

Contents

Preface 27

PART ONE Introduction and Review

CHAPTER 1 Economic Questions and Data 43

1.1 Economic Questions We Examine 43

Question #1: Does Reducing Class Size Improve Elementary School Education? 43

Question #2: Is There Racial Discrimination in the Market for Home Loans? 44

Question #3: Does Healthcare Spending Improve Health Outcomes? 45

Question #4: By How Much Will U.S. GDP Grow Next Year? 46

Quantitative Questions, Quantitative Answers 47

1.2 Causal Effects and Idealized Experiments 47

Estimation of Causal Effects 48

Prediction, Forecasting, and Causality 48

1.3 Data: Sources and Types 49

Experimental versus Observational Data 49

Cross-Sectional Data 50

Time Series Data 51

Panel Data 52

CHAPTER 2 Review of Probability 55

2.1 Random Variables and Probability Distributions 56

Probabilities, the Sample Space, and Random Variables 56

Probability Distribution of a Discrete Random Variable 56

Probability Distribution of a Continuous Random Variable 58

2.2 Expected Values, Mean, and Variance 60

The Expected Value of a Random Variable 60

The Standard Deviation and Variance 61

Mean and Variance of a Linear Function of a Random Variable 62

Other Measures of the Shape of a Distribution 63

Standardized Random Variables 65

2.3 Two Random Variables 65

Joint and Marginal Distributions 65

Conditional Distributions 66

Independence 70

Covariance and Correlation 70

The Mean and Variance of Sums of Random Variables 71

- 2.4 The Normal, Chi-Squared, Student t , and F Distributions 75
 - The Normal Distribution 75
 - The Chi-Squared Distribution 80
 - The Student t Distribution 80
 - The F Distribution 80
- 2.5 Random Sampling and the Distribution of the Sample Average 81
 - Random Sampling 81
 - The Sampling Distribution of the Sample Average 82
- 2.6 Large-Sample Approximations to Sampling Distributions 85
 - The Law of Large Numbers and Consistency 85
 - The Central Limit Theorem 86
 - APPENDIX 2.1 Derivation of Results in Key Concept 2.3 100
 - APPENDIX 2.2 The Conditional Mean as the Minimum Mean Squared Error Predictor 101

CHAPTER 3 Review of Statistics 103

- 3.1 Estimation of the Population Mean 104
 - Estimators and Their Properties 104
 - Properties of \bar{Y} 106
 - The Importance of Random Sampling 108
- 3.2 Hypothesis Tests Concerning the Population Mean 109
 - Null and Alternative Hypotheses 109
 - The p -Value 110
 - Calculating the p -Value When σ_Y Is Known 111
 - The Sample Variance, Sample Standard Deviation, and Standard Error 112
 - Calculating the p -Value When σ_Y Is Unknown 113
 - The t -Statistic 113
 - Hypothesis Testing with a Prespecified Significance Level 114
 - One-Sided Alternatives 116
- 3.3 Confidence Intervals for the Population Mean 117
- 3.4 Comparing Means from Different Populations 119
 - Hypothesis Tests for the Difference Between Two Means 119
 - Confidence Intervals for the Difference Between Two Population Means 120
- 3.5 Differences-of-Means Estimation of Causal Effects Using Experimental Data 121
 - The Causal Effect as a Difference of Conditional Expectations 121
 - Estimation of the Causal Effect Using Differences of Means 121
- 3.6 Using the t -Statistic When the Sample Size Is Small 123
 - The t -Statistic and the Student t Distribution 125
 - Use of the Student t Distribution in Practice 126

- 3.7 Scatterplots, the Sample Covariance, and the Sample Correlation 127
 - Scatterplots 127
 - Sample Covariance and Correlation 127
 - APPENDIX 3.1 The U.S. Current Population Survey 141
 - APPENDIX 3.2 Two Proofs That \bar{Y} Is the Least Squares Estimator of μ_Y 141
 - APPENDIX 3.3 A Proof That the Sample Variance Is Consistent 142

