

BRIEF CONTENTS



	Examples and Applications	25	
	Preface	33	
Part I	The Linear Regression Model		
Chapter 1	Econometrics	41	
Chapter 2	The Linear Regression Model	51	
Chapter 3	Least Squares	66	
Chapter 4	The Least Squares Estimator	91	
Chapter 5	Hypothesis Tests and Model Selection	148	
Chapter 6	Functional Form and Structural Change	189	
Chapter 7	Nonlinear, Semiparametric, and Nonparametric Regression Models	221	
Chapter 8	Endogeneity and Instrumental Variable Estimation	259	
Part II	Generalized Regression Model and Equation Systems		
Chapter 9	The Generalized Regression Model and Heteroscedasticity		297
Chapter 10	Systems of Equations	330	
Chapter 11	Models for Panel Data	383	
Part III	Estimation Methodology		
Chapter 12	Estimation Frameworks in Econometrics	472	
Chapter 13	Minimum Distance Estimation and the Generalized Method of Moments	495	
Chapter 14	Maximum Likelihood Estimation	549	
Chapter 15	Simulation-Based Estimation and Inference and Random Parameter Models	643	
Chapter 16	Bayesian Estimation and Inference	695	
Part IV	Cross Sections, Panel Data, and Microeconometrics		
Chapter 17	Discrete Choice	721	
Chapter 18	Discrete Choices and Event Counts	800	
Chapter 19	Limited Dependent Variables—Truncation, Censoring, and Sample Selection	873	

Part V Time Series and Macroeconometrics

Chapter 20	Serial Correlation	943
Chapter 21	Nonstationary Data	982

Part VI Appendices

Appendix A	Matrix Algebra	1013
Appendix B	Probability and Distribution Theory	1055
Appendix C	Estimation and Inference	1087
Appendix D	Large-Sample Distribution Theory	1106
Appendix E	Computation and Optimization	1129
Appendix F	Data Sets Used in Applications	1149
References		1155
Combined Author and Subject Index		1201

CONTENTS



Examples and Applications 25

Preface 33

PART I The Linear Regression Model

CHAPTER 1 Econometrics 41

- 1.1 Introduction 41
- 1.2 The Paradigm of Econometrics 41
- 1.3 The Practice of Econometrics 43
- 1.4 Econometric Modeling 44
- 1.5 Plan of the Book 47
- 1.6 Preliminaries 49
 - 1.6.1 *Numerical Examples* 49
 - 1.6.2 *Software and Replication* 49
 - 1.6.3 *Notational Conventions* 49

CHAPTER 2 The Linear Regression Model 51

- 2.1 Introduction 51
- 2.2 The Linear Regression Model 52
- 2.3 Assumptions of the Linear Regression Model 55
 - 2.3.1 *Linearity of the Regression Model* 55
 - 2.3.2 *Full Rank* 59
 - 2.3.3 *Regression* 60
 - 2.3.4 *Spherical Disturbances* 61
 - 2.3.5 *Data Generating Process for the Regressors* 63
 - 2.3.6 *Normality* 63
 - 2.3.7 *Independence* 64
- 2.4 Summary and Conclusions 65

CHAPTER 3 Least Squares 66

- 3.1 Introduction 66
- 3.2 Least Squares Regression 66
 - 3.2.1 *The Least Squares Coefficient Vector* 67

3.2.2	<i>Application: An Investment Equation</i>	68
3.2.3	<i>Algebraic Aspects of the Least Squares Solution</i>	70
3.2.4	<i>Projection</i>	71
3.3	Partitioned Regression and Partial Regression	72
3.4	Partial Regression and Partial Correlation Coefficients	76
3.5	Goodness of Fit and the Analysis of Variance	79
3.5.1	<i>The Adjusted R-Squared and a Measure of Fit</i>	82
3.5.2	<i>R-Squared and the Constant Term in the Model</i>	84
3.5.3	<i>Comparing Models</i>	85
3.6	Linearly Transformed Regression	86
3.7	Summary and Conclusions	87
CHAPTER 4	The Least Squares Estimator	91
4.1	Introduction	91
4.2	Motivating Least Squares	92
4.2.1	<i>The Population Orthogonality Conditions</i>	92
4.2.2	<i>Minimum Mean Squared Error Predictor</i>	93
4.2.3	<i>Minimum Variance Linear Unbiased Estimation</i>	94
4.3	Finite Sample Properties of Least Squares	94
4.3.1	<i>Unbiased Estimation</i>	95
4.3.2	<i>Bias Caused by Omission of Relevant Variables</i>	96
4.3.3	<i>Inclusion of Irrelevant Variables</i>	98
4.3.4	<i>The Variance of the Least Squares Estimator</i>	98
4.3.5	<i>The Gauss–Markov Theorem</i>	100
4.3.6	<i>The Implications of Stochastic Regressors</i>	100
4.3.7	<i>Estimating the Variance of the Least Squares Estimator</i>	101
4.3.8	<i>The Normality Assumption</i>	103
4.4	Large Sample Properties of the Least Squares Estimator	103
4.4.1	<i>Consistency of the Least Squares Estimator of β</i>	103
4.4.2	<i>Asymptotic Normality of the Least Squares Estimator</i>	105
4.4.3	<i>Consistency of s^2 and the Estimator of Asy. Var[\mathbf{b}]</i>	107
4.4.4	<i>Asymptotic Distribution of a Function of \mathbf{b}: The Delta Method</i>	108
4.4.5	<i>Asymptotic Efficiency</i>	109
4.4.6	<i>Maximum Likelihood Estimation</i>	113
4.5	Interval Estimation	115
4.5.1	<i>Forming a Confidence Interval for a Coefficient</i>	116
4.5.2	<i>Confidence Intervals Based on Large Samples</i>	118
4.5.3	<i>Confidence Interval for a Linear Combination of Coefficients: The Oaxaca Decomposition</i>	119
4.6	Prediction and Forecasting	120
4.6.1	<i>Prediction Intervals</i>	121
4.6.2	<i>Predicting y When the Regression Model Describes $\log y$</i>	121

