

Contents

<i>Preface</i>	<i>page</i>	<i>xiii</i>
1 What This Book Is About		1
1.1 Overview: Where Morphometrics Draws Its Ideas		1
1.2 Our Basic Orientation: From Arithmetic to Understanding		8
1.3 The Professional Setting (A Brief Intellectual History)		12
1.4 A More Detailed Preview of Coming Attractions		18
2 Getting Started: One or Two Measurements Only		23
2.1 Elementary Averages from an Intermediate Standpoint		26
2.1.1 Averages as Least-Squares		26
2.1.2 Precision of Averages		29
2.1.3 Weighted Averages		33
2.1.4 Averages and Likelihoods		35
2.2 Lines for Laws		40
2.2.1 Why Organismal Biologists Compute Regressions		40
2.2.2 From Errors-in-Variables to Errors-in-Equations		42
2.2.3 The Role of Regressions as Lawlike Explanations: Two Examples		55
2.3 Gaussian Distributions and Galton's Quincunx		59
2.3.1 Milestone 1: Limits of Binomials		60
2.3.2 Milestone 2: Galton's Machine		64
2.3.3 Milestone 3: Regression on the Quincunx		68
2.3.4 Milestone 4: A More Elegant Notation		72
2.3.5 Milestone 5: Other Origins of the Gaussian Distribution		75
2.3.6 "Regression to the Mean": Geometry of Regression as Diagrammed via an Ellipse		80

viii	Contents	
2.4	Correlation	86
2.4.1	Galton's Other Insight	86
2.4.2	Example 2.3: Pearson's Study of Limb Lengths: Every Family Member, Every Limb	89
2.4.3	Example 2.4: Wright's Chickens: All 15 Pairwise Relationships	96
2.4.4	Working Backward from One Single Correlation	97
2.5	Further Useful Formulas for This Setting	100
2.5.1	Acrobatics on the Quincunx	100
2.5.2	Tukey's Approximation	103
2.5.3	The Hat Matrix	105
2.6	Other Data Structures	112
2.6.1	Growth Series	113
2.6.2	Random Walks	124
2.6.3	Data on Phylogenies	132
3	Multiple Regression, in General and in Special Settings	137
3.1	The General Logic of Multiple Regression	140
3.1.1	Interpretation 1: The Counterfactual of Uncorrelated Predictors	144
3.1.2	Interpretation 2: The Path Analysis	153
3.1.3	Interpretation 3: Least Squares	157
3.1.4	Rethinking All Three Versions	158
3.2	Added-Variable Plots	163
3.2.1	The Problem, the Solution, and the Proofs	163
3.2.2	Example 3.2: Prenatal Ultrasound and Birthweight	166
3.2.3	A Note on "Optimism" in Model-Fitting	173
3.3	Special Case 1: Analysis of Covariance	177
3.3.1	Group Differences in Regressions as a Path Model	177
3.3.2	Example 3.4. Brain Weight – Body Weight Allometry	184
3.3.3	A Regression Line Concealed within a Data Model	191
3.3.4	Ecological Regressions and the Ecological Fallacy	192
3.4	Special Case 2: Growth Series	198
3.4.1	Persistence of Growth: Partial Correlations along Growth Series	199
3.4.2	Uncertainties of Correlations	203
3.4.3	Predicting a Summary Growth Measure from Its Components	205
3.5	Special Case 3a: Linear Discriminant Analysis	208