PART TWO Fundamentals of Regression Analysis

CHAPTER 4 Linear Regression with One Regressor 143

- 4.1 The Linear Regression Model 144
- 4.2 Estimating the Coefficients of the Linear Regression Model 147
 - The Ordinary Least Squares Estimator 148
 - OLS Estimates of the Relationship Between Test Scores and the Student-Teacher Ratio 149
 - Why Use the OLS Estimator? 151
- 4.3 Measures of Fit and Prediction Accuracy 153
 - The R^2 153
 - The Standard Error of the Regression 154
 - Prediction Using OLS 155
 - Application to the Test Score Data 155
- 4.4 The Least Squares Assumptions for Causal Inference 156
 - Assumption 1: The Conditional Distribution of u_i , Given X_i Has a Mean of Zero 157
 - Assumption 2: (X_i, Y_i) , $i = 1, \dots, n$, Are Independently and Identically Distributed 158
 - Assumption 3: Large Outliers Are Unlikely 159
 - Use of the Least Squares Assumptions 160
- 4.5 The Sampling Distribution of the OLS Estimators 161
- 4.6 Conclusion 164
 - APPENDIX 4.1 The California Test Score Data Set 172
 - APPENDIX 4.2 Derivation of the OLS Estimators 172
 - APPENDIX 4.3 Sampling Distribution of the OLS Estimator 173
 - APPENDIX 4.4 The Least Squares Assumptions for Prediction 176

CHAPTER 5 Regression with a Single Regressor: Hypothesis Tests and Confidence Intervals 178

- 5.1 Testing Hypotheses About One of the Regression Coefficients 178
 - Two-Sided Hypotheses Concerning β_1 179
 - One-Sided Hypotheses Concerning β_1 182
 - Testing Hypotheses About the Intercept β_0 184
- 5.2 Confidence Intervals for a Regression Coefficient 184

- 5.3 Regression When X Is a Binary Variable 186
 - Interpretation of the Regression Coefficients 186
- 5.4 Heteroskedasticity and Homoskedasticity 188
 - What Are Heteroskedasticity and Homoskedasticity? 188
 - Mathematical Implications of Homoskedasticity 190
 - What Does This Mean in Practice? 192
- 5.5 The Theoretical Foundations of Ordinary Least Squares 194
 - Linear Conditionally Unbiased Estimators and the Gauss–Markov Theorem 194
 - Regression Estimators Other Than OLS 195
- 5.6 Using the t -Statistic in Regression When the Sample Size Is Small 196
 - The t -Statistic and the Student t Distribution 196
 - Use of the Student t Distribution in Practice 197
- 5.7 Conclusion 197
 - APPENDIX 5.1 Formulas for OLS Standard Errors 206
 - APPENDIX 5.2 The Gauss–Markov Conditions and a Proof of the Gauss–Markov Theorem 207

CHAPTER 6 Linear Regression with Multiple Regressors 211

- 6.1 Omitted Variable Bias 211
 - Definition of Omitted Variable Bias 212
 - A Formula for Omitted Variable Bias 214
 - Addressing Omitted Variable Bias by Dividing the Data into Groups 215
- 6.2 The Multiple Regression Model 217
 - The Population Regression Line 217
 - The Population Multiple Regression Model 218
- 6.3 The OLS Estimator in Multiple Regression 220
 - The OLS Estimator 220
 - Application to Test Scores and the Student–Teacher Ratio 221
- 6.4 Measures of Fit in Multiple Regression 222
 - The Standard Error of the Regression (SER) 222
 - The R^2 223
 - The Adjusted R^2 223
 - Application to Test Scores 224
- 6.5 The Least Squares Assumptions for Causal Inference in Multiple Regression 225
 - Assumption 1: The Conditional Distribution of u_i Given $X_{1i}, X_{2i}, \dots, X_{ki}$ Has a Mean of 0 225
 - Assumption 2: $(X_{1i}, X_{2i}, \dots, X_{ki}, Y_i), i = 1, \dots, n$, Are i.i.d. 225
 - Assumption 3: Large Outliers Are Unlikely 225
 - Assumption 4: No Perfect Multicollinearity 226