4.6.3	<i>Prediction Interval for y When the Regression Model Describes $\log y$</i>	123
4.6.4	<i>Forecasting</i>	127
4.7	Data Problems	128
4.7.1	<i>Multicollinearity</i>	129
4.7.2	<i>Pretest Estimation</i>	131
4.7.3	<i>Principal Components</i>	132
4.7.4	<i>Missing Values and Data Imputation</i>	134
4.7.5	<i>Measurement Error</i>	137
4.7.6	<i>Outliers and Influential Observations</i>	139
4.8	Summary and Conclusions	142
CHAPTER 5 Hypothesis Tests and Model Selection		148
5.1	Introduction	148
5.2	Hypothesis Testing Methodology	148
5.2.1	<i>Restrictions and Hypotheses</i>	149
5.2.2	<i>Nested Models</i>	150
5.2.3	<i>Testing Procedures—Neyman–Pearson Methodology</i>	151
5.2.4	<i>Size, Power, and Consistency of a Test</i>	151
5.2.5	<i>A Methodological Dilemma: Bayesian versus Classical Testing</i>	152
5.3	Two Approaches to Testing Hypotheses	152
5.4	Wald Tests Based on the Distance Measure	155
5.4.1	<i>Testing a Hypothesis about a Coefficient</i>	155
5.4.2	<i>The F Statistic and the Least Squares Discrepancy</i>	157
5.5	Testing Restrictions Using the Fit of the Regression	161
5.5.1	<i>The Restricted Least Squares Estimator</i>	161
5.5.2	<i>The Loss of Fit from Restricted Least Squares</i>	162
5.5.3	<i>Testing the Significance of the Regression</i>	166
5.5.4	<i>Solving Out the Restrictions and a Caution about Using R^2</i>	166
5.6	Nonnormal Disturbances and Large-Sample Tests	167
5.7	Testing Nonlinear Restrictions	171
5.8	Choosing between Nonnested Models	174
5.8.1	<i>Testing Nonnested Hypotheses</i>	174
5.8.2	<i>An Encompassing Model</i>	175
5.8.3	<i>Comprehensive Approach—The J Test</i>	176
5.9	A Specification Test	177
5.10	Model Building—A General to Simple Strategy	178
5.10.1	<i>Model Selection Criteria</i>	179
5.10.2	<i>Model Selection</i>	180
5.10.3	<i>Classical Model Selection</i>	180
5.10.4	<i>Bayesian Model Averaging</i>	181
5.11	Summary and Conclusions	183

CHAPTER 6	Functional Form and Structural Change	189
6.1	Introduction	189
6.2	Using Binary Variables	189
6.2.1	<i>Binary Variables in Regression</i>	189
6.2.2	<i>Several Categories</i>	192
6.2.3	<i>Several Groupings</i>	192
6.2.4	<i>Threshold Effects and Categorical Variables</i>	194
6.2.5	<i>Treatment Effects and Differences in Differences Regression</i>	195
6.3	Nonlinearity in the Variables	198
6.3.1	<i>Piecewise Linear Regression</i>	198
6.3.2	<i>Functional Forms</i>	200
6.3.3	<i>Interaction Effects</i>	201
6.3.4	<i>Identifying Nonlinearity</i>	202
6.3.5	<i>Intrinsically Linear Models</i>	205
6.4	Modeling and Testing for a Structural Break	208
6.4.1	<i>Different Parameter Vectors</i>	208
6.4.2	<i>Insufficient Observations</i>	209
6.4.3	<i>Change in a Subset of Coefficients</i>	210
6.4.4	<i>Tests of Structural Break with Unequal Variances</i>	211
6.4.5	<i>Predictive Test of Model Stability</i>	214
6.5	Summary and Conclusions	215
CHAPTER 7	Nonlinear, Semiparametric, and Nonparametric Regression Models	221
7.1	Introduction	221
7.2	Nonlinear Regression Models	222
7.2.1	<i>Assumptions of the Nonlinear Regression Model</i>	222
7.2.2	<i>The Nonlinear Least Squares Estimator</i>	224
7.2.3	<i>Large Sample Properties of the Nonlinear Least Squares Estimator</i>	226
7.2.4	<i>Hypothesis Testing and Parametric Restrictions</i>	229
7.2.5	<i>Applications</i>	231
7.2.6	<i>Computing the Nonlinear Least Squares Estimator</i>	240
7.3	Median and Quantile Regression	242
7.3.1	<i>Least Absolute Deviations Estimation</i>	243
7.3.2	<i>Quantile Regression Models</i>	247
7.4	Partially Linear Regression	250
7.5	Nonparametric Regression	252
7.6	Summary and Conclusions	255
CHAPTER 8	Endogeneity and Instrumental Variable Estimation	259
8.1	Introduction	259
8.2	Assumptions of the Extended Model	263

8.3	Estimation	264
8.3.1	<i>Least Squares</i>	265
8.3.2	<i>The Instrumental Variables Estimator</i>	265
8.3.3	<i>Motivating the Instrumental Variables Estimator</i>	267
8.3.4	<i>Two-Stage Least Squares</i>	270
8.4	Two Specification Tests	273
8.4.1	<i>The Hausman and Wu Specification Tests</i>	274
8.4.2	<i>A Test for Overidentification</i>	278
8.5	Measurement Error	279
8.5.1	<i>Least Squares Attenuation</i>	280
8.5.2	<i>Instrumental Variables Estimation</i>	282
8.5.3	<i>Proxy Variables</i>	282
8.6	Nonlinear Instrumental Variables Estimation	286
8.7	Weak Instruments	289
8.8	Natural Experiments and the Search for Causal Effects	291
8.9	Summary and Conclusions	294

