EIGHTH EDITION

ECONOMETRIC ANALYSIS

William H. Greene

Percentiles of the Chi-Squared Distribution. Table Entry Is c Such That $\text{Prob}[\chi_n^2 \leq c] = P$

n	*.005*	*.010*	*.025*	*.050*	*.100*	*.250*	*.500*	*.750*	*.900*	*.950*	*.975*	*.990*	*.995*
1	.00004	.0002	.001	.004	.02	.10	.45	1.32	2.71	3.84	5.02	6.63	7.88
2	.01	.02	.05	.10	.21	.58	1.39	2.77	4.61	5.99	7.38	9.21	10.60
3	.07	.11	.22	.35	.58	1.21	2.37	4.11	6.25	7.81	9.35	11.34	12.84
4	.21	.30	.48	.71	1.06	1.92	3.36	5.39	7.78	9.49	11.14	13.28	14.86
5	.41	.55	.83	1.15	1.61	2.67	4.35	6.63	9.24	11.07	12.83	15.09	16.75
6	.68	.87	1.24	1.64	2.20	3.45	5.35	7.84	10.64	12.59	14.45	16.81	18.55
7	.99	1.24	1.69	2.17	2.83	4.25	6.35	9.04	12.02	14.07	16.01	18.48	20.28
8	1.34	1.65	2.18	2.73	3.49	5.07	7.34	10.22	13.36	15.51	17.53	20.09	21.95
9	1.73	2.09	2.70	3.33	4.17	5.90	8.34	11.39	14.68	16.92	19.02	21.67	23.59
10	2.16	2.56	3.25	3.94	4.87	6.74	9.34	12.55	15.99	18.31	20.48	23.21	25.19
11	2.60	3.05	3.82	4.57	5.58	7.58	10.34	13.70	17.28	19.68	21.92	24.72	26.76
12	3.07	3.57	4.40	5.23	6.30	8.44	11.34	14.85	18.55	21.03	23.34	26.22	28.30
13	3.57	4.11	5.01	5.89	7.04	9.30	12.34	15.98	19.81	22.36	24.74	27.69	29.82
14	4.07	4.66	5.63	6.57	7.79	10.17	13.34	17.12	21.06	23.68	26.12	29.14	31.32
15	4.60	5.23	6.26	7.26	8.55	11.04	14.34	18.25	22.31	25.00	27.49	30.58	32.80
16	5.14	5.81	6.91	7.96	9.31	11.91	15.34	19.37	23.54	26.30	28.85	32.00	34.27
17	5.70	6.41	7.56	8.67	10.09	12.79	16.34	20.49	24.77	27.59	30.19	33.41	35.72
18	6.26	7.01	8.23	9.39	10.86	13.68	17.34	21.60	25.99	28.87	31.53	34.81	37.16
19	6.84	7.63	8.91	10.12	11.65	14.56	18.34	22.72	27.20	30.14	32.85	36.19	38.58
20	7.43	8.26	9.59	10.85	12.44	15.45	19.34	23.83	28.41	31.41	34.17	37.57	40.00
21	8.03	8.90	10.28	11.59	13.24	16.34	20.34	24.93	29.62	32.67	35.48	38.93	41.40
22	8.64	9.54	10.98	12.34	14.04	17.24	21.34	26.04	30.81	33.92	36.78	40.29	42.80
23	9.26	10.20	11.69	13.09	14.85	18.14	22.34	27.14	32.01	35.17	38.08	41.64	44.18
24	9.89	10.86	12.40	13.85	15.66	19.04	23.34	28.24	33.20	36.42	39.36	42.98	45.56
25	10.52	11.52	13.12	14.61	16.47	19.94	24.34	29.34	34.38	37.65	40.65	44.31	46.93
30	13.79	14.95	16.79	18.49	20.60	24.48	29.34	34.80	40.26	43.77	46.98	50.89	53.67
35	17.19	18.51	20.57	22.47	24.80	29.05	34.34	40.22	46.06	49.80	53.20	57.34	60.27
40	20.71	22.16	24.43	26.51	29.05	33.66	39.34	45.62	51.81	55.76	59.34	63.69	66.77
45	24.31	25.90	28.37	30.61	33.35	38.29	44.34	50.98	57.51	61.66	65.41	69.96	73.17
50	27.99	29.71	32.36	34.76	37.69	42.94	49.33	56.33	63.17	67.50	71.42	76.15	79.49

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PREFACE

ECONOMETRIC ANALYSIS

Econometric Analysis is a broad introduction to the field of econometrics. This field grows continually. A (not complete) list of journals devoted at least in part to econometrics now includes: *Econometric Reviews; Econometric Theory; Econometrica; Econometrics; Econometrics and Statistics; The Econometrics Journal; Empirical Economics; Foundations and Trends in Econometrics; The Journal of Applied Econometrics; The Journal of Business and Economic Statistics; The Journal of Choice Modelling; The Journal of Econometric Methods; The Journal of Econometrics; The Journal of Time Series Analysis; The Review of Economics and Statistics*. Constructing a textbook-style survey to introduce the topic at a graduate level has become increasingly ambitious. Nonetheless, that is what I seek to do here. This text attempts to present, at an entry graduate level, enough of the topics in econometrics that a student can comfortably move on from here to practice or to more advanced study. For example, the literature on "Treatment Effects" is already vast, rapidly growing, complex in the extreme, and occasionally even contradictory. But, there are a few bedrock principles presented in Chapter 8 that (I hope) can help the interested practitioner or student get started as they wade into this segment of the literature. The book is intended as a bridge between an introduction to econometrics and the professional literature.

