Contents in brief

Preface xxvii Acknowledgments xxxi About the authors xxxiii

PART 1 INTRODUCTION TO STATISTICS

- 1. Statistics and samples 1
- INTERLEAF 1 Biology and the history of statistics 23
 - 2. Displaying data 25
 - 3. Describing data 65
 - 4. Estimating with uncertainty 95
- INTERLEAF 2 Pseudoreplication 115
 - 5. Probability 117
 - 6. Hypothesis testing 149
- INTERLEAF 3 Why statistical significance is not the same as biological importance 176

PART 2 PROPORTIONS AND FREQUENCIES

- 7. Analyzing proportions 179
- INTERLEAF 4 Correlation does not require causation 201
 - 8. Fitting probability models to frequency data 203

INTERLEAF 5 Making a plan 233

9. Contingency analysis: associations between categorical variables 235

Review Problems 1 269

PART 3 COMPARING NUMERICAL VALUES

- 10. The normal distribution 273
- INTERLEAF 6 Controls in medical studies 301
 - 11. Inference for a normal population 303
 - 12. Comparing two means 327
- INTERLEAF 7 Which test should I use? 366
 - Handling violations of assumptions 369
 Review Problems 2 417
 - 14. Designing experiments 423
- INTERLEAF 8 Data dredging 456
 - 15. Comparing means of more than two groups 459
- INTERLEAF 9 Experimental and statistical mistakes 500

PART 4 REGRESSION AND CORRELATION

- 16. Correlation between numerical variables 503
- INTERLEAF 10 Publication bias 535
 - 17. Regression 539
- INTERLEAF 11 Using species as data points 593 Review Problems 3 597

PART 5 MODERN STATISTICAL METHODS

- 18. Multiple explanatory variables 605
- 19. Computer-intensive methods 635
- 20. Likelihood 655
- 21. Meta-analysis: combining information from multiple studies 681

Statistical tables 701 Literature cited 725 Answers to practice problems 747 Photo credits 803 Index 807

Contents

Preface xxvii Acknowledgments xxxi About the authors xxxiii

PART 1 INTRODUCTION TO STATISTICS

- 1. Statistics and samples 1
 - 1.1 What is statistics? 1
 - 1.2 Sampling populations 3 Example 1.2: Raining cats 3 Populations and samples 4 Properties of good samples 5 Random sampling 7 How to take a random sample 8 The sample of convenience 9 Volunteer bias 10 Data in the real world 11
 - 1.3 Types of data and variables 11 Categorical and numerical variables 11 Explanatory and response variables 13
 - 1.4 Frequency distributions and probability distributions 13
 - 1.5 Types of studies 15
 - 1.6 Summary 16 Practice problems 17 Assignment problems 19
- INTERLEAF 1 Biology and the history of statistics 23
 - 2. Displaying data 25
 - 2.1 Guidelines for effective graphs 26 How to draw a bad graph 26 How to draw a good graph 27
 - 2.2 Showing data for one variable 30 Showing categorical data: frequency table and bar graph 30

		Example 2.2A: Crouching tiger 31 Making a good bar graph 32 A bar graph is usually better than a pie chart 33 Showing numerical data: frequency table and histogram 33 Example 2.2B: Abundance of desert bird species 34 Describing the shape of a histogram 36 How to draw a good histogram 37
	• •	Other graphs for numerical data 38
	2.3	Showing association between two variables 58 Showing association between categorical variables 38
		Example 2.3A: Reproductive effort and avian malaria 39
		Showing association between numerical variables: scatter plot 42
		Example 2.3B: Sins of the father 42
		Showing association between a numerical and a categorical variable 43
		Example 2.3C: Blood responses to high elevation 43
	2.4	Showing trends in time and space 46 Line graph 46
		Example 2.4A: Bad science can be deadly 46 Maps 47
		Example 2.4B: Biodiversity hotspots 48
	2.5	How to make good tables 48 Follow similar principles for display tables 49
	2.6	Summary 51
		Practice problems 52
		Assignment problems 58
3.	Desc	ribing data 65
	3.1	Arithmetic mean and standard deviation 66 Example 3.1: Gliding snakes 66
		The sample mean 67 Variance and standard deviation 68 Rounding means, standard deviations, and other quantities 70 Coefficient of variation 70 Calculating mean and standard deviation from
		a frequency table 71 Effect of changing measurement scale 72
	3.2	Median and interquartile range 73
		Example 3.2: I'd give my right arm for a female 74 The median 74

