and Samples	177
7.1 Expected value and variance	177
7.2 Linear functions and sums - expected value and variance . .	179
7.3 Sample mean - expected value and variance	180
7.4 Sample variance - expected value	181
7.5 Sample calculations and simulation - SAS demo	182
7.6 Central limit theorem	190
7.6.1 Central limit theorem - SAS demo	190
7.7 Applications of the central limit theorem	197
7.8 References	198
7.9 Problems	199
8 Sampling and Estimation	201
8.1 Random samples	201
8.2 Parameter estimation	202
8.2.1 Maximum likelihood for Poisson data	203
8.2.2 Poisson likelihood function - SAS demo	205
8.2.3 Maximum likelihood for normal data	210
8.2.4 Normal likelihood function - SAS demo	211
8.3 Optimality of maximum likelihood estimates	216
8.4 References	216

8.5 Problems	217
9 Confidence Intervals	219
9.1 Preliminaries to confidence intervals	219
9.1.1 Parameters and estimates	219
9.1.2 Sampling distributions	220
9.2 Confidence intervals	225
9.2.1 Confidence intervals for μ when σ^2 is known	226
9.2.2 Confidence intervals for μ when σ^2 is estimated	228
9.2.3 Confidence intervals for σ^2 and σ	230
9.2.4 Confidence intervals - SAS demo	232
9.2.5 Confidence interval size	233
9.3 References	239
9.4 Problems	240
10 Hypothesis Testing	241
10.1 The null and alternative hypotheses	241
10.2 Test statistics	242
10.3 Acceptance and rejection regions – Type I error	243
10.3.1 One-sample Z test - sample calculation	246
10.4 P values	246
10.5 Type II error and power	249
10.6 Summary table	254
10.7 One-sample t test	255
10.7.1 One-sample t test - sample calculation	256
10.7.2 Hypothesis testing - SAS demo	257
10.7.3 Power analysis for one-sample t tests - SAS demo	260
10.8 One-tailed t test	264
10.8.1 One-tailed t test - sample calculation	266
10.8.2 One-tailed t test - SAS demo	266
10.8.3 One-tailed tests - a warning	267
10.9 Confidence intervals and tests	268
10.10 Likelihood ratio tests	269
10.10.1 Example of a likelihood ratio test	269
10.11 References	273
10.12 Problems	274

11 Analysis of Variance (One-Way)	277
11.1 ANOVA models	281
11.1.1 Fixed and random effects	281
11.1.2 Fixed effects model	282
11.1.3 Random effects model	285
11.2 Hypothesis testing for ANOVA	287
11.2.1 Sums of squares and mean squares	287
11.2.2 <i>F</i> statistic and distribution	290
11.2.3 ANOVA tables	292
11.2.4 One-way ANOVA for Example 1 - SAS demo	295
11.2.5 One-way ANOVA for Example 2 - sample calculation .	302
11.2.6 One-way ANOVA for Example 2 - SAS demo	304
11.3 Maximum likelihood estimates	311
11.4 <i>F</i> test as a likelihood ratio test	313
11.5 One-way ANOVA and two-sample <i>t</i> tests	314
11.5.1 Two-sample <i>t</i> test for Example 1 - SAS demo	314
11.6 References	319
11.7 Problems	320
12 Power Analysis for One-Way ANOVA	323
12.1 Power analysis for one-way ANOVA	324
12.2 Power analysis - SAS Demo	328
12.3 Power analysis continued - SAS demo	332
12.4 Power analysis continued - SAS demo	335
12.5 References	337
12.6 Problems	338
13 Multiple Comparisons	339
13.1 Models for multiple comparisons	339
13.2 Error rates in multiple comparisons	340
13.3 All pairwise comparisons	342
13.3.1 Least significant difference	343
13.3.2 Least significant difference - SAS demo	345
13.3.3 The Tukey procedure	353
13.3.4 Tukey procedure - SAS demo	354
13.3.5 Multiple range tests - REGW	357
13.3.6 REGW procedure - SAS demo	359
13.4 Comparisons with a control - Dunnett procedure	361

13.4.1 Dunnett's procedure - SAS demo	361
13.5 Bonferroni and Sidak corrections	363
13.6 Vascular plant cover - SAS demo	365
13.7 False discovery rate procedure	374
13.7.1 False discovery rate - SAS demo	376
13.8 References	379
13.9 Problems	380
14 Analysis of Variance (Two-Way)	383
14.1 Random assignment of treatments	389
14.1.1 Random assignment of treatments - SAS Demo	390
14.2 Two-way fixed effects model	393
14.2.1 Factor A effect	394
14.2.2 Factor B effect	394
14.2.3 Factor A and B effect	394
14.2.4 Interaction effect	394
14.3 Hypothesis testing for two-way ANOVA	398
14.3.1 Sum of squares and mean squares	398
14.3.2 ANOVA tables and tests	402
14.3.3 Two-way ANOVA for Example 1 - SAS demo	405
14.3.4 Two-way ANOVA for Example 2 - SAS demo	411
14.3.5 Tests for main effects with interaction	416
14.4 Unbalanced designs and two-way ANOVA	420
14.5 Two-way ANOVA without replication	423
14.5.1 Hypothesis testing	423
14.5.2 Two-way ANOVA no replication - SAS demo	430
14.6 Randomized block designs	436
14.6.1 Randomized block models	438
14.6.2 Hypothesis testing and variance components	438
14.6.3 Randomized block design - SAS demo	439
14.6.4 Likelihood ratio test for the block effect	447
14.7 References	452
14.8 Problems	453
15 Assumptions and Transformations	455
15.1 ANOVA assumptions	455
15.1.1 Independence of observations	455
15.1.2 Homogeneity of variances	456