The book has two objectives. The first is to introduce students to *applied econometrics*, including basic techniques in linear regression analysis and some of the rich variety of models that are used when the linear model proves inadequate or inappropriate. Modern software has made complicated modeling very easy to put into practice. The second objective is to present sufficient *theoretical background* so that the reader will (1) understand the advanced techniques that are made so simple in modern software and (2) recognize new variants of the models learned about here as merely natural extensions that fit within a common body of principles. This book contains a substantial amount of theoretical material, such as that on the GMM, maximum likelihood estimation, and asymptotic results for regression models.

One overriding purpose has motivated all eight editions of *Econometric Analysis*. The vast majority of readers of this book will be users, not developers, of econometrics. I believe that it is not sufficient to teach econometrics by reciting (and proving) the theories of estimation and inference. Although the often-subtle theory is extremely important, the application is equally crucial. To that end, I have provided hundreds of worked numerical examples and extracts from applications in the received empirical literature in many fields. My purpose in writing this work, and in my continuing efforts to update it, is to show readers how to *do* econometric analysis. But, I also believe that readers want (and need) to know what is going on behind the curtain when they use ever more sophisticated modern software for ever more complex econometric analyses.

I have taught econometrics at the level of *Econometric Analysis* at NYU for many years. I ask my students to learn how to use a (any) modern econometrics program as part of their study. I've lost track of the number of my students who recount to me their disappointment in a previous course in which they were taught how to use software, but not the theory and motivation of the techniques. In October, 2014, Google Scholar published its list of the 100 most cited works over all fields and all time. (www.nature.com/polopoly_fs/7.21245!/file/GoogleScholartop100.xlsx). *Econometric Analysis*, the only work in econometrics on the list, ranked number 34 with 48,100 citations. (As of this writing, November 2016, the number of citations to the first 7 editions in all languages approaches 60,000.) I take this extremely gratifying result as evidence that there are readers in many fields who agree that the practice of econometrics calls for an understanding of *why*, as well as *how* to use the tools in modern software. This book is for them.

THE EIGHTH EDITION OF *ECONOMETRIC ANALYSIS*

This text is intended for a one-year graduate course for social scientists. Prerequisites should include calculus, mathematical statistics, and an introduction to econometrics at the level of, say, Gujarati and Porter's (2011) *Basic Econometrics*, Stock and Watson's (2014) *Introduction to Econometrics*, Kennedy's (2008) *Guide to Econometrics*, or Wooldridge's (2015) *Introductory Econometrics: A Modern Approach*. I assume, for example, that the reader has already learned about the basics of econometric methodology including the fundamental role of economic and statistical assumptions; the distinctions between cross-section, time-series, and panel data sets; and the essential ingredients of estimation, inference, and prediction with the multiple linear regression model. Self-contained (for our purposes) summaries of the matrix algebra, mathematical statistics, and statistical theory used throughout the book are given in Appendices A through D. I rely heavily on matrix algebra throughout. This may be a bit daunting to some early on but matrix algebra is an indispensable tool and I hope the reader will come to agree that it is a means to an end, not an end in itself. With matrices, the unity of a variety of results will emerge without being obscured by a curtain of summation signs. Appendix E and Chapter 15 contain a description of numerical methods that will be useful to practicing econometricians (and to us in the later chapters of the book).

Estimation of advanced nonlinear models is now as routine as least squares. I have included five chapters on estimation methods used in current research and five chapters on applications in micro- and macroeconometrics. The nonlinear models used in these fields are now the staples of the applied econometrics literature. As a consequence, this book also contains a fair amount of material that will extend beyond many first courses in econometrics. Once again, I have included this in the hope of laying a foundation for study of the professional literature in these areas.

PLAN OF THE BOOK

The arrangement of the book is as follows:

Part I begins the formal development of econometrics with its fundamental pillar, the *linear multiple regression model*. Estimation and inference with the linear least squares estimator are analyzed in Chapters 2 through 6. The *nonlinear regression model* is introduced in Chapter 7 along with quantile, semi- and nonparametric regression, all as extensions of the familiar linear model. *Instrumental variables estimation* is developed in Chapter 8.

Part II presents three major extensions of the regression model. Chapter 9 presents the consequences of relaxing one of the main assumptions of the linear model, homoscedastic nonautocorrelated disturbances, to introduce the *generalized regression model*. The focus here is on heteroscedasticity; autocorrelation is mentioned, but a detailed treatment is deferred to Chapter 20 in the context of time-series data. Chapter 10 introduces systems of regression equations, in principle, as the approach to modeling simultaneously a set of random variables and, in practical terms, as an extension of the generalized linear regression model. Finally, *panel data methods*, primarily fixed and random effects models of heterogeneity, are presented in Chapter 11.

The second half of the book is devoted to topics that extend the linear regression model in many directions. Beginning with Chapter 12, we proceed to the more involved methods of analysis that contemporary researchers use in analysis of "real-world" data. Chapters 12 to 16 in Part III present different estimation methodologies. Chapter 12 presents an overview by making the distinctions between *parametric*, *semiparametric* and *nonparametric methods*. The leading application of semiparametric estimation in the current literature is the *generalized method of moments (GMM) estimator* presented in Chapter 13. This technique provides the platform for much of modern econometrics. *Maximum likelihood estimation* is developed in Chapter 14. *Monte Carlo* and *simulation-based methods* such as *bootstrapping* that have become a major component of current research are developed in Chapter 15. Finally, *Bayesian methods* are introduced in Chapter 16.