PART II Generalized Regression Model and Equation Systems

CHAPTER 9 The Generalized Regression Model and Heteroscedasticity 297

9.1	Introduction	297
9.2	Inefficient Estimation by Least Squares and Instrumental Variables	298
9.2.1	<i>Finite-Sample Properties of Ordinary Least Squares</i>	299
9.2.2	<i>Asymptotic Properties of Ordinary Least Squares</i>	299
9.2.3	<i>Robust Estimation of Asymptotic Covariance Matrices</i>	301
9.2.4	<i>Instrumental Variable Estimation</i>	302
9.3	Efficient Estimation by Generalized Least Squares	304
9.3.1	<i>Generalized Least Squares (GLS)</i>	304
9.3.2	<i>Feasible Generalized Least Squares (FGLS)</i>	306
9.4	Heteroscedasticity and Weighted Least Squares	308
9.4.1	<i>Ordinary Least Squares Estimation</i>	309
9.4.2	<i>Inefficiency of Ordinary Least Squares</i>	310
9.4.3	<i>The Estimated Covariance Matrix of \mathbf{b}</i>	310
9.4.4	<i>Estimating the Appropriate Covariance Matrix for Ordinary Least Squares</i>	312
9.5	Testing for Heteroscedasticity	315
9.5.1	<i>White's General Test</i>	315
9.5.2	<i>The Breusch-Pagan/Godfrey LM Test</i>	316
9.6	Weighted Least Squares	317
9.6.1	<i>Weighted Least Squares with Known Ω</i>	318
9.6.2	<i>Estimation When Ω Contains Unknown Parameters</i>	319

- 9.7 Applications 320
 - 9.7.1 *Multiplicative Heteroscedasticity* 320
 - 9.7.2 *Groupwise Heteroscedasticity* 322
- 9.8 Summary and Conclusions 325

CHAPTER 10 Systems of Equations 330

- 10.1 Introduction 330
- 10.2 The Seemingly Unrelated Regressions Model 332
 - 10.2.1 *Generalized Least Squares* 333
 - 10.2.2 *Seemingly Unrelated Regressions with Identical Regressors* 335
 - 10.2.3 *Feasible Generalized Least Squares* 336
 - 10.2.4 *Testing Hypotheses* 336
 - 10.2.5 *A Specification Test for the SUR Model* 337
 - 10.2.6 *The Pooled Model* 339
- 10.3 Seemingly Unrelated Generalized Regression Models 344
- 10.4 Nonlinear Systems of Equations 345
- 10.5 Systems of Demand Equations: Singular Systems 347
 - 10.5.1 *Cobb–Douglas Cost Function* 347
 - 10.5.2 *Flexible Functional Forms: The Translog Cost Function* 350
- 10.6 Simultaneous Equations Models 354
 - 10.6.1 *Systems of Equations* 355
 - 10.6.2 *A General Notation for Linear Simultaneous Equations Models* 358
 - 10.6.3 *The Problem of Identification* 361
 - 10.6.4 *Single Equation Estimation and Inference* 366
 - 10.6.5 *System Methods of Estimation* 369
 - 10.6.6 *Testing in the Presence of Weak Instruments* 374
- 10.7 Summary and Conclusions 376

CHAPTER 11 Models for Panel Data 383

- 11.1 Introduction 383
- 11.2 Panel Data Models 384
 - 11.2.1 *General Modeling Framework for Analyzing Panel Data* 385
 - 11.2.2 *Model Structures* 386
 - 11.2.3 *Extensions* 387
 - 11.2.4 *Balanced and Unbalanced Panels* 388
 - 11.2.5 *Well-Behaved Panel Data* 388
- 11.3 The Pooled Regression Model 389
 - 11.3.1 *Least Squares Estimation of the Pooled Model* 389
 - 11.3.2 *Robust Covariance Matrix Estimation* 390
 - 11.3.3 *Clustering and Stratification* 392
 - 11.3.4 *Robust Estimation Using Group Means* 394

11.3.5	<i>Estimation with First Differences</i>	395
11.3.6	<i>The Within- and Between-Groups Estimators</i>	397
11.4	The Fixed Effects Model	399
11.4.1	<i>Least Squares Estimation</i>	400
11.4.2	<i>Small T Asymptotics</i>	402
11.4.3	<i>Testing the Significance of the Group Effects</i>	403
11.4.4	<i>Fixed Time and Group Effects</i>	403
11.4.5	<i>Time-Invariant Variables and Fixed Effects Vector Decomposition</i>	404
11.5	Random Effects	410
11.5.1	<i>Least Squares Estimation</i>	412
11.5.2	<i>Generalized Least Squares</i>	413
11.5.3	<i>Feasible Generalized Least Squares When Σ Is Unknown</i>	414
11.5.4	<i>Testing for Random Effects</i>	416
11.5.5	<i>Hausman's Specification Test for the Random Effects Model</i>	419
11.5.6	<i>Extending the Unobserved Effects Model: Mundlak's Approach</i>	420
11.5.7	<i>Extending the Random and Fixed Effects Models: Chamberlain's Approach</i>	421
11.6	Nonspherical Disturbances and Robust Covariance Estimation	425
11.6.1	<i>Robust Estimation of the Fixed Effects Model</i>	425
11.6.2	<i>Heteroscedasticity in the Random Effects Model</i>	427
11.6.3	<i>Autocorrelation in Panel Data Models</i>	428
11.6.4	<i>Cluster (and Panel) Robust Covariance Matrices for Fixed and Random Effects Estimators</i>	428
11.7	Spatial Autocorrelation	429
11.8	Endogeneity	434
11.8.1	<i>Hausman and Taylor's Instrumental Variables Estimator</i>	434
11.8.2	<i>Consistent Estimation of Dynamic Panel Data Models: Anderson and Hsiao's IV Estimator</i>	438
11.8.3	<i>Efficient Estimation of Dynamic Panel Data Models—The Arellano/Bond Estimators</i>	440
11.8.4	<i>Nonstationary Data and Panel Data Models</i>	450
11.9	Nonlinear Regression with Panel Data	451
11.9.1	<i>A Robust Covariance Matrix for Nonlinear Least Squares</i>	451
11.9.2	<i>Fixed Effects</i>	452
11.9.3	<i>Random Effects</i>	454
11.10	Systems of Equations	455
11.11	Parameter Heterogeneity	456
11.11.1	<i>The Random Coefficients Model</i>	457
11.11.2	<i>A Hierarchical Linear Model</i>	460
11.11.3	<i>Parameter Heterogeneity and Dynamic Panel Data Models</i>	461
11.12	Summary and Conclusions	466