6.6	The Distribution of the OLS Estimators in Multiple Regression	227
6.7	Multicollinearity	228
	Examples of Perfect Multicollinearity	228
	Imperfect Multicollinearity	230
6.8	Control Variables and Conditional Mean Independence	231
	Control Variables and Conditional Mean Independence	232
6.9	Conclusion	234
	APPENDIX 6.1 Derivation of Equation (6.1)	242
	APPENDIX 6.2 Distribution of the OLS Estimators When There Are Two Regressors and Homoskedastic Errors	243
	APPENDIX 6.3 The Frisch–Waugh Theorem	243
	APPENDIX 6.4 The Least Squares Assumptions for Prediction with Multiple Regressors	244
	APPENDIX 6.5 Distribution of OLS Estimators in Multiple Regression with Control Variables	245
CHAPTER 7	Hypothesis Tests and Confidence Intervals in Multiple Regression	247
7.1	Hypothesis Tests and Confidence Intervals for a Single Coefficient	247
	Standard Errors for the OLS Estimators	247
	Hypothesis Tests for a Single Coefficient	248
	Confidence Intervals for a Single Coefficient	249
	Application to Test Scores and the Student–Teacher Ratio	249
7.2	Tests of Joint Hypotheses	251
	Testing Hypotheses on Two or More Coefficients	252
	The F -Statistic	253
	Application to Test Scores and the Student–Teacher Ratio	255
	The Homoskedasticity-Only F -Statistic	256
7.3	Testing Single Restrictions Involving Multiple Coefficients	258
7.4	Confidence Sets for Multiple Coefficients	259
7.5	Model Specification for Multiple Regression	260
	Model Specification and Choosing Control Variables	261
	Interpreting the R^2 and the Adjusted R^2 in Practice	262
7.6	Analysis of the Test Score Data Set	262
7.7	Conclusion	268
	APPENDIX 7.1 The Bonferroni Test of a Joint Hypothesis	274

CHAPTER 8	Nonlinear Regression Functions	277
8.1	A General Strategy for Modeling Nonlinear Regression Functions	279
	Test Scores and District Income	279
	The Effect on Y of a Change in X in Nonlinear Specifications	282
	A General Approach to Modeling Nonlinearities Using Multiple Regression	285
8.2	Nonlinear Functions of a Single Independent Variable	286
	Polynomials	286
	Logarithms	288
	Polynomial and Logarithmic Models of Test Scores and District Income	296
8.3	Interactions Between Independent Variables	297
	Interactions Between Two Binary Variables	298
	Interactions Between a Continuous and a Binary Variable	300
	Interactions Between Two Continuous Variables	305
8.4	Nonlinear Effects on Test Scores of the Student–Teacher Ratio	310
	Discussion of Regression Results	310
	Summary of Findings	314
8.5	Conclusion	315
	APPENDIX 8.1 Regression Functions That Are Nonlinear in the Parameters	325
	APPENDIX 8.2 Slopes and Elasticities for Nonlinear Regression Functions	328
CHAPTER 9	Assessing Studies Based on Multiple Regression	330
9.1	Internal and External Validity	330
	Threats to Internal Validity	331
	Threats to External Validity	332
9.2	Threats to Internal Validity of Multiple Regression Analysis	333
	Omitted Variable Bias	334
	Misspecification of the Functional Form of the Regression Function	336
	Measurement Error and Errors-in-Variables Bias	336
	Missing Data and Sample Selection	339
	Simultaneous Causality	341
	Sources of Inconsistency of OLS Standard Errors	343
9.3	Internal and External Validity When the Regression Is Used for Prediction	344
9.4	Example: Test Scores and Class Size	345
	External Validity	346
	Internal Validity	352
	Discussion and Implications	353
9.5	Conclusion	354
	APPENDIX 9.1 The Massachusetts Elementary School Testing Data	360