Parts IV and V develop two major subfields of econometric methods, *microeconometrics*, which is typically based on cross-section and panel data, and *macroeconometrics*, which is usually associated with analysis of time-series data. In Part IV, Chapters 17 to 19 are concerned with models of *discrete choice, censoring, truncation, sample selection, duration* and the analysis of *counts of events*. In Part V, Chapters 20 and 21, we consider two topics in time-series analysis, models of *serial correlation* and regression models for *nonstationary data*—the usual substance of macroeconomic analysis.

REVISIONS

With only a couple exceptions noted below, I have retained the broad outline of the text. I have revised the presentation throughout the book (including this preface) to streamline the development of topics, in some cases (I hope), to improve the clarity of the derivations. Major revisions include:

- I have moved the material related to "causal inference" forward to the early chapters of the book – these topics are now taught earlier in the graduate sequence than heretofore and I've placed them in the context of the models and methods where they appear rather than as separate topics in the more advanced sections of the seventh edition. Difference in difference regression as a method, and regression discontinuity designs now appear in Chapter 6 with the discussion of functional forms and in the context of extensive applications extracted from the literature. The analysis of treatment effects has all been moved from Chapter 19 (on censoring and truncation) to Chapter 8 on endogeneity under the heading of "Endogenous

Dummy Variables." Chapter 8, as a whole, now includes a much more detailed treatment of instrumental variable methods.

- I have added many new examples, some as extracts from applications in the received literature, and others as worked numerical examples. I have drawn applications from many different fields including industrial organization, transportation, health economics, popular culture and sports, urban development and labor economics.
- Chapter 10 on systems of equations has been shifted (yet further) from its early emphasis on formal simultaneous linear equations models to systems of regression equations and the leading application, the single endogenous variable in a two equation recursive model – this is the implicit form of the regression model that contains one "endogenous" variable.
- The use of robust estimation and inference methods has been woven more extensively into the general methodology, in practice and throughout this text. The ideas of robust estimation and inference are introduced immediately with the linear regression model in Chapters 4 and 5, rather than as accommodations to nonspherical disturbances in Chapter 9. The role that a robust variance estimator will play in the Wald statistic is developed immediately when the result is first presented in Chapter 5.
- Chapters 4 (Least Squares), 6 (Functional Forms), 8 (Endogeneity), 10 (Equation Systems) and 11 (Panel Data) have been heavily revised to emphasize both contemporary econometric methods and the applications.
- I have moved Appendices A-F to the Companion Web site, at www.pearsonhighered.com/greene, that accompanies this text. Students can access them at no cost.

The first semester of study in a course based on Econometric Analysis would focus on Chapters 1-6 (the linear regression model), 8 (endogeneity and causal modeling), and possibly some of 11 (panel data). Most of the revisions in the eighth edition appear in these chapters.

SOFTWARE AND DATA

There are many computer programs that are widely used for the computations described in this book. All were written by econometricians or statisticians, and in general, all are regularly updated to incorporate new developments in applied econometrics. A sampling of the most widely used packages and Web sites where you can find information about them are

EViews	www.eviews.com	(QMS, Irvine, CA)
Gauss	www.aptech.com	(Aptech Systems, Kent, WA)
LIMDEP	www.limdep.com	(Econometric Software, Plainview, NY)
MATLAB	www.mathworks.com	(Mathworks, Natick, MA)
NLOGIT	www.nlogit.com	(Econometric Software, Plainview, NY)
R	www.r-project.org/	(The R Project for Statistical Computing)
RATS	www.estima.com	(Estima, Evanston, IL)
SAS	www.sas.com	(SAS, Cary, NC)
Shazam	econometrics.com	(Northwest Econometrics Ltd., Gibsons, Canada)
Stata	www.stata.com	(Stata, College Station, TX)

A more extensive list of computer software used for econometric analysis can be found at the resource Web site, http://www.oswego.edu/~economic/econsoftware.htm.

With only a few exceptions, the computations described in this book can be carried out with any of the packages listed. *NLOGIT* was used for the computations in most of the applications. This text contains no instruction on using any particular program or language. Many authors have produced *RATS*, *LIMDEP/NLOGIT*, *EViews*, *SAS*, or *Stata* code for some of the applications, including, in a few cases, in the documentation for their computer programs. There are also quite a few volumes now specifically devoted to econometrics associated with particular packages, such as Cameron and Trivedi's (2009) companion to their treatise on microeconometrics.

The data sets used in the examples are also available on the Web site for the text, http://people.stern.nyu.edu/wgreene/Text/econometricanalysis.htm. Throughout the text, these data sets are referred to "Table Fn.m," for example Table F4.1. The "F" refers to Appendix F available on the Companion web site which contains descriptions of the data sets. The actual data are posted in generic ASCII and portable formats on the Web site with the other supplementary materials for the text. There are now thousands of interesting Web sites containing software, data sets, papers, and commentary on econometrics. It would be hopeless to attempt any kind of a survey. One code/data site that is particularly agreeably structured and well targeted for readers of this book is the data archive for the *Journal of Applied Econometrics* (*JAE*). They have archived all the nonconfidential data sets used in their publications since 1988 (with some gaps before 1995). This useful site can be found at http://qed.econ.queensu.ca/jae/. Several of the examples in the text use the *JAE* data sets. Where we have done so, we direct the reader to the *JAE*'s Web site, rather than our own, for replication. Other journals have begun to ask their authors to provide code and data to encourage replication. Another easy-to-navigate site for aggregate data on the U.S. economy is https://datahub.io/dataset/economagic.