		The interquartile range 75 The box plot 76
	3.3	How measures of location and spread compare 77
		Example 3.3: Disarming fish 77
		Mean versus median 78
		Standard deviation versus interquartile range 80
	3.4	Cumulative frequency distribution 80
		Displaying cumulative relative frequencies 81
	3.5	Proportions 82
		Calculating a proportion 82 The proportion is like a sample mean 83
	3.6	Summary 83
	3.7	Quick Formula Summary 84
		Practice problems 85
		Assignment problems 89
4.	Estir	nating with uncertainty 95
	4.1	The sampling distribution of an estimate 96
		Example 4.1: The length of human genes 96
		Estimating mean gene length with a random sample 98 The sampling distribution of \overline{Y} 99
	4.2	Measuring the uncertainty of an estimate 100 Standard error 101 The standard error of \overline{Y} 101 The standard error of \overline{Y} from data 101
	4.3	Confidence intervals 102 The 2SE rule of thumb 104
	4.4	Error bars 104
	4.5	Summary 106
	4.6	Quick Formula Summary 107
		Practice problems 107
		Assignment problems 110
INTERLEAF 2	Pseu	doreplication 115
5.	Prob	ability 117
	5.1	The probability of an event 117
	5.2	Venn diagrams 119
	5.3	Mutually exclusive events 120

	5.4	Probability distributions 120 Discrete probability distributions 121 Continuous probability distributions 121
	5.5	Either this or that: adding probabilities 123 The addition rule 123 The probabilities of all possible mutually exclusive outcomes add to one 124 The general addition rule 125
	5.6	Independence and the multiplication rule 126 Multiplication rule 127
		Example 5.6A: Smoking and high blood pressure 127 "And" versus "or" 128 Independence of more than two events 128 Example 5.6B: Mendel's peas 128
	5.7	Probability trees 129 Example 5.7: Sex and birth order 129
	5.8	Dependent events 131
		Example 5.8: Is this meat taken? 131
	5.9	Conditional probability and Bayes' theorem 133 Conditional probability 134 The general multiplication rule 135 Sampling without replacement 136 Bayes' theorem 136
		Example 5.9: Detection of Down syndrome 137
	5.10	Summary 138
		Practice problems 139
		Assignment problems 144
6. Hypothesis testing 149		thesis testing 149
	6.1	Making and using hypotheses 150 Null hypothesis 151 Alternative hypothesis 152 To reject or not to reject 152
	6.2	Hypothesis testing: an example 153
		Example 6.2: The right hand of toad 153
		Stating the hypotheses 153 The test statistic 154 The null distribution 154 Quantifying uncertainty: the <i>P</i> -value 156 Draw the appropriate conclusion 158
		Reporting the results 159

190

- 6.3 Errors in hypothesis testing 159 Type I and Type II errors 160
- 6.4 When the null hypothesis is not rejected 161
 Example 6.4: The genetics of mirror-image flowers 161
 The test 162
 Interpreting a non-significant result 163
- 6.5 One-sided tests 164
- 6.6 Hypothesis testing versus confidence intervals 166
- 6.7 Summary 167 Practice problems 168 Assignment problems 170
- INTERLEAF 3 Why statistical significance is not the same as biological importance 176

PART 2 PROPORTIONS AND FREQUENCIES

7. Analyzing proportions 179 7.1 The binomial distribution 180 Formula for the binomial distribution 180

- Number of successes in a random sample 182 Sampling distribution of the proportion 183
- 7.2 Testing a proportion: the binomial test 185 Example 7.2: Sex and the X 185 Approximations for the binomial test 188

7.3 Estimating proportions 188

- Example 7.3: Radiologists' missing sons 189 Estimating the standard error of a proportion 189 Confidence intervals for proportions the Agresti–Coull method 189 Confidence intervals for proportions—the Wald method
- 7.4 Deriving the binomial distribution 191
- 7.5 Summary 192
- 7.6 Quick Formula Summary 192 Practice problems 193 Assignment problems 198
- INTERLEAF 4 Correlation does not require causation 201