PART THREE Further Topics in Regression Analysis

CHAPTER 10 Regression with Panel Data 361

- 10.1 Panel Data 362
 - Example: Traffic Deaths and Alcohol Taxes 362
- 10.2 Panel Data with Two Time Periods: “Before and After” Comparisons 365
- 10.3 Fixed Effects Regression 367
 - The Fixed Effects Regression Model 367
 - Estimation and Inference 369
 - Application to Traffic Deaths 370
- 10.4 Regression with Time Fixed Effects 371
 - Time Effects Only 371
 - Both Entity and Time Fixed Effects 372
- 10.5 The Fixed Effects Regression Assumptions and Standard Errors for Fixed Effects Regression 374
 - The Fixed Effects Regression Assumptions 374
 - Standard Errors for Fixed Effects Regression 376
- 10.6 Drunk Driving Laws and Traffic Deaths 377
- 10.7 Conclusion 381
 - APPENDIX 10.1 The State Traffic Fatality Data Set 387
 - APPENDIX 10.2 Standard Errors for Fixed Effects Regression 388

CHAPTER 11 Regression with a Binary Dependent Variable 392

- 11.1 Binary Dependent Variables and the Linear Probability Model 393
 - Binary Dependent Variables 393
 - The Linear Probability Model 395
- 11.2 Probit and Logit Regression 397
 - Probit Regression 397
 - Logit Regression 401
 - Comparing the Linear Probability, Probit, and Logit Models 403
- 11.3 Estimation and Inference in the Logit and Probit Models 404
 - Nonlinear Least Squares Estimation 404
 - Maximum Likelihood Estimation 405
 - Measures of Fit 406
- 11.4 Application to the Boston HMDA Data 407
- 11.5 Conclusion 413
 - APPENDIX 11.1 The Boston HMDA Data Set 421
 - APPENDIX 11.2 Maximum Likelihood Estimation 421
 - APPENDIX 11.3 Other Limited Dependent Variable Models 424

CHAPTER 12	Instrumental Variables Regression	427
12.1	The IV Estimator with a Single Regressor and a Single Instrument	428
	The IV Model and Assumptions	428
	The Two Stage Least Squares Estimator	429
	Why Does IV Regression Work?	429
	The Sampling Distribution of the TSLS Estimator	434
	Application to the Demand for Cigarettes	435
12.2	The General IV Regression Model	437
	TSLS in the General IV Model	439
	Instrument Relevance and Exogeneity in the General IV Model	440
	The IV Regression Assumptions and Sampling Distribution of the TSLS Estimator	441
	Inference Using the TSLS Estimator	442
	Application to the Demand for Cigarettes	443
12.3	Checking Instrument Validity	444
	Assumption 1: Instrument Relevance	444
	Assumption 2: Instrument Exogeneity	446
12.4	Application to the Demand for Cigarettes	450
12.5	Where Do Valid Instruments Come From?	454
	Three Examples	455
12.6	Conclusion	459
	APPENDIX 12.1 The Cigarette Consumption Panel Data Set	467
	APPENDIX 12.2 Derivation of the Formula for the TSLS Estimator in Equation (12.4)	467
	APPENDIX 12.3 Large-Sample Distribution of the TSLS Estimator	468
	APPENDIX 12.4 Large-Sample Distribution of the TSLS Estimator When the Instrument Is Not Valid	469
	APPENDIX 12.5 Instrumental Variables Analysis with Weak Instruments	470
	APPENDIX 12.6 TSLS with Control Variables	472
CHAPTER 13	Experiments and Quasi-Experiments	474
13.1	Potential Outcomes, Causal Effects, and Idealized Experiments	475
	Potential Outcomes and the Average Causal Effect	475
	Econometric Methods for Analyzing Experimental Data	476
13.2	Threats to Validity of Experiments	478
	Threats to Internal Validity	478
	Threats to External Validity	481
13.3	Experimental Estimates of the Effect of Class Size Reductions	482
	Experimental Design	482
	Analysis of the STAR Data	483
	Comparison of the Observational and Experimental Estimates of Class Size Effects	488