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It is a pleasure to express my appreciation to those who have influenced this work. I remain grateful to Arthur Goldberger (dec.), Arnold Zellner (dec.), Dennis Aigner, Bill Becker, and Laurits Christensen for their encouragement and guidance. After eight editions of this book, the number of individuals who have significantly improved it through their comments, criticisms, and encouragement has become far too large for me to thank each of them individually. I am grateful for their help and I hope that all of them see their contribution to this edition. Any number of people have submitted tips about the text. You can find many of them listed in the errata pages on the text Web site, http://people.stern.nyu.edu/wgreene/Text/econometricanalysis.htm, in particular: David Hoaglin, University of Massachusetts; Randall Campbell, Mississippi State University; Carter Hill, Louisiana State University; and Tom Doan, Estima Corp. I would also like to thank two colleagues who have worked on translations of *Econometric Analysis*, Marina Turuntseva (the Russian edition) and Umit Senesen (the Turkish translation). I must also acknowledge the mail I've received from hundreds of readers and practitioners from the world over who have given me a view into topics and questions that practitioners are interested in, and have provided a vast trove of helpful material for my econometrics courses.

I also acknowledge the many reviewers of my work whose careful reading has vastly improved the book through this edition: Scott Atkinson, University of Georgia; Badi Baltagi, Syracuse University; Neal Beck, New York University; William E. Becker (Ret.), Indiana University; Eric J. Belasko, Texas Tech University; Anil Bera, University of Illinois; John Burkett, University of Rhode Island; Leonard Carlson, Emory University; Frank Chaloupka, University of Illinois at Chicago; Chris Cornwell, University of Georgia; Craig Depken II, University of Texas at Arlington; Frank Diebold, University of Pennsylvania; Edward Dwyer, Clemson University; Michael Ellis, Wesleyan University; Martin Evans, Georgetown University; Vahagn Galstyan, Trinity College Dublin; Paul Glewwe, University of Minnesota; Ed Greenberg, Washington University at St. Louis; Miguel Herce, University of North Carolina; Joseph Hilbe, Arizona State University; Dr. Uwe Jensen, Christian-Albrecht University; K. Rao Kadiyala, Purdue University; William Lott, University of Connecticut; Thomas L. Marsh, Washington State University; Edward Mathis, Villanova University; Mary McGarvey, University of Nebraska–Lincoln; Ed Melnick, New York University; Thad Mirer, State University of New York at Albany; Cyril Pasche, University of Geneva; Paul Ruud, University of California at Berkeley; Sherrie Rhine, Federal Deposit Insurance Corp.; Terry G. Seaks (Ret.), University of North Carolina at Greensboro; Donald Snyder, California State University at Los Angeles; Steven Stern, University of Virginia; Houston Stokes, University of Illinois at Chicago; Dmitrios Thomakos, Columbia University; Paul Wachtel, New York University; Mary Beth Walker, Georgia State University; Mark Watson, Harvard University; and Kenneth West, University of Wisconsin. My numerous discussions with Bruce McCullough of Drexel University have improved Appendix E and at the same time increased my appreciation for numerical analysis. I am especially grateful to Jan Kiviet of the University of Amsterdam, who subjected my third edition to a microscopic examination and provided literally scores of suggestions, virtually all of which appear herein. Professor Pedro Bacao, University of Coimbra, Portugal, and Mark Strahan of Sand Hill Econometrics and Umit Senesen of Istanbul Technical University did likewise with the sixth and seventh editions.

I would also like to thank the many people at Pearson Education who have put this book together with me: Adrienne D' Ambrosio, Neeraj Bhalla, Sugandh Juneja, and Nicole Suddeth and the composition team at SPi Global.

For over 25 years since the first edition, I've enjoyed the generous support and encouragement of many people, some close to me, especially my family, and many not so close. I'm especially grateful for the help, support and priceless encouragement of my wife, Sherrie Rhine, whose unending enthusiasm for this project has made it much less daunting, and much more fun.

William H. Greene
February 2017

1
ECONOMETRICS

1.1 INTRODUCTION

This book will present an introductory survey of econometrics. We will discuss the fundamental ideas that define the methodology and examine a large number of specific models, tools, and methods that econometricians use in analyzing data. This chapter will introduce the central ideas that are the paradigm of econometrics. Section 1.2 defines the field and notes the role that theory plays in motivating econometric practice. Sections 1.3 and 1.4 discuss the types of applications that are the focus of econometric analyses. The process of econometric modeling is presented in Section 1.5 with a classic application, Keynes's consumption function. A broad outline of the text is presented in Section 1.6. Section 1.7 notes some specific aspects of the presentation, including the use of numerical examples and the mathematical notation that will be used throughout the text.

1.2 THE PARADIGM OF ECONOMETRICS

> In the first issue of *Econometrica*, the Econometric Society stated that its main object shall be to promote studies that aim at a unification of the theoretical-quantitative and the empirical-quantitative approach to economic problems and that are penetrated by constructive and rigorous thinking similar to that which has come to dominate the natural sciences. . . . But there are several aspects of the quantitative approach to economics, and no single one of these aspects taken by itself, should be confounded with econometrics. Thus, econometrics is by no means the same as economic statistics. Nor is it identical with what we call general economic theory, although a considerable portion of this theory has a definitely quantitative character. Nor should econometrics be taken as synonomous [sic] with the application of mathematics to economics. Experience has shown that each of these three viewpoints, that of statistics, economic theory, and mathematics, is a necessary, but not by itself a sufficient, condition for a real understanding of the quantitative relations in modern economic life. It is the *unification* of all three that is powerful. And it is this unification that constitutes econometrics.