8.	Fitting probability models to frequency data 203			
	8.1	Example of a probability model: the proportional model 204		
		Example 8.1: No weekend getaway 204		
	8.2	χ^2 goodness-of-fit test 205 Null and alternative hypotheses 205 Observed and expected frequencies 206 The χ^2 test statistic 207 The sampling distribution of χ^2 under the null hypothesis 208 Calculating the <i>P</i> -value 209 Critical values for the χ^2 distribution 210		
	8.3	Assumptions of the χ^2 goodness-of-fit test 212		
	8.4	Goodness-of-fit tests when there are only two categories 213		
		Example 8.4: Gene content of the human X chromosome 213		
	8.5	Fitting the binomial distribution 214		
		Example 8.5: Designer two-child families? 215		
	8.6	Random in space or time: the Poisson distribution 217 Formula for the Poisson distribution 219 Testing randomness with the Poisson distribution 219		
		Example 8.6: Mass extinctions 219 Comparing the variance to the mean 223		
	8.7	Summary 223		
	8.8	Quick Formula Summary 224		
		Practice problems 225		
		Assignment problems 228		
INTERLEAF 5	Maki	ng a plan 233		
9.	Conti varia	ngency analysis: associations between categorical bles 235		
	9.1	Associating two categorical variables 236		
	9.2	Estimating association in 2 \times 2 tables: odds ratio 236 Odds 237		
		Example 9.2: Take two aspirin and call me in the morning? 238 Odds ratio 239 Standard error and confidence interval for odds ratio 240		
	9.3	Estimating association in 2×2 table: relative risk 242 Odds ratio vs. relative ristk 242		
	o (Example 9.3: Your litter box and your brain 243		
	9.4	Example 9.4: The gnarly worm gets the bird 246		

Hypotheses 247 Expected frequencies assuming independence 247 The χ^2 statistic 249 Degrees of freedom 249 *P*-value and conclusion 249 A shortcut for calculating the expected frequencies 250 The χ^2 contingency test is a special case of the χ^2 goodness-of-fit test 251 Assumptions of the χ^2 contingency test 251 Correction for continuity 251

- 9.5 Fisher's exact test 252 Example 9.5: The feeding habits of vampire bats 252
- 9.6 G-tests 254
- 9.7 Summary 255
- 9.8 Quick Formula Summary 255 Practice problems 257 Assignment problems 262

Review Problems 1 269

PART 3: COMPARING NUMERICAL VALUES

10. The normal distribution 273

- 10.1 Bell-shaped curves and the normal distribution 274
- 10.2 The formula for the normal distribution 276
- 10.3 Properties of the normal distribution 277
- 10.4 The standard normal distribution and statistical tables 278 Using the standard normal table 279 Using the standard normal to describe any normal distribution 280

Example 10.4: One small step for man? 281

- 10.5 The normal distribution of sample means 283 Calculating probabilities of sample means 285
- 10.6 Central limit theorem 286 Example 10.6: Young adults and the Spanish flu 286
- 10.7 Normal approximation to the binomial distribution 289 Example 10.7: The only good bug is a dead bug 289
- 10.8 Summary 292
- 10.9 Quick Formula Summary 293

xviii

		Practice problems 293 Assignment problems 297
	•	
INTERLEAF 6	Contr	rols in medical studies 301
11.	Infere	ence for a normal population 303
	11.1	The <i>t</i> -distribution for sample means 304 Student's <i>t</i> -distribution 304 Finding critical values of the <i>t</i> -distribution 306
	11.2	The confidence interval for the mean of a normal distribution 307
		Example 11.2: Eye to eye 307
		The 95% confidence interval for the mean308The 99% confidence interval for the mean309
	11.3	The one-sample <i>t</i> -test 310
		Example 11.3: Human body temperature 310
		The effects of larger sample size—body temperature revisited 313
	11.4	Assumptions of the one-sample <i>t</i> -test 314
	11.5	Estimating the standard deviation and variance of a normal population 314 Confidence limits for the variance 315 Confidence limits for the standard deviation 316 Assumptions 316
	11.6	Summary 317
	11.7	Quick Formula Summary 317
		Practice problems 318
		Assignment problems 321
12.	Com	paring two means 327
	12.1	Paired sample versus two independent samples 328
	12.2	Paired comparison of means 329 Estimating mean difference from paired data 330 Example 12.2: So macho it makes you sick? 330 Paired <i>t</i> -test 333
		Assumptions 334
	12.3	Iwo-sample comparison of means 335

Example 12.3: Spike or be spiked 335

Confidence interval for the difference between two means 336 Two-sample *t*-test 338 Assumptions 340 A two-sample *t*-test when standard deviations are unequal 341