13.4	Quasi-Experiments	490
	Examples	490
	The Differences-in-Differences Estimator	492
	Instrumental Variables Estimators	494
	Regression Discontinuity Estimators	495
13.5	Potential Problems with Quasi-Experiments	496
	Threats to Internal Validity	496
	Threats to External Validity	498
13.6	Experimental and Quasi-Experimental Estimates in Heterogeneous Populations	498
	OLS with Heterogeneous Causal Effects	499
	IV Regression with Heterogeneous Causal Effects	500
13.7	Conclusion	503
	APPENDIX 13.1 The Project STAR Data Set	510
	APPENDIX 13.2 IV Estimation When the Causal Effect Varies Across Individuals	511
	APPENDIX 13.3 The Potential Outcomes Framework for Analyzing Data from Experiments	512
CHAPTER 14	Prediction with Many Regressors and Big Data	514
14.1	What Is “Big Data”?	515
14.2	The Many-Predictor Problem and OLS	516
	The Mean Squared Prediction Error	518
	The First Least Squares Assumption for Prediction	519
	The Predictive Regression Model with Standardized Regressors	519
	The MSPE of OLS and the Principle of Shrinkage	521
	Estimation of the MSPE	522
14.3	Ridge Regression	524
	Shrinkage via Penalization and Ridge Regression	524
	Estimation of the Ridge Shrinkage Parameter by Cross Validation	525
	Application to School Test Scores	526
14.4	The Lasso	527
	Shrinkage Using the Lasso	528
	Application to School Test Scores	531
14.5	Principal Components	532
	Principals Components with Two Variables	532
	Principal Components with k Variables	534
	Application to School Test Scores	536
14.6	Predicting School Test Scores with Many Predictors	537

- 14.7 Conclusion 542
 - APPENDIX 14.1 The California School Test Score Data Set 551
 - APPENDIX 14.2 Derivation of Equation (14.4) for $k = 1$ 551
 - APPENDIX 14.3 The Ridge Regression Estimator When $k = 1$ 551
 - APPENDIX 14.4 The Lasso Estimator When $k = 1$ 552
 - APPENDIX 14.5 Computing Out-of-Sample Predictions in the Standardized Regression Model 552

PART FOUR Regression Analysis of Economic Time Series Data

CHAPTER 15 Introduction to Time Series Regression and Forecasting 554

- 15.1 Introduction to Time Series Data and Serial Correlation 555
 - Real GDP in the United States 555
 - Lags, First Differences, Logarithms, and Growth Rates 555
 - Autocorrelation 558
 - Other Examples of Economic Time Series 560
- 15.2 Stationarity and the Mean Squared Forecast Error 561
 - Stationarity 561
 - Forecasts and Forecast Errors 562
 - The Mean Squared Forecast Error 563
- 15.3 Autoregressions 565
 - The First-Order Autoregressive Model 565
 - The p^{th} -Order Autoregressive Model 567
- 15.4 Time Series Regression with Additional Predictors and the Autoregressive Distributed Lag Model 568
 - Forecasting GDP Growth Using the Term Spread 569
 - The Autoregressive Distributed Lag Model 570
 - The Least Squares Assumptions for Forecasting with Multiple Predictors 571
- 15.5 Estimation of the MSFE and Forecast Intervals 573
 - Estimation of the MSFE 573
 - Forecast Uncertainty and Forecast Intervals 576
- 15.6 Estimating the Lag Length Using Information Criteria 578
 - Determining the Order of an Autoregression 578
 - Lag Length Selection in Time Series Regression with Multiple Predictors 581
- 15.7 Nonstationarity I: Trends 582
 - What Is a Trend? 582
 - Problems Caused by Stochastic Trends 584
 - Detecting Stochastic Trends: Testing for a Unit AR Root 586
 - Avoiding the Problems Caused by Stochastic Trends 588