The Society responded to an unprecedented accumulation of statistical information. It saw a need to establish a body of principles that could organize what would otherwise become a bewildering mass of data. Neither the pillars nor the objectives of econometrics have changed in the years since this editorial appeared. Econometrics concerns itself with the application of mathematical statistics and the tools of statistical inference to the empirical measurement of relationships postulated by an underlying theory.

It is interesting to observe the response to a contemporary, likewise unprecedented accumulation of massive amounts of quantitative information in the form of "Big Data." Consider the following assessment of what Kitchin (2014) sees as a paradigm shift in the analysis of data.

> This article examines how the availability of Big Data, coupled with new data analytics, challenges established epistemologies across the sciences, social sciences and humanities, and assesses the extent to which they are engendering paradigm shifts across multiple disciplines. In particular, it critically explores new forms of empiricism that declare 'the end of theory,' the creation of data-driven rather than knowledge-driven science, and the development of digital humanities and computational social sciences that propose radically different ways to make sense of culture, history, economy and society. It is argued that: (1) Big Data and new data analytics are disruptive innovations which are reconfiguring in many instances how research is conducted; and (2) there is an urgent need for wider critical reflection within the academy on the epistemological implications of the unfolding data revolution, a task that has barely begun to be tackled despite the rapid changes in research practices presently taking place.

We note the suggestion that data-driven analytics are proposed to replace theory (and econometrics as envisioned by Frisch) for providing the organizing principles to guide empirical research. (We will examine an example in Chapter 18 where we consider analyzing survey data with ordered choice models. Also, see Varian (2014) for a more balanced view.) The focus is driven partly by the startling computational power that would have been unavailable to Frisch. It seems likely that the success of this new paradigm will turn at least partly on the questions pursued. Whether the interesting features of an underlying data-generating process can be revealed by appealing to the data themselves without a theoretical platform seems to be a prospect raised by the author. The article does focus on the role of an underlying theory in empirical research—this is a central pillar of econometric methodology. As of this writing, the success story of Big Data analysis is still being written.

The crucial role that econometrics plays in economics has grown over time. The Nobel Prize in Economics has recognized this contribution with numerous awards to econometricians, including the first which was given to (the same) Ragnar Frisch in 1969. Lawrence Klein in 1980, Trygve Haavelmo in 1989, James Heckman and Daniel McFadden in 2000, Robert Engle and Clive Granger in 2003. Christopher Sims in 2011 and Lars Hansen in 2013 were recognized for their empirical research. The 2000 prize was noteworthy in that it celebrated the work of two scientists whose research was devoted to the marriage of behavioral theory and econometric modeling.

Example 1.1 Behavioral Models and the Nobel Laureates

The pioneering work by both James Heckman and Dan McFadden rests firmly on a theoretical foundation of utility maximization.

For Heckman's, we begin with the standard theory of household utility maximization over consumption and leisure. The textbook model of utility maximization produces a demand for leisure time that translates into a supply function of labor. When home production (i.e., work in the home as opposed to the outside, formal labor market) is considered in the calculus, then desired *hours* of (formal) labor can be negative. An important conditioning variable is the *reservation wage*—the wage rate that will induce formal labor market participation. On the demand side of the labor market, we have firms that offer market wages that respond to such attributes as age, education, and experience. What can we learn about labor supply behavior based on observed market wages, these attributes, and observed hours in the formal market? Less than it might seem, intuitively because our observed data omit half the market—the data on formal labor market activity are not randomly drawn from the whole population.

Heckman's observations about this implicit truncation of the distribution of hours or wages revolutionized the analysis of labor markets. Parallel interpretations have since guided analyses in every area of the social sciences. The analysis of policy interventions such as education initiatives, job training and employment policies, health insurance programs, market creation, financial regulation, and a host of others is heavily influenced by Heckman's pioneering idea that when participation is part of the behavior being studied, the analyst must be cognizant of the impact of common influences in both the presence of the intervention and the outcome. We will visit the literature on sample selection and treatment/program evaluation in Chapters 5, 6, 8 and 19.

Textbook presentations of the theories of demand for goods that produce utility, because they deal in continuous variables, are conspicuously silent on the kinds of discrete choices that consumers make every day—what brand of product to choose, whether to buy a large commodity such as a car or a refrigerator, how to travel to work, whether to rent or buy a home, where to live, what candidate to vote for, and so on. Nonetheless, a model of *random utility* defined over the alternatives available to the consumer provides a theoretically sound platform for studying such choices. Important variables include, as always, income and relative prices. What can we learn about underlying preference structures from the discrete choices that consumers make? What must be assumed about these preferences to allow this kind of inference? What kinds of statistical models will allow us to draw inferences about preferences? McFadden's work on how commuters choose to travel to work, and on the underlying theory appropriate to this kind of modeling, has guided empirical research in discrete consumer choices for several decades. We will examine McFadden's models of discrete choice in Chapter 18.