PART III Estimation Methodology

CHAPTER 12 Estimation Frameworks in Econometrics	472
12.1 Introduction	472
12.2 Parametric Estimation and Inference	474
12.2.1 <i>Classical Likelihood-Based Estimation</i>	474
12.2.2 <i>Modeling Joint Distributions with Copula Functions</i>	476
12.3 Semiparametric Estimation	479
12.3.1 <i>GMM Estimation in Econometrics</i>	479
12.3.2 <i>Maximum Empirical Likelihood Estimation</i>	480
12.3.3 <i>Least Absolute Deviations Estimation and Quantile Regression</i>	481
12.3.4 <i>Kernel Density Methods</i>	482
12.3.5 <i>Comparing Parametric and Semiparametric Analyses</i>	483
12.4 Nonparametric Estimation	484
12.4.1 <i>Kernel Density Estimation</i>	485
12.5 Properties of Estimators	487
12.5.1 <i>Statistical Properties of Estimators</i>	488
12.5.2 <i>Extremum Estimators</i>	489
12.5.3 <i>Assumptions for Asymptotic Properties of Extremum Estimators</i>	489
12.5.4 <i>Asymptotic Properties of Estimators</i>	492
12.5.5 <i>Testing Hypotheses</i>	493
12.6 Summary and Conclusions	494
CHAPTER 13 Minimum Distance Estimation and the Generalized Method of Moments	495
13.1 Introduction	495
13.2 Consistent Estimation: The Method of Moments	496
13.2.1 <i>Random Sampling and Estimating the Parameters of Distributions</i>	497
13.2.2 <i>Asymptotic Properties of the Method of Moments Estimator</i>	501
13.2.3 <i>Summary—The Method of Moments</i>	503
13.3 Minimum Distance Estimation	503
13.4 The Generalized Method of Moments (GMM) Estimator	508
13.4.1 <i>Estimation Based on Orthogonality Conditions</i>	508
13.4.2 <i>Generalizing the Method of Moments</i>	510
13.4.3 <i>Properties of the GMM Estimator</i>	514
13.5 Testing Hypotheses in the GMM Framework	519
13.5.1 <i>Testing the Validity of the Moment Restrictions</i>	519
13.5.2 <i>GMM Counterparts to the WALD, LM, and LR Tests</i>	520

14 Contents

13.6	GMM Estimation of Econometric Models	522
13.6.1	<i>Single-Equation Linear Models</i>	522
13.6.2	<i>Single-Equation Nonlinear Models</i>	528
13.6.3	<i>Seemingly Unrelated Regression Models</i>	531
13.6.4	<i>Simultaneous Equations Models with Heteroscedasticity</i>	533
13.6.5	<i>GMM Estimation of Dynamic Panel Data Models</i>	536
13.7	Summary and Conclusions	547

CHAPTER 14 Maximum Likelihood Estimation 549

14.1	Introduction	549
14.2	The Likelihood Function and Identification of the Parameters	549
14.3	Efficient Estimation: The Principle of Maximum Likelihood	551
14.4	Properties of Maximum Likelihood Estimators	553
14.4.1	<i>Regularity Conditions</i>	554
14.4.2	<i>Properties of Regular Densities</i>	555
14.4.3	<i>The Likelihood Equation</i>	557
14.4.4	<i>The Information Matrix Equality</i>	557
14.4.5	<i>Asymptotic Properties of the Maximum Likelihood Estimator</i>	557
14.4.5.a	<i>Consistency</i>	558
14.4.5.b	<i>Asymptotic Normality</i>	559
14.4.5.c	<i>Asymptotic Efficiency</i>	560
14.4.5.d	<i>Invariance</i>	561
14.4.5.e	<i>Conclusion</i>	561
14.4.6	<i>Estimating the Asymptotic Variance of the Maximum Likelihood Estimator</i>	561
14.5	Conditional Likelihoods, Econometric Models, and the GMM Estimator	563
14.6	Hypothesis and Specification Tests and Fit Measures	564
14.6.1	<i>The Likelihood Ratio Test</i>	566
14.6.2	<i>The Wald Test</i>	567
14.6.3	<i>The Lagrange Multiplier Test</i>	569
14.6.4	<i>An Application of the Likelihood-Based Test Procedures</i>	571
14.6.5	<i>Comparing Models and Computing Model Fit</i>	573
14.6.6	<i>Vuong's Test and the Kullback–Leibler Information Criterion</i>	574
14.7	Two-Step Maximum Likelihood Estimation	576
14.8	Pseudo-Maximum Likelihood Estimation and Robust Asymptotic Covariance Matrices	582
14.8.1	<i>Maximum Likelihood and GMM Estimation</i>	583
14.8.2	<i>Maximum Likelihood and M Estimation</i>	583
14.8.3	<i>Sandwich Estimators</i>	585
14.8.4	<i>Cluster Estimators</i>	586

14.9	Applications of Maximum Likelihood Estimation	588
14.9.1	<i>The Normal Linear Regression Model</i>	588
14.9.2	<i>The Generalized Regression Model</i>	592
14.9.2.a	<i>Multiplicative Heteroscedasticity</i>	594
14.9.2.b	<i>Autocorrelation</i>	597
14.9.3	<i>Seemingly Unrelated Regression Models</i>	600
14.9.3.a	<i>The Pooled Model</i>	600
14.9.3.b	<i>The SUR Model</i>	602
14.9.3.c	<i>Exclusion Restrictions</i>	602
14.9.4	<i>Simultaneous Equations Models</i>	607
14.9.5	<i>Maximum Likelihood Estimation of Nonlinear Regression Models</i>	608
14.9.6	<i>Panel Data Applications</i>	613
14.9.6.a	<i>ML Estimation of the Linear Random Effects Model</i>	614
14.9.6.b	<i>Nested Random Effects</i>	616
14.9.6.c	<i>Random Effects in Nonlinear Models: MLE Using Quadrature</i>	620
14.9.6.d	<i>Fixed Effects in Nonlinear Models: Full MLE</i>	624
14.10	Latent Class and Finite Mixture Models	628
14.10.1	<i>A Finite Mixture Model</i>	629
14.10.2	<i>Measured and Unmeasured Heterogeneity</i>	631
14.10.3	<i>Predicting Class Membership</i>	631
14.10.4	<i>A Conditional Latent Class Model</i>	632
14.10.5	<i>Determining the Number of Classes</i>	634
14.10.6	<i>A Panel Data Application</i>	635
14.11	Summary and Conclusions	638