15.8	Nonstationarity II: Breaks	589
	What Is a Break?	589
	Testing for Breaks	589
	Detecting Breaks Using Pseudo Out-of-Sample Forecasts	594
	Avoiding the Problems Caused by Breaks	595
15.9	Conclusion	596
	APPENDIX 15.1 Time Series Data Used in Chapter 15	604
	APPENDIX 15.2 Stationarity in the AR(1) Model	605
	APPENDIX 15.3 Lag Operator Notation	606
	APPENDIX 15.4 ARMA Models	607
	APPENDIX 15.5 Consistency of the BIC Lag Length Estimator	607
CHAPTER 16	Estimation of Dynamic Causal Effects	609
16.1	An Initial Taste of the Orange Juice Data	610
16.2	Dynamic Causal Effects	612
	Causal Effects and Time Series Data	612
	Two Types of Exogeneity	615
16.3	Estimation of Dynamic Causal Effects with Exogenous Regressors	617
	The Distributed Lag Model Assumptions	617
	Autocorrelated u_t , Standard Errors, and Inference	618
	Dynamic Multipliers and Cumulative Dynamic Multipliers	618
16.4	Heteroskedasticity- and Autocorrelation-Consistent Standard Errors	620
	Distribution of the OLS Estimator with Autocorrelated Errors	620
	HAC Standard Errors	621
16.5	Estimation of Dynamic Causal Effects with Strictly Exogenous Regressors	624
	The Distributed Lag Model with AR(1) Errors	625
	OLS Estimation of the ADL Model	627
	GLS Estimation	628
16.6	Orange Juice Prices and Cold Weather	630
16.7	Is Exogeneity Plausible? Some Examples	637
	U.S. Income and Australian Exports	637
	Oil Prices and Inflation	637
	Monetary Policy and Inflation	638
	The Growth Rate of GDP and the Term Spread	638
16.8	Conclusion	639
	APPENDIX 16.1 The Orange Juice Data Set	646
	APPENDIX 16.2 The ADL Model and Generalized Least Squares in Lag Operator Notation	647

CHAPTER 17	Additional Topics in Time Series Regression	649
17.1	Vector Autoregressions	649
	The VAR Model	650
	A VAR Model of the Growth Rate of GDP and the Term Spread	653
17.2	Multi-period Forecasts	654
	Iterated Multi-period Forecasts	654
	Direct Multi-period Forecasts	656
	Which Method Should You Use?	658
17.3	Orders of Integration and the Nonnormality of Unit Root Test Statistics	658
	Other Models of Trends and Orders of Integration	659
	Why Do Unit Root Tests Have Nonnormal Distributions?	661
17.4	Cointegration	663
	Cointegration and Error Correction	663
	How Can You Tell Whether Two Variables Are Cointegrated?	664
	Estimation of Cointegrating Coefficients	665
	Extension to Multiple Cointegrated Variables	666
17.5	Volatility Clustering and Autoregressive Conditional Heteroskedasticity	667
	Volatility Clustering	667
	Realized Volatility	668
	Autoregressive Conditional Heteroskedasticity	669
	Application to Stock Price Volatility	670
17.6	Forecasting with Many Predictors Using Dynamic Factor Models and Principal Components	671
	The Dynamic Factor Model	672
	The DFM: Estimation and Forecasting	673
	Application to U.S. Macroeconomic Data	676
17.7	Conclusion	682
	APPENDIX 17.1 The Quarterly U.S. Macro Data Set	686

PART FIVE Regression Analysis of Economic Time Series Data

CHAPTER 18	The Theory of Linear Regression with One Regressor	687
18.1	The Extended Least Squares Assumptions and the OLS Estimator	688
	The Extended Least Squares Assumptions	688
	The OLS Estimator	689
18.2	Fundamentals of Asymptotic Distribution Theory	690
	Convergence in Probability and the Law of Large Numbers	690
	The Central Limit Theorem and Convergence in Distribution	692