1.3 THE PRACTICE OF ECONOMETRICS

We can make a useful distinction between *theoretical econometrics* and *applied econometrics*. Theorists develop new techniques for estimation and hypothesis testing and analyze the consequences of applying particular methods when the assumptions that justify those methods are not met. Applied econometricians are the users of these techniques and the analysts of data (real world and simulated). The distinction is far from sharp; practitioners routinely develop new analytical tools for the purposes of the study that they are involved in. This text contains a large amount of econometric theory, but it is directed toward applied econometrics. We have attempted to survey techniques, admittedly some quite elaborate and intricate, that have seen wide use in the field.

Applied econometric methods will be used for estimation of important quantities, analysis of economic outcomes such as policy changes, markets or individual behavior, testing theories, and for forecasting. The last of these is an art and science in itself that is the subject of a vast library of sources. Although we will briefly discuss some aspects of forecasting, our interest in this text will be on estimation and analysis of models. The presentation, where there is a distinction to be made, will contain a blend of microeconometric and macroeconometric techniques and applications. It is also necessary to distinguish between *time-series analysis* (which is not our focus) and methods that primarily use *time-series data*. The former is, like forecasting, a growth industry served by its own literature in many fields. While we will employ some of the techniques of time-series analysis, we will spend relatively little time developing first principles.

1.4 MICROECONOMETRICS AND MACROECONOMETRICS

The connection between underlying behavioral models and the modern practice of econometrics is increasingly strong. Another distinction is made between *microeconometrics* and *macroeconometrics*. The former is characterized by its analysis of cross section and panel data and by its focus on individual consumers, firms, and micro-level decision makers. Practitioners rely heavily on the theoretical tools of microeconomics including utility maximization, profit maximization, and market equilibrium. The analyses are directed at subtle, difficult questions that often require intricate formulations. A few applications are as follows:

- What are the likely effects on labor supply behavior of proposed negative income taxes? [Ashenfelter and Heckman (1974)]
- Does attending an elite college bring an expected payoff in expected lifetime income sufficient to justify the higher tuition? [Kreuger and Dale (1999) and Kreuger (2000)]
- Does a voluntary training program produce tangible benefits? Can these benefits be accurately measured? [Angrist (2001)]
- Does an increase in the minimum wage lead to reduced employment? [Card and Krueger (1994)]
- Do smaller class sizes bring real benefits in student performance? [Hanuschek (1999), Hoxby (2000), and Angrist and Lavy (1999)]
- Does the presence of health insurance induce individuals to make heavier use of the health care system—is moral hazard a measurable problem? [Riphahn et al. (2003)]
- Did the intervention addressing anticompetitive behavior of a group of 50 boarding schools by the UK Office of Fair Trading produce a measurable impact on fees charged? [Pesaresi, Flanagan, Scott, and Tragear (2015)]

Macroeconometrics is involved in the analysis of time-series data, usually of broad aggregates such as price levels, the money supply, exchange rates, output, investment, economic growth, and so on. The boundaries are not sharp. For example, an application that we will examine in this text concerns spending patterns of municipalities, which rests somewhere between the two fields. The very large field of financial econometrics is concerned with long time-series data and occasionally vast panel data sets, but with a sharply focused orientation toward models of individual behavior. The analysis of market returns and exchange rate behavior is neither exclusively macro- nor microeconometric. [We will not be spending any time in this text on financial econometrics. For those with an interest in this field, We would recommend the celebrated work by Campbell, Lo, and Mackinlay (1997), or for a more time-series–oriented approach, Tsay (2005).]

Macroeconomic model builders rely on the interactions between economic agents and policy makers. For example:

- Does a monetary policy regime that is strongly oriented toward controlling inflation impose a real cost in terms of lost output on the U.S. economy? [Cecchetti and Rich (2001)]
- Did 2001's largest federal tax cut in U.S. history contribute to or dampen the concurrent recession? Or was it irrelevant?

Each of these analyses would depart from a formal model of the process underlying the observed data.

The techniques used in econometrics have been employed in a widening variety of fields, including political methodology, sociology,[1] health economics, medical research (e.g., how do we handle attrition from medical treatment studies?) environmental economics, economic geography, transportation engineering, and numerous others. Practitioners in these fields and many more are all heavy users of the techniques described in this text.

1.5 ECONOMETRIC MODELING

Econometric analysis usually begins with a statement of a theoretical proposition. Consider, for example, a classic application by one of Frisch's contemporaries:

Example 1.2 Keynes's Consumption Function

From Keynes's (1936) *General Theory of Employment, Interest and Money*:

We shall therefore define what we shall call the propensity to consume as the functional relationship f between X, a given level of income, and C, the expenditure on consumption out of the level of income, so that $C = f(X)$.

The amount that the community spends on consumption depends (i) partly on the amount of its income, (ii) partly on other objective attendant circumstances, and (iii) partly on the subjective needs and the psychological propensities and habits of the individuals composing it. The fundamental psychological law upon which we are entitled to depend with great confidence, both a priori from our knowledge of human nature and from the detailed facts of experience, is that men are disposed, as a rule and on the average, to increase their consumption as their income increases, but not by as much as the increase in their income. That is, . . . dC/dX is positive and less than unity.

But, apart from short period changes in the level of income, it is also obvious that a higher absolute level of income will tend as a rule to widen the gap between income and consumption. . . . These reasons will lead, as a rule, to a greater proportion of income being saved as real income increases.