3.5.1	Classification via a Likelihood Ratio Loglinear in the Data	208
3.5.2	Why This Works: The Algebra of Linear Discrimination	212
3.5.3	Example 3.7: Bumpus's Snow-Beset Sparrows	215
3.6	Special Case 3b: Quadratic Discrimination	222
3.6.1	Classification When Variances Are Not the Same	222
3.6.2	Classification When Covariances Are Not the Same	224
3.6.3	Example 3.8: An Adult Fetal Alcohol Brain Study	226
3.6.4	Example 3.9: The Same for Infants	230
3.6.5	Back to Bumpus's Birds	234
3.6.6	Changing One Group's Covariance Can Change a Likelihood Ratio by a Lot	235
4	Transition to Multivariate Analysis	241
4.1	Aspects of Covariance Structure: An Introduction	242
4.1.1	The Three Dimensions of a Bivariate Covariance Ellipse	242
4.1.2	The Centrality of Multivariate Analysis for Studies of Complex Organized Systems	249
4.1.3	Inverses versus Eigenanalysis: The Two Roles of the Matrix	251
4.2	The Singular-Value Decomposition and Its Applications in Morphometrics	264
4.2.1	The SVD Theorem and Its Component Parts	265
4.2.2	Principal Component Scores and the Biplot	269
4.2.3	Partial Least Squares: Least-Squares Analysis of Covariance Patterns	279
4.2.4	Principal Coordinates Analysis	287
4.3	The Wishart Distribution: Its Formula and a Sketch of Its Justification	290
4.3.1	A Handy Mathematical Fact about Gaussian Likelihoods	291
4.3.2	The Wishart Distribution Is Comprehensible	296
4.3.3	A Useful Approximation	303
4.3.4	Example: Fitting a Single-Factor Model	305
4.3.5	A Special Case: Allometry	312
4.3.6	Interpreting the Sum in Equation (4.47) as a Distance	317
5	Geometric Morphometrics: Its Geometry and Its Pattern Analysis	322
5.1	The Data of Geometric Morphometrics: How We Keep Our Place in an Anatomy	327

5.1.1	Hints about the Limits of Geometric Morphometrics	337
5.1.2	The Role of Words Today: The “Foundational Model for Anatomy”	339
5.1.3	From the Last Century, I: Standardizing Where We Point within an Image	344
5.1.4	From the Last Century, II: The Origin of Morphometric Quantifications	351
5.2	Pattern Descriptors for Landmarks Taken Three at a Time	361
5.2.1	Tensors as Morphometric Pattern Descriptors	362
5.2.2	The Circle Construction for Triangles	367
5.2.3	Extensions and Examples	374
5.2.4	A Further Comment on Distance Ratios	381
5.3	Procrustes Matters: The Least-Squares Approach to Morphometrics	384
5.3.1	The Conventional Procrustes Shape Distance	385
5.3.2	Principal Coordinates of Procrustes Distance	390
5.3.3	Example: The Gunz Skull Data Set, II	393
5.3.4	Procrustes Form Distance	394
5.4	Procrustes Coordinates, a Different Set of Shape Coordinates	397
5.4.1	A Language for “Shape Coordinates,” Not for “Shape”	397
5.4.2	Gower’s “Generalized Procrustes Analysis”	399
5.4.3	Examples	402
5.4.4	The Isotropic Mardia–Dryden Distribution	407
5.4.5	Covariance Distance	414
5.4.6	GPA Subtleties, Some Standard, Some New	415
5.5	Thin-Plate Splines	425
5.5.1	The Basic Formula	425
5.5.2	Bending Energy and Its Principal and Partial Warps	431
5.5.3	The Uniform Component	436
5.5.4	Semilandmarks	439
5.6	Finishing the Main Examples, Along with Some New Ones	448
5.6.1	Splines for Data Screening	449
5.6.2	Splines for Pairwise Contrasts of Specimens or Group Mean Differences	449
5.6.3	Splines for Regressions	451
5.6.4	Splines for Relative Warps	453
5.6.5	Splines for Partial Warps	458
5.6.6	Splines for Partial Least Squares	463
5.6.7	Bilateral Symmetry and Asymmetry	469

Contents		xi
5.6.8	“Modularity” and “Integration”	474
5.6.9	Two Recent Extensions	484
5.7	Envoi	489
	<i>References</i>	494
	<i>Index</i>	506

Appendices to this book, including thirteen of the data sets used for examples, along with `Splus` code for the main software tools, some useful auxiliary routines, and nearly half of the book’s figures, can be found on the book’s website, <http://www.cambridge.org/9781107190948>.