	12.4	Using the correct sampling units 341 Example 12.4: So long: thanks to all the fish 342
	12.5	The fallacy of indirect comparison 344
		Example 12.5: Mommy's baby, Daddy's maybe 345
	12.6	Interpreting overlap of confidence intervals 346
	12.7	Comparing variances 347 The F-test of equal variances 348 Levene's test for homogeneity of variances 348
	12.8	Summary 349
	12.9	Quick Formula Summary 350
		Practice problems 353
		Assignment problems 360
INTERLEAF 7	Whic	h test should I use? 366
13.	Hand	lling violations of assumptions 369
	13.1	Detecting deviations from normality 370 Graphical methods 370
		Example 13.1: The benefits of marine reserves 373
		Formal test of normality 374
	13.2	When to ignore violations of assumptions 375 Violations of normality 375 Unequal standard deviations 376
	13.3	Data transformations 377 Log transformation 377 Arcsine transformation 380 The square-root transformation 381 Other transformations 381 Confidence intervals with transformations 381 A caveat: Avoid multiple testing with transformations 382
	13.4	Nonparametric alternatives to one-sample and paired <i>t</i> -tests 383 Sign test 383
		Example 13.4: Sexual conflict and the origin of new species 384
		The Wilcoxon signed-rank test 387
	13.5	Comparing two groups: the Mann–Whitney U-test 387
		Example 13.5: Sexual cannibalism in sagebrush crickets 387
		Tied ranks 391
		Large samples and the normal approximation 392
	13.6	Assumptions of nonparametric tests 392

	13.7 13.8	Type I and Type II error rates of nonparametric methods Permutation tests 394 Assumptions of permutation tests 397	393			
	13.9	Quick Formula Summary 399				
	19.10	Practice problems 400				
		Assignment problems 408				
	Revie	w Problems 2 417				
14.	Desig	Designing experiments 423				
	14.1	Why do experiments? 424 Confounding variables 424 Experimental artifacts 425				
	14.2	Lessons from clinical trials 426				
		Example 14.2: Reducing HIV transmission 426 Design components 426				
	14.3	How to reduce bias 428 Simultaneous control group 428 Randomization 429 Blinding 430				
	14.4	How to reduce the influence of sampling error 431 Replication 432 Balance 434 Blocking 434				
		Example 14.4A: Holey waters 436				
		Extreme treatments 437				
		Example 14.4B: Plastic hormones 437				
	14.5	Experiments with more than one factor 438				
	446	Example 14.5: Lethal combination 439				
	14.6	Mat if you can't do experiments? 440 Match and adjust 440				
	14.7	Choosing a sample size 441 Plan for precision 442 Plan for power 444 Plan for data loss 445				
	14.8	Summary 445				
	14 .9	Quick Formula Summary 447				
		Practice problems 450				
		Assignment problems 453				

INTERLEAF 8 Data dredging 456

15.	Comparing means of more than two groups 459				
	15.1	The analysis of variance 460			
		Example 15.1: The knees who say night 460			
		Hypotheses 461			
		ANOVA in a nutshell 462			
		ANOVA tables 463			
		Partitioning the sum of squares 464			
		The variance ratio. F 467			
		Variation explained: R^2 469			
		ANOVA with two groups 470			
	15.2	Assumptions and alternatives 470			
		The robustness of ANOVA 470			
		Nonparametric alternatives to ANOVA 471			
	15.3	Planned comparisons 471			
		Planned comparison between two means 472			
	15.4	Unplanned comparisons 473			
		Example 15.4: Wood wide web 474			
		Testing all pairs of means using the Tukey–Kramer method 475 Assumptions 477			
	15.5	Fixed and random effects 477			
	15.6	ANOVA with randomly chosen groups 478			
		Example 15.6: Walking stick limbs 478			
		ANOVA calculations 479			
		Variance components 480			
		Assumptions 482			
	15.7	Summary 482			
	15.8	Quick Formula Summary 483			
		Practice problems 486			
		Assignment problems 492			
INTERLEAF 9	Expe	rimental and statistical mistakes 500			

PART 4 REGRESSION AND CORRELATION

- 16. Correlation between numerical variables 503
 - 16.1 Estimating a linear correlation coefficient 504 The correlation coefficient 504 Example 16.1: Flipping the bird 506

		Standard error 508 Approximate confidence interval 508
	16.2	Testing the null hypothesis of zero correlation 510
		Example 16.2: What big inbreeding coefficients you have 510
	16.3	Assumptions 512
	16.4	The correlation coefficient depends on the range 514
	16.5	Spearman's rank correlation 515
		Example 16.5: The miracles of memory 516
		Procedure for large <i>n</i> 518 Assumptions of Spearman's correlation 519
	16.6	The effects of measurement error on correlation 519
	16.7	Summary 520
	16.8	Quick Formula Summary 521
		Practice problems 524
		Assignment problems 529
INTERLEAF 10	Publ	ication bias 535
17.	Regr	ession 539
	17.1	Linear regression 541
		Example 17.1: The lion's nose 541
		The method of least squares 542
		Formula for the line 543
		Populations and samples 545
		Predicted values 546
		Residuals 546
		Standard error of slope 547
		Confidence interval for the slope 548
	17.2	Confidence in predictions 548
		Extrapolation 550
	17.3	Testing hypotheses about a slope 551
		Example 17.3: Prairie home campion 551
		The <i>t</i> -test of regression slope 552
		The ANOVA approach 554 Using R^2 to measure the fit of the line to data 555
	17.4	Regression toward the mean 555
	17.5	Assumptions of regression 557 Outliers 558