The theory asserts a relationship between consumption and income, $C = f(X)$, and claims in the second paragraph that the marginal propensity to consume (MPC), dC/dX, is between zero and one.[2] The final paragraph asserts that the average propensity to consume (APC), C/X, falls as income rises, or $d(C/X)/dX = (\text{MPC} - \text{APC})/X < 0$. It follows that MPC < APC. The

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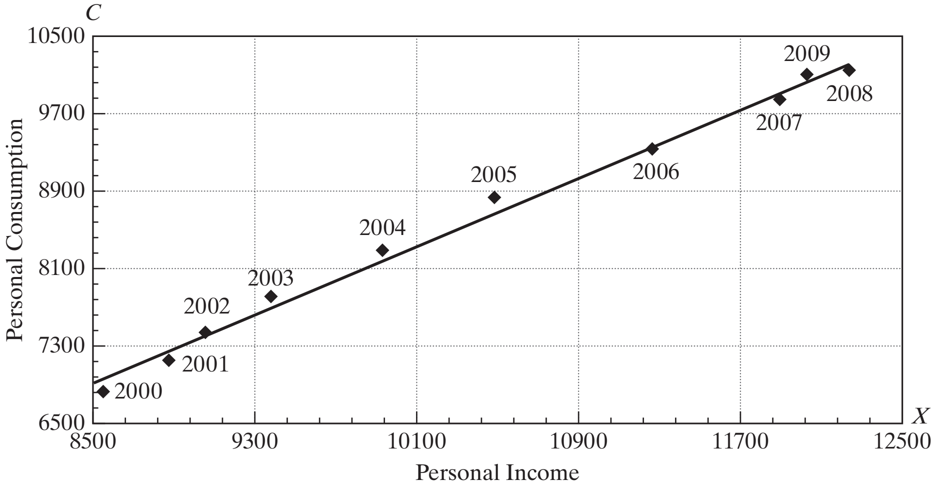
[1] See, for example, Long (1997) and DeMaris (2004).

[2] Modern economists are rarely this confident about their theories. More contemporary applications generally begin from first principles and behavioral axioms, rather than simple observation.

FIGURE 1.1 Aggregate U.S. Consumption and Income Data, 2000–2009.



most common formulation of the consumption function is a linear relationship, $C = \alpha + X\beta$, that satisfies Keynes's "laws" if β lies between zero and one and if α is greater than zero.

These theoretical propositions provide the basis for an econometric study. Given an appropriate data set, we could investigate whether the theory appears to be consistent with the observed "facts." For example, we could see whether the linear specification appears to be a satisfactory description of the relationship between consumption and income, and, if so, whether α is positive and β is between zero and one. Some issues that might be studied are (1) whether this relationship is stable through time or whether the parameters of the relationship change from one generation to the next (a change in the average propensity to save, $1 - \text{APC}$, might represent a fundamental change in the behavior of consumers in the economy); (2) whether there are systematic differences in the relationship across different countries, and, if so, what explains these differences; and (3) whether there are other factors that would improve the ability of the model to explain the relationship between consumption and income. For example, Figure 1.1 presents aggregate consumption and personal income in constant dollars for the United States for the 10 years of 2000–2009. (See Appendix Table F1.1.) Apparently, at least superficially, the data (the facts) are consistent with the theory. The relationship appears to be linear, albeit only approximately, the intercept of a line that lies close to most of the points is positive and the slope is less than one, although not by much. (However, if the line is fit by linear least squares regression, the intercept is negative, not positive.) Moreover, observers might disagree on what is meant by relationship in this description.

Economic theories such as Keynes's are typically sharp and unambiguous. Models of demand, production, labor supply, individual choice, educational attainment, income and wages, investment, market equilibrium, and aggregate consumption all specify precise, *deterministic relationships*. Dependent and independent variables are identified, a functional form is specified, and in most cases, at least a qualitative statement is made about the directions of effects that occur when independent variables in the model change. The model is only a simplification of reality. It will include the salient features of the relationship of interest but will leave unaccounted for influences that might well be present but are regarded as unimportant.

Correlations among economic variables are easily observable through descriptive statistics and techniques such as linear regression methods. The ultimate goal of the econometric model builder is often to uncover the deeper causal connections through elaborate structural, behavioral models. Note, for example, Keynes's use of the behavior of a *representative consumer* to motivate the behavior of macroeconomic variables, such as income and consumption. Heckman's model of labor supply noted in Example 1.1 is framed in a model of individual behavior. Berry, Levinsohn, and Pakes's (1995) detailed model of equilibrium pricing in the automobile market is another.

No model could hope to encompass the myriad essentially random aspects of economic life. It is thus also necessary to incorporate stochastic elements. As a consequence, observations on a variable will display variation attributable not only to differences in variables that are explicitly accounted for in the model, but also to the randomness of human behavior and the interaction of countless minor influences that are not. It is understood that the introduction of a random disturbance into a deterministic model is not intended merely to paper over its inadequacies. It is essential to examine the results of the study, in an ex post analysis, to ensure that the allegedly random, unexplained factor is truly unexplainable. If it is not, the model is, in fact, inadequate.[3] The stochastic element endows the model with its statistical properties. Observations on the variable(s) under study are thus taken to be the outcomes of a random process. With a sufficiently detailed stochastic structure and adequate data, the analysis will become a matter of deducing the properties of a probability distribution. The tools and methods of mathematical statistics will provide the operating principles.