CHAPTER 15 Simulation-Based Estimation and Inference and Random Parameter Models 643

15.1	Introduction	643
15.2	Random Number Generation	645
15.2.1	<i>Generating Pseudo-Random Numbers</i>	645
15.2.2	<i>Sampling from a Standard Uniform Population</i>	646
15.2.3	<i>Sampling from Continuous Distributions</i>	647
15.2.4	<i>Sampling from a Multivariate Normal Population</i>	648
15.2.5	<i>Sampling from Discrete Populations</i>	648
15.3	Simulation-Based Statistical Inference: The Method of Krinsky and Robb	649
15.4	Bootstrapping Standard Errors and Confidence Intervals	651
15.5	Monte Carlo Studies	655
15.5.1	<i>A Monte Carlo Study: Behavior of a Test Statistic</i>	657
15.5.2	<i>A Monte Carlo Study: The Incidental Parameters Problem</i>	659
15.6	Simulation-Based Estimation	661
15.6.1	<i>Random Effects in a Nonlinear Model</i>	661

15.6.2	<i>Monte Carlo Integration</i>	663
15.6.2.a	<i>Halton Sequences and Random Draws for Simulation-Based Integration</i>	665
15.6.2.b	<i>Computing Multivariate Normal Probabilities Using the GHK Simulator</i>	667
15.6.3	<i>Simulation-Based Estimation of Random Effects Models</i>	669
15.7	A Random Parameters Linear Regression Model	674
15.8	Hierarchical Linear Models	679
15.9	Nonlinear Random Parameter Models	681
15.10	Individual Parameter Estimates	682
15.11	Mixed Models and Latent Class Models	690
15.12	Summary and Conclusions	693
CHAPTER 16	Bayesian Estimation and Inference	695
16.1	Introduction	695
16.2	Bayes Theorem and the Posterior Density	696
16.3	Bayesian Analysis of the Classical Regression Model	698
16.3.1	<i>Analysis with a Noninformative Prior</i>	699
16.3.2	<i>Estimation with an Informative Prior Density</i>	701
16.4	Bayesian Inference	704
16.4.1	<i>Point Estimation</i>	704
16.4.2	<i>Interval Estimation</i>	705
16.4.3	<i>Hypothesis Testing</i>	706
16.4.4	<i>Large-Sample Results</i>	708
16.5	Posterior Distributions and the Gibbs Sampler	708
16.6	Application: Binomial Probit Model	711
16.7	Panel Data Application: Individual Effects Models	714
16.8	Hierarchical Bayes Estimation of a Random Parameters Model	716
16.9	Summary and Conclusions	718
PART IV Cross Sections, Panel Data, and Microeconometrics		
CHAPTER 17	Discrete Choice	721
17.1	Introduction	721
17.2	Models for Binary Outcomes	723
17.2.1	<i>Random Utility Models for Individual Choice</i>	724
17.2.2	<i>A Latent Regression Model</i>	726
17.2.3	<i>Functional Form and Regression</i>	727
17.3	Estimation and Inference in Binary Choice Models	730
17.3.1	<i>Robust Covariance Matrix Estimation</i>	732
17.3.2	<i>Marginal Effects and Average Partial Effects</i>	733

	17.3.2.a	<i>Average Partial Effects</i>	736
	17.3.2.b	<i>Interaction Effects</i>	739
	17.3.3	<i>Measuring Goodness of Fit</i>	741
	17.3.4	<i>Hypothesis Tests</i>	743
	17.3.5	<i>Endogenous Right-Hand-Side Variables in Binary Choice Models</i>	746
	17.3.6	<i>Endogenous Choice-Based Sampling</i>	750
	17.3.7	<i>Specification Analysis</i>	751
		17.3.7.a <i>Omitted Variables</i>	753
		17.3.7.b <i>Heteroscedasticity</i>	754
17.4		<i>Binary Choice Models for Panel Data</i>	756
	17.4.1	<i>The Pooled Estimator</i>	757
	17.4.2	<i>Random Effects Models</i>	758
	17.4.3	<i>Fixed Effects Models</i>	761
	17.4.4	<i>A Conditional Fixed Effects Estimator</i>	762
	17.4.5	<i>Mundlak's Approach, Variable Addition, and Bias Reduction</i>	767
	17.4.6	<i>Dynamic Binary Choice Models</i>	769
	17.4.7	<i>A Semiparametric Model for Individual Heterogeneity</i>	771
	17.4.8	<i>Modeling Parameter Heterogeneity</i>	773
	17.4.9	<i>Nonresponse, Attrition, and Inverse Probability Weighting</i>	774
17.5		<i>Bivariate and Multivariate Probit Models</i>	778
	17.5.1	<i>Maximum Likelihood Estimation</i>	779
	17.5.2	<i>Testing for Zero Correlation</i>	782
	17.5.3	<i>Partial Effects</i>	782
	17.5.4	<i>A Panel Data Model for Bivariate Binary Response</i>	784
	17.5.5	<i>Endogenous Binary Variable in a Recursive Bivariate Probit Model</i>	785
	17.5.6	<i>Endogenous Sampling in a Binary Choice Model</i>	789
	17.5.7	<i>A Multivariate Probit Model</i>	792
17.6		<i>Summary and Conclusions</i>	795