15.1.3	Normality	457
15.1.4	Absence of outliers	457
15.1.5	Additivity	458
15.2	Variance-stabilizing transformations	459
15.3	Residual analysis	460
15.3.1	Models, estimates, and predictors	461
15.3.2	Predicted and residual values	461
15.3.3	Evaluating ANOVA assumptions	463
15.3.4	Residual analysis and transformations - SAS demo . .	464
15.3.5	$\arcsin(\sqrt{Y})$ transformation - SAS demo	470
15.3.6	Transformations when data are limited	478
15.4	References	479
16	Nonparametric Tests	481
16.1	Wilcoxon two-sample test	485
16.1.1	Wilcoxon test for Example 1 - SAS demo	487
16.2	Kruskal-Wallis test	494
16.2.1	Kruskal-Wallis test for Example 1 - SAS demo . . .	495
16.2.2	Kruskal-Wallis test for Example 2 - SAS demo . . .	496
16.3	Kolmogorov-Smirnov test	499
16.3.1	Kolmogorov-Smirnov test for Example 1 - SAS demo .	500
16.4	Randomization tests	504
16.4.1	Randomization test for Example 3 - SAS demo . . .	506
16.5	Limitations of nonparametric tests	513
16.6	References	515
16.7	Problems	516
17	Linear Regression	517
17.1	Linear regression model	521
17.2	Linear regression and likelihood	521
17.2.1	Sample calculation - $\hat{\beta}$, $\hat{\alpha}$, and F test	527
17.3	Confidence and prediction intervals	530
17.3.1	Sample calculation - confidence and prediction intervals	532
17.4	R^2 values	534
17.5	Linear regression for Example 1 - SAS demo	535
17.6	Assumptions and transformations	544
17.6.1	Species-area data - SAS demo	545
17.6.2	Population growth rates - SAS demo	552

17.7 References	558
17.8 Problems	559
18 Correlation	561
18.1 Correlation model	564
18.2 Correlation and maximum likelihood	570
18.2.1 Correlation for Example 1 - SAS demo	572
18.2.2 Testing $H_0 : \rho = \rho_0$ - SAS demo	577
18.2.3 Correlation for <i>I. setosa</i> , all data - SAS demo	578
18.3 Correlation assumptions	583
18.4 Nonparametric correlation	585
18.4.1 Spearman rank correlation for Example 1 - SAS demo .	587
18.5 References	588
18.6 Problems	589
19 More Complex ANOVA Designs	591
19.1 Three-way ANOVA	591
19.1.1 Three-way fixed effects model	594
19.1.2 Three-way ANOVA for Example 1 - SAS demo	595
19.1.3 Tests for main effects with interaction	604
19.1.4 Other three-way designs	608
19.2 One-way nested ANOVA	609
19.2.1 Nested ANOVA models	611
19.2.2 Nested ANOVA for Example 2 - SAS demo	612
19.3 Analysis of covariance	620
19.3.1 ANCOVA model	622
19.3.2 ANCOVA for Example 3 - SAS demo	622
19.4 References	629
19.5 Problems	630
20 Methods for Categorical Data	633
20.1 Goodness-of-fit tests	635
20.1.1 Goodness-of-fit tests for a categories	642
20.1.2 Goodness-of-fit tests with estimated parameters	647
20.1.3 Corn borers - SAS demo	647
20.2 Tests of independence	653
20.2.1 Test of independence - sample calculation	655
20.2.2 Test of independence - SAS demo	656

CONTENTS	11
----------	----

20.2.3 Test of independence - SAS demo 2	662
20.3 References	668
20.4 Problems	669
21 Multiple Regression	671
21.1 Multiple regression model	676
21.2 Multiple regression in matrix form	676
21.3 Multiple regression and likelihood	680
21.4 Tests and confidence intervals for β	687
21.5 Standardized regression coefficients	688
21.6 R^2 values	688
21.7 Multiple regression for Example 1 - SAS demo	689
21.8 Visualizing the multiple regression model	697
21.9 Collinearity in multiple regression	699
21.10 Multiple regression for Example 2 - SAS demo	699
21.11 Power analysis for multiple regression	707
21.12 Polynomial regression	710
21.13 Population growth experiment - SAS demo	710
21.14 Model selection using information criteria	717
21.15 Model selection for Example 3 - SAS demo	723
21.16 References	731
21.17 Problems	732
22 Data Sets	737
22.1 Elytra Length	738
22.2 Development Time	742
22.3 Plant Biomass	745
22.4 <i>Anagrus</i> fecundity	747
22.5 Fitness of <i>T. dubius</i>	755
22.6 <i>Iris</i> flower measurements	757
22.7 References	759
23 Statistical Tables	761
23.1 Table Z: Probabilities for the standard normal distribution.	762
23.2 Table T: Quantiles of the <i>t</i> distribution	764
23.3 Table C: Quantiles of the χ^2 distribution	767
23.4 Table F: Quantiles of the <i>F</i> distribution	770

24 Matrix Programs	781
24.1 Matrix calculations	782
24.2 Multiple regression in matrix form	783
24.3 References	785