A model (or theory) can never truly be confirmed unless it is made so broad as to include every possibility. But it may be subjected to ever more rigorous scrutiny and, in the face of contradictory evidence, refuted. A deterministic theory will be invalidated by a single contradictory observation. The introduction of stochastic elements into the model changes it from an exact statement to a probabilistic description about expected outcomes and carries with it an important implication. Only a preponderance of contradictory evidence can convincingly invalidate the probabilistic model, and what constitutes a preponderance of evidence is a matter of interpretation. Thus, the probabilistic model is less precise but at the same time, more robust.[4]

The process of econometric analysis departs from the specification of a theoretical relationship. We initially proceed on the optimistic assumption that we can obtain precise measurements on all the variables in a correctly specified model. If the ideal conditions are met at every step, the subsequent analysis will be routine. Unfortunately, they rarely are. Some of the difficulties one can expect to encounter are the following:

- The data may be badly measured or may correspond only vaguely to the variables in the model. "The interest rate" is one example.

[3] In the example given earlier, the estimated constant term in the linear least squares regression is negative. Is the theory wrong, or is the finding due to random fluctuation in the data? Another possibility is that the theory is broadly correct, but the world changed between 1936 when Keynes devised his theory and 2000–2009 when the data (outcomes) were generated. Or, perhaps linear least squares is not the appropriate technique to use for this model, and that is responsible for the inconvenient result (the negative intercept).

[4] See Keuzenkamp and Magnus (1995) for a lengthy symposium on testing in econometrics.

- Some of the variables may be inherently unmeasurable. "Expectations" is a case in point.
- The theory may make only a rough guess as to the correct form of the model, if it makes any at all, and we may be forced to choose from an embarrassingly long menu of possibilities.
- The assumed stochastic properties of the random terms in the model may be demonstrably violated, which may call into question the methods of estimation and inference procedures we have used.
- Some relevant variables may be missing from the model.
- The conditions under which data are collected lead to a sample of observations that is systematically unrepresentative of the population we wish to study.

The ensuing steps of the analysis consist of coping with these problems and attempting to extract whatever information is likely to be present in such obviously imperfect data. The methodology is that of mathematical statistics and economic theory. The product is an econometric model.

1.6 PLAN OF THE BOOK

Our objective in this survey is to develop in detail a set of tools, then use those tools in applications. The following set of applications will include many that readers will use in practice. But it is not exhaustive. We will attempt to present our results in sufficient generality that the tools we develop here can be extended to other kinds of situations and applications not described here.

One possible approach is to organize (and orient) the areas of study by the type of data being analyzed—cross section, panel, discrete data, then time series being the obvious organization.

Alternatively, we could distinguish at the outset between micro- and macroeconometrics.[5] Ultimately, all of these will require a common set of tools, including, for example, the multiple regression model, the use of moment conditions for estimation, instrumental variables (IV), and maximum likelihood estimation. With that in mind, the organization of this book is as follows: The first half of the text develops fundamental results that are common to all the applications. The concept of multiple regression and the linear regression model in particular constitutes the underlying platform of most modeling, even if the linear model itself is not ultimately used as the empirical specification. This part of the text concludes with developments of IV estimation and the general topic of panel data modeling. The latter pulls together many features of modern econometrics, such as, again, IV estimation, modeling heterogeneity, and a rich variety of extensions of the linear model. The second half of the text presents a variety

[5] An excellent reference on the former that is at a more advanced level than this text is Cameron and Trivedi (2005). There does not appear to be available a counterpart, large-scale pedagogical survey of macroeconometrics that includes both econometric theory and applications. The numerous more focused studies include books such as Bardsen et al. (2005).

of topics. Part III is an overview of estimation methods. Finally, Parts IV and V present results from microeconometrics and macroeconometrics, respectively. The broad outline is as follows:

I. **Regression Modeling**
Chapters 2 through 6 present the multiple linear regression model. We will discuss specification, estimation, and statistical inference. This part develops the ideas of estimation, robust analysis, functional form, and principles of model specification.

II. **Generalized Regression, Instrumental Variables, and Panel Data**
Chapter 7 extends the regression model to nonlinear functional forms. The method of instrumental variables is presented in Chapter 8. Chapters 9 and 10 introduce the generalized regression model and systems of regression models. This section ends with Chapter 11 on panel data methods.

III. **Estimation Methods**
Chapters 12 through 16 present general results on different methods of estimation including GMM, maximum likelihood, and simulation-based methods. Various estimation frameworks, including non- and semiparametric and Bayesian estimation, are presented in Chapters 12 and 16.

IV. **Microeconometric Methods**
Chapters 17 through 19 are about microeconometrics, discrete choice modeling, limited dependent variables, and the analysis of data on events—how many occur in a given setting and when they occur. Chapters 17 through 19 are devoted to methods more suited to cross sections and panel data sets.

V. **Macroeconometric Methods**
Chapters 20 and 21 focus on time-series modeling and macroeconometrics.

VI. **Background Materials**
Appendices A through E present background material on tools used in econometrics including matrix algebra, probability and distribution theory, estimation, and asymptotic distribution theory. Appendix E presents results on computation. The data sets used in the numerical examples are described in Appendix F. The actual data sets and other supplementary materials can be downloaded from the author's Web site for the text: http://people.stern.nyu.edu/wgreene/Text/.

1.7 PRELIMINARIES

Before beginning, we note some specific aspects of the presentation in the text.

1.7.1 NUMERICAL EXAMPLES

There are many numerical examples given throughout the discussion. Most of these are either self-contained exercises or extracts from published studies. In general, their purpose is to provide a limited application to illustrate a method or model. The reader can replicate them with the data sets provided. This will generally not entail attempting to replicate the full published study. Rather, we use the data sets to provide applications that relate to the published study in a limited fashion that also focuses on a particular