CHAPTER 18 Discrete Choices and Event Counts 800

18.1		<i>Introduction</i>	800
18.2		<i>Models for Unordered Multiple Choices</i>	801
	18.2.1	<i>Random Utility Basis of the Multinomial Logit Model</i>	801
	18.2.2	<i>The Multinomial Logit Model</i>	803
	18.2.3	<i>The Conditional Logit Model</i>	806
	18.2.4	<i>The Independence from Irrelevant Alternatives Assumption</i>	807
	18.2.5	<i>Nested Logit Models</i>	808
	18.2.6	<i>The Multinomial Probit Model</i>	810
	18.2.7	<i>The Mixed Logit Model</i>	811
	18.2.8	<i>A Generalized Mixed Logit Model</i>	812

18.2.9	<i>Application: Conditional Logit Model for Travel Mode Choice</i>	813
18.2.10	<i>Estimating Willingness to Pay</i>	819
18.2.11	<i>Panel Data and Stated Choice Experiments</i>	821
18.2.12	<i>Aggregate Market Share Data—The BLP Random Parameters Model</i>	822
18.3	Random Utility Models for Ordered Choices	824
18.3.1	<i>The Ordered Probit Model</i>	827
18.3.2	<i>A Specification Test for the Ordered Choice Model</i>	831
18.3.3	<i>Bivariate Ordered Probit Models</i>	832
18.3.4	<i>Panel Data Applications</i>	834
	18.3.4.a <i>Ordered Probit Models with Fixed Effects</i>	834
	18.3.4.b <i>Ordered Probit Models with Random Effects</i>	835
18.3.5	<i>Extensions of the Ordered Probit Model</i>	838
	18.3.5.a <i>Threshold Models—Generalized Ordered Choice Models</i>	839
	18.3.5.b <i>Thresholds and Heterogeneity—Anchoring Vignettes</i>	840
18.4	Models for Counts of Events	842
18.4.1	<i>The Poisson Regression Model</i>	843
18.4.2	<i>Measuring Goodness of Fit</i>	844
18.4.3	<i>Testing for Overdispersion</i>	845
18.4.4	<i>Heterogeneity and the Negative Binomial Regression Model</i>	846
18.4.5	<i>Functional Forms for Count Data Models</i>	847
18.4.6	<i>Truncation and Censoring in Models for Counts</i>	850
18.4.7	<i>Panel Data Models</i>	855
	18.4.7.a <i>Robust Covariance Matrices for Pooled Estimators</i>	856
	18.4.7.b <i>Fixed Effects</i>	857
	18.4.7.c <i>Random Effects</i>	858
18.4.8	<i>Two-Part Models: Zero Inflation and Hurdle Models</i>	861
18.4.9	<i>Endogenous Variables and Endogenous Participation</i>	866
18.5	Summary and Conclusions	869

CHAPTER 19 Limited Dependent Variables—Truncation, Censoring, and Sample Selection 873

19.1	Introduction	873
19.2	Truncation	873
	19.2.1 <i>Truncated Distributions</i>	874
	19.2.2 <i>Moments of Truncated Distributions</i>	875
	19.2.3 <i>The Truncated Regression Model</i>	877
	19.2.4 <i>The Stochastic Frontier Model</i>	879
19.3	Censored Data	885
	19.3.1 <i>The Censored Normal Distribution</i>	886

19.3.2	<i>The Censored Regression (Tobit) Model</i>	888
19.3.3	<i>Estimation</i>	890
19.3.4	<i>Two-Part Models and Corner Solutions</i>	892
19.3.5	<i>Some Issues in Specification</i>	898
	19.3.5.a <i>Heteroscedasticity</i>	898
	19.3.5.b <i>Nonnormality</i>	899
19.3.6	<i>Panel Data Applications</i>	900
19.4	<i>Models for Duration</i>	901
	19.4.1 <i>Models for Duration Data</i>	902
	19.4.2 <i>Duration Data</i>	902
	19.4.3 <i>A Regression-Like Approach: Parametric Models of Duration</i>	903
	19.4.3.a <i>Theoretical Background</i>	903
	19.4.3.b <i>Models of the Hazard Function</i>	904
	19.4.3.c <i>Maximum Likelihood Estimation</i>	906
	19.4.3.d <i>Exogenous Variables</i>	907
	19.4.3.e <i>Heterogeneity</i>	908
	19.4.4 <i>Nonparametric and Semiparametric Approaches</i>	909
19.5	<i>Incidental Truncation and Sample Selection</i>	912
	19.5.1 <i>Incidental Truncation in a Bivariate Distribution</i>	913
	19.5.2 <i>Regression in a Model of Selection</i>	913
	19.5.3 <i>Two-Step and Maximum Likelihood Estimation</i>	916
	19.5.4 <i>Sample Selection in Nonlinear Models</i>	920
	19.5.5 <i>Panel Data Applications of Sample Selection Models</i>	923
	19.5.5.a <i>Common Effects in Sample Selection Models</i>	924
	19.5.5.b <i>Attrition</i>	926
19.6	<i>Evaluating Treatment Effects</i>	928
	19.6.1 <i>Regression Analysis of Treatment Effects</i>	930
	19.6.1.a <i>The Normality Assumption</i>	932
	19.6.1.b <i>Estimating the Effect of Treatment on the Treated</i>	933
	19.6.2 <i>Propensity Score Matching</i>	934
	19.6.3 <i>Regression Discontinuity</i>	937
19.7	<i>Summary and Conclusions</i>	938

PART V Time Series and Macroeconometrics

CHAPTER 20 Serial Correlation 943

20.1	<i>Introduction</i>	943
20.2	<i>The Analysis of Time-Series Data</i>	946
20.3	<i>Disturbance Processes</i>	949
	20.3.1 <i>Characteristics of Disturbance Processes</i>	949
	20.3.2 <i>AR(1) Disturbances</i>	950