	Slutsky's Theorem and the Continuous Mapping Theorem	693
	Application to the t -Statistic Based on the Sample Mean	694
18.3	Asymptotic Distribution of the OLS Estimator and t -Statistic	695
	Consistency and Asymptotic Normality of the OLS Estimators	695
	Consistency of Heteroskedasticity-Robust Standard Errors	695
	Asymptotic Normality of the Heteroskedasticity-Robust t -Statistic	696
18.4	Exact Sampling Distributions When the Errors Are Normally Distributed	697
	Distribution of $\hat{\beta}_1$ with Normal Errors	697
	Distribution of the Homoskedasticity-Only t -Statistic	698
18.5	Weighted Least Squares	699
	WLS with Known Heteroskedasticity	700
	WLS with Heteroskedasticity of Known Functional Form	701
	Heteroskedasticity-Robust Standard Errors or WLS?	703
	APPENDIX 18.1 The Normal and Related Distributions and Moments of Continuous Random Variables	709
	APPENDIX 18.2 Two Inequalities	711
CHAPTER 19	The Theory of Multiple Regression	713
19.1	The Linear Multiple Regression Model and OLS Estimator in Matrix Form	714
	The Multiple Regression Model in Matrix Notation	714
	The Extended Least Squares Assumptions	715
	The OLS Estimator	716
19.2	Asymptotic Distribution of the OLS Estimator and t -Statistic	717
	The Multivariate Central Limit Theorem	718
	Asymptotic Normality of $\hat{\beta}$	718
	Heteroskedasticity-Robust Standard Errors	719
	Confidence Intervals for Predicted Effects	720
	Asymptotic Distribution of the t -Statistic	720
19.3	Tests of Joint Hypotheses	721
	Joint Hypotheses in Matrix Notation	721
	Asymptotic Distribution of the F -Statistic	721
	Confidence Sets for Multiple Coefficients	722
19.4	Distribution of Regression Statistics with Normal Errors	722
	Matrix Representations of OLS Regression Statistics	723
	Distribution of $\hat{\beta}$ with Independent Normal Errors	724
	Distribution of $s_{\hat{\beta}}^2$	724
	Homoskedasticity-Only Standard Errors	724
	Distribution of the t -Statistic	725
	Distribution of the F -Statistic	725

19.5	Efficiency of the OLS Estimator with Homoskedastic Errors	726
	The Gauss–Markov Conditions for Multiple Regression	726
	Linear Conditionally Unbiased Estimators	726
	The Gauss–Markov Theorem for Multiple Regression	727
19.6	Generalized Least Squares	728
	The GLS Assumptions	729
	GLS When Ω Is Known	730
	GLS When Ω Contains Unknown Parameters	731
	The Conditional Mean Zero Assumption and GLS	731
19.7	Instrumental Variables and Generalized Method of Moments Estimation	733
	The IV Estimator in Matrix Form	733
	Asymptotic Distribution of the TSLS Estimator	734
	Properties of TSLS When the Errors Are Homoskedastic	735
	Generalized Method of Moments Estimation in Linear Models	738
	APPENDIX 19.1 Summary of Matrix Algebra	748
	APPENDIX 19.2 Multivariate Distributions	752
	APPENDIX 19.3 Derivation of the Asymptotic Distribution of $\hat{\beta}$	753
	APPENDIX 19.4 Derivations of Exact Distributions of OLS Test Statistics with Normal Errors	754
	APPENDIX 19.5 Proof of the Gauss–Markov Theorem for Multiple Regression	755
	APPENDIX 19.6 Proof of Selected Results for IV and GMM Estimation	756
	APPENDIX 19.7 Regression with Many Predictors: MSPE, Ridge Regression, and Principal Components Analysis	758
	Appendix	763
	References	771
	Glossary	775
	Index	785