Detecting nonlinearity 559 Detecting non-normality and unequal variance 559 17.6 Transformations 560 The effects of measurement error on regression 562 17.7 17.8 Nonlinear regression 563 A curve with an asymptote 564 Ouadratic curves 565 Formula-free curve fitting 566 Example 17.8: The incredible shrinking seal 566 Logistic regression: fitting a binary response variable 567 17.9 17.10 Summary 571 17.11 Quick Formula Summary 572 Practice problems 576 Assignment problems 582 INTERLEAF 11 Using species as data points 593 Review Problems 3 597 PART 5 MODERN STATISTICAL METHODS

18. Multiple explanatory variables 605

18.1 ANOVA and linear regression are linear models 606 Modeling with linear regression 607 Generalizing linear regression 608 General linear models 610

18.2 Analyzing experiments with blocking 611

 Analyzing data from a randomized block design 611
 Example 18.2: Zooplankton depredation 612

Model formula 612 Fitting the model to data 613

18.3 Analyzing factorial designs 614
Example 18.3: Interaction zone 615
Model formula 616
Testing the factors 617
The importance of distinguishing fixed and random factors 619
18.4 Adjusting for the effects of a covariate 619

Example 18.4: Mole-rat layabouts 620 Testing interaction 621 Fitting a model without an interaction term 622

	18.5	Assumptions of general linear models 623			
	18.6. Summary 624				
Practice problems 626					
		Assignment problems 629			
19.	Comp	outer-intensive methods 635			
	19.1	Hypothesis testing using simulation 636			
		Example 19.1: How did he know? The nonrandomness of haphazard choice 636			
	19.2	Bootstrap standard errors and confidence intervals 639			
		Example 19.2: The language center in chimps' brains 640 Bootstrap standard error 642 Confidence intervals by bootstrapping 644 Bootstrapping with multiple groups 644 Assumptions and limitations of the bootstrap 646			
	19.3	Summary 646			
		Practice problems 647			
		Assignment problems 651			
20.	Likeli	Likelihood 655			
	20.1	What is likelihood? 656			
	20.2	Two uses of likelihood in biology 657 Phylogeny estimation 657 Gene mapping 658			
	20.3	Maximum likelihood estimation 659			
		Example 20.3: Unruly passengers 659 Probability model 660 The likelihood formula 660 The maximum likelihood estimate 661 Likelihood-based confidence intervals 664			
	20.4	Versatility of maximum likelihood estimation 665			
		Example 20.4: Conservation scoop 665			
		Probability model 666 The likelihood formula 666 The maximum likelihood estimate 667 Bias 668			
	20.5	Log-likelihood ratio test 668 Likelihood ratio test statistic 669 Testing a population proportion 669			

20.7 Quick Formula Summary 671 Practice problems 672 Assignment problems 676 21. Meta-analysis: combining information from multiple studies 681 21.1 What is meta-analysis? 683 Why repeat a study? 683 21.2 The power of meta-analysis 684 Example 21.2: Aspirin and myocardial infarction 684 21.3 Meta-analysis can give a balanced view 686 Example 21.3: The Transylvania effect 686 21.4 The steps of a meta-analysis 687 Define the question 687 Example 21.4: Testosterone and aggression 688 Review the literature 688 Compute effect sizes 689 Determine the average effect size 692 Calculate confidence intervals and test hypotheses 692 Look for effects of study quality 693 Look for associations 693 21.5 File-drawer problem 694 21.6 How to make your paper accessible to meta-analysis 695 21.7 Summary 695 21.8 Quick Formula Summary 696 Practice problems 697 Assignment problems 698 Statistical Tables 701 Using statistical tables 701 Statistical Table A: The χ^2 distribution 703 Statistical Table B: The standard normal (Z) distribution 706 Statistical Table C: The Student *t*-distribution 708 Statistical Table D: The F-distribution 711 Statistical Table E: Mann–Whitney U-distribution 718 Statistical Table F: Tukey–Kramer *a*-distribution 720 Statistical Table G: Critical values for the Spearman's rank correlation 722 Literature cited 725 Answers to practice problems 747 Photo credits 803 Index 807