20.4	Some Asymptotic Results for Analyzing Time-Series Data	952
20.4.1	<i>Convergence of Moments—The Ergodic Theorem</i>	953
20.4.2	<i>Convergence to Normality—A Central Limit Theorem</i>	955
20.5	Least Squares Estimation	958
20.5.1	<i>Asymptotic Properties of Least Squares</i>	958
20.5.2	<i>Estimating the Variance of the Least Squares Estimator</i>	959
20.6	GMM Estimation	961
20.7	Testing for Autocorrelation	962
20.7.1	<i>Lagrange Multiplier Test</i>	962
20.7.2	<i>Box and Pierce’s Test and Ljung’s Refinement</i>	962
20.7.3	<i>The Durbin–Watson Test</i>	963
20.7.4	<i>Testing in the Presence of a Lagged Dependent Variable</i>	963
20.7.5	<i>Summary of Testing Procedures</i>	964
20.8	Efficient Estimation When Ω Is Known	964
20.9	Estimation When Ω Is Unknown	966
20.9.1	<i>AR(1) Disturbances</i>	966
20.9.2	<i>Application: Estimation of a Model with Autocorrelation</i>	967
20.9.3	<i>Estimation with a Lagged Dependent Variable</i>	969
20.10	Autoregressive Conditional Heteroscedasticity	970
20.10.1	<i>The ARCH(1) Model</i>	971
20.10.2	<i>ARCH(q), ARCH-in-Mean, and Generalized ARCH Models</i>	972
20.10.3	<i>Maximum Likelihood Estimation of the Garch Model</i>	974
20.10.4	<i>Testing for Garch Effects</i>	976
20.10.5	<i>Pseudo–Maximum Likelihood Estimation</i>	977
20.11	Summary and Conclusions	979

CHAPTER 21 Nonstationary Data 982

21.1	Introduction	982
21.2	Nonstationary Processes and Unit Roots	982
21.2.1	<i>Integrated Processes and Differencing</i>	982
21.2.2	<i>Random Walks, Trends, and Spurious Regressions</i>	984
21.2.3	<i>Tests for Unit Roots in Economic Data</i>	987
21.2.4	<i>The Dickey–Fuller Tests</i>	988
21.2.5	<i>The KPSS Test of Stationarity</i>	998
21.3	Cointegration	999
21.3.1	<i>Common Trends</i>	1002
21.3.2	<i>Error Correction and VAR Representations</i>	1003
21.3.3	<i>Testing for Cointegration</i>	1005
21.3.4	<i>Estimating Cointegration Relationships</i>	1007
21.3.5	<i>Application: German Money Demand</i>	1007
	21.3.5.a <i>Cointegration Analysis and a Long-Run Theoretical Model</i>	1008
	21.3.5.b <i>Testing for Model Instability</i>	1009

21.4	Nonstationary Panel Data	1010
21.5	Summary and Conclusions	1011

PART VI Appendices

Appendix A	Matrix Algebra	1013
A.1	Terminology	1013
A.2	Algebraic Manipulation of Matrices	1013
A.2.1	<i>Equality of Matrices</i>	1013
A.2.2	<i>Transposition</i>	1014
A.2.3	<i>Matrix Addition</i>	1014
A.2.4	<i>Vector Multiplication</i>	1015
A.2.5	<i>A Notation for Rows and Columns of a Matrix</i>	1015
A.2.6	<i>Matrix Multiplication and Scalar Multiplication</i>	1015
A.2.7	<i>Sums of Values</i>	1017
A.2.8	<i>A Useful Idempotent Matrix</i>	1018
A.3	Geometry of Matrices	1019
A.3.1	<i>Vector Spaces</i>	1019
A.3.2	<i>Linear Combinations of Vectors and Basis Vectors</i>	1021
A.3.3	<i>Linear Dependence</i>	1022
A.3.4	<i>Subspaces</i>	1023
A.3.5	<i>Rank of a Matrix</i>	1024
A.3.6	<i>Determinant of a Matrix</i>	1026
A.3.7	<i>A Least Squares Problem</i>	1027
A.4	Solution of a System of Linear Equations	1029
A.4.1	<i>Systems of Linear Equations</i>	1029
A.4.2	<i>Inverse Matrices</i>	1030
A.4.3	<i>Nonhomogeneous Systems of Equations</i>	1032
A.4.4	<i>Solving the Least Squares Problem</i>	1032
A.5	Partitioned Matrices	1032
A.5.1	<i>Addition and Multiplication of Partitioned Matrices</i>	1033
A.5.2	<i>Determinants of Partitioned Matrices</i>	1033
A.5.3	<i>Inverses of Partitioned Matrices</i>	1033
A.5.4	<i>Deviations from Means</i>	1034
A.5.5	<i>Kronecker Products</i>	1034
A.6	Characteristic Roots and Vectors	1035
A.6.1	<i>The Characteristic Equation</i>	1035
A.6.2	<i>Characteristic Vectors</i>	1036
A.6.3	<i>General Results for Characteristic Roots and Vectors</i>	1036
A.6.4	<i>Diagonalization and Spectral Decomposition of a Matrix</i>	1037
A.6.5	<i>Rank of a Matrix</i>	1037
A.6.6	<i>Condition Number of a Matrix</i>	1039
A.6.7	<i>Trace of a Matrix</i>	1039
A.6.8	<i>Determinant of a Matrix</i>	1040
A.6.9	<i>Powers of a Matrix</i>	1040
A.6.10	<i>Idempotent Matrices</i>	1042

	A.6.11	<i>Factoring a Matrix</i>	1042
	A.6.12	<i>The Generalized Inverse of a Matrix</i>	1043
A.7		Quadratic Forms and Definite Matrices	1044
	A.7.1	<i>Nonnegative Definite Matrices</i>	1045
	A.7.2	<i>Idempotent Quadratic Forms</i>	1046
	A.7.3	<i>Comparing Matrices</i>	1046
A.8		Calculus and Matrix Algebra	1047
	A.8.1	<i>Differentiation and the Taylor Series</i>	1047
	A.8.2	<i>Optimization</i>	1050
	A.8.3	<i>Constrained Optimization</i>	1052
	A.8.4	<i>Transformations</i>	1054
Appendix B		Probability and Distribution Theory	1055
B.1		Introduction	1055
B.2		Random Variables	1055
	B.2.1	<i>Probability Distributions</i>	1055
	B.2.2	<i>Cumulative Distribution Function</i>	1056
B.3		Expectations of a Random Variable	1057
B.4		Some Specific Probability Distributions	1059
	B.4.1	<i>The Normal Distribution</i>	1059
	B.4.2	<i>The Chi-Squared, t, and F Distributions</i>	1061
	B.4.3	<i>Distributions with Large Degrees of Freedom</i>	1063
	B.4.4	<i>Size Distributions: The Lognormal Distribution</i>	1064
	B.4.5	<i>The Gamma and Exponential Distributions</i>	1064
	B.4.6	<i>The Beta Distribution</i>	1065
	B.4.7	<i>The Logistic Distribution</i>	1065
	B.4.8	<i>The Wishart Distribution</i>	1065
	B.4.9	<i>Discrete Random Variables</i>	1066
B.5		The Distribution of a Function of a Random Variable	1066
B.6		Representations of a Probability Distribution	1068
B.7		Joint Distributions	1070
	B.7.1	<i>Marginal Distributions</i>	1070
	B.7.2	<i>Expectations in a Joint Distribution</i>	1071
	B.7.3	<i>Covariance and Correlation</i>	1071
	B.7.4	<i>Distribution of a Function of Bivariate Random Variables</i>	1072
B.8		Conditioning in a Bivariate Distribution	1074
	B.8.1	<i>Regression: The Conditional Mean</i>	1074
	B.8.2	<i>Conditional Variance</i>	1075
	B.8.3	<i>Relationships Among Marginal and Conditional Moments</i>	1075
	B.8.4	<i>The Analysis of Variance</i>	1077
B.9		The Bivariate Normal Distribution	1077
B.10		Multivariate Distributions	1078
	B.10.1	<i>Moments</i>	1078

	<i>B.10.2</i>	<i>Sets of Linear Functions</i>	1079
	<i>B.10.3</i>	<i>Nonlinear Functions</i>	1080
B.11		The Multivariate Normal Distribution	1081
	<i>B.11.1</i>	<i>Marginal and Conditional Normal Distributions</i>	1081
	<i>B.11.2</i>	<i>The Classical Normal Linear Regression Model</i>	1082
	<i>B.11.3</i>	<i>Linear Functions of a Normal Vector</i>	1083
	<i>B.11.4</i>	<i>Quadratic forms in a Standard Normal Vector</i>	1083
	<i>B.11.5</i>	<i>The F Distribution</i>	1085
	<i>B.11.6</i>	<i>A Full Rank Quadratic Form</i>	1085
	<i>B.11.7</i>	<i>Independence of a Linear and a Quadratic Form</i>	1086
Appendix C		Estimation and Inference	1087
C.1		Introduction	1087
C.2		Samples and Random Sampling	1088
C.3		Descriptive Statistics	1088
C.4		Statistics as Estimators—Sampling Distributions	1091
C.5		Point Estimation of Parameters	1095
	<i>C.5.1</i>	<i>Estimation in a Finite Sample</i>	1095
	<i>C.5.2</i>	<i>Efficient Unbiased Estimation</i>	1098
C.6		Interval Estimation	1100
C.7		Hypothesis Testing	1102
	<i>C.7.1</i>	<i>Classical Testing Procedures</i>	1102
	<i>C.7.2</i>	<i>Tests Based on Confidence Intervals</i>	1105
	<i>C.7.3</i>	<i>Specification Tests</i>	1106
Appendix D		Large-Sample Distribution Theory	1106
D.1		Introduction	1106
D.2		Large-Sample Distribution Theory	1107
	<i>D.2.1</i>	<i>Convergence in Probability</i>	1107
	<i>D.2.2</i>	<i>Other forms of Convergence and Laws of Large Numbers</i>	1110
	<i>D.2.3</i>	<i>Convergence of Functions</i>	1113
	<i>D.2.4</i>	<i>Convergence to a Random Variable</i>	1114
	<i>D.2.5</i>	<i>Convergence in Distribution: Limiting Distributions</i>	1116
	<i>D.2.6</i>	<i>Central Limit Theorems</i>	1118
	<i>D.2.7</i>	<i>The Delta Method</i>	1123
D.3		Asymptotic Distributions	1124
	<i>D.3.1</i>	<i>Asymptotic Distribution of a Nonlinear Function</i>	1126
	<i>D.3.2</i>	<i>Asymptotic Expectations</i>	1127
D.4		Sequences and the Order of a Sequence	1128
Appendix E		Computation and Optimization	1129
E.1		Introduction	1129
E.2		Computation in Econometrics	1130
	<i>E.2.1</i>	<i>Computing Integrals</i>	1130

24 Contents

	<i>E.2.2</i>	<i>The Standard Normal Cumulative Distribution Function</i>	1130
	<i>E.2.3</i>	<i>The Gamma and Related Functions</i>	1131
	<i>E.2.4</i>	<i>Approximating Integrals by Quadrature</i>	1132
E.3	Optimization		1133
	<i>E.3.1</i>	<i>Algorithms</i>	1135
	<i>E.3.2</i>	<i>Computing Derivatives</i>	1136
	<i>E.3.3</i>	<i>Gradient Methods</i>	1137
	<i>E.3.4</i>	<i>Aspects of Maximum Likelihood Estimation</i>	1140
	<i>E.3.5</i>	<i>Optimization with Constraints</i>	1141
	<i>E.3.6</i>	<i>Some Practical Considerations</i>	1142
	<i>E.3.7</i>	<i>The EM Algorithm</i>	1144
E.4	Examples		1146
	<i>E.4.1</i>	<i>Function of One Parameter</i>	1146
	<i>E.4.2</i>	<i>Function of Two Parameters: The Gamma Distribution</i>	1147
	<i>E.4.3</i>	<i>A Concentrated Log-Likelihood Function</i>	1148
Appendix F	Data Sets Used in Applications		1149
References			1155
Combined Author and Subject Index			1201