Introduction

Volume I

At the beginning of the twentieth century, there was very little fundamental theory of time series analysis and surely very few economic time series data. Autoregressive models and moving average models were introduced more or less simultaneously and independently by the British statistician Yule (1921, 1926, 1927) and the Russian statistician Slutsky (1927). The mathematical foundations of stationary stochastic processes were developed by Wold (1938), Kolmogorov (1933, 1941a, 1941b), Khintchine (1934), and Mann and Wald (1943). Thus, modern time series analysis is a mere eight decades old. Clive W. J. Granger has been working in the field for nearly half of its young life. His ideas and insights have had a fundamental impact on statistics, econometrics, and dynamic economic theory.

Granger summarized his research activity in a recent ET Interview (Phillips 1997), which appears as the first reprint in this volume, by saying, "I plant a lot of seeds, a few of them come up, and most of them do not." Many of the seeds that he planted now stand tall and majestic like the Torrey Pines along the California coastline just north of the University of California, San Diego, campus in La Jolla, where he has been an economics faculty member since 1947. Phillips notes in the ET Interview that "It is now virtually impossible to do empirical work in time series econometrics without using some of his [Granger's] methods or being influenced by some of his ideas." Indeed, applied time series econometricians come across at least one of his path-breaking ideas almost on a daily basis. For example, many of his contributions in the areas of spectral analysis, long memory, causality, forecasting, spurious regression, and cointegration are seminal. His influence on the profession continues with no apparent signs of abatement.

SPECTRAL METHODS

In his ET Interview, Granger explains that early in his career he was confronted with many applied statistical issues from various disciplines because he was the only statistician on the campus of the University of Nottingham, where he completed his PhD in statistics and served as lecturer for a number of years. This led to his first publications, which were not in the field of economics. Indeed, the first reprint in Volume II of this set contains one of his first published works, a paper in the field of hydrology. Granger's first influential work in time series econometrics emerged from his research with Michio Hatanaka. Both were working under the supervision of Oskar Morgenstern at Princeton and were guided by John Tukey. Cramér (1942) had developed the spectral decomposition of weakly stationary processes, and the 1950s and early 1960s were marked by intense research efforts devoted to spectral analysis. Many prominent scholars of the time, including Milton Friedman, John von Neumann, and Oskar Morgenstern, saw much promise in the application of Fourier analysis to economic data. In 1964, Princeton University Press published a monograph by Granger and Hatanaka, which was the first systematic and rigorous treatment of spectral analysis in the field of economic time series. Spectral methods have the appealing feature that they do not require the specification of a model but instead follow directly from the assumption of stationarity. Interestingly, more than three decades after its initial publication, the book remains a basic reference in the field.

The work of Granger and Hatanaka was influential in many dimensions. The notion of business cycle fluctuations had been elaborately discussed in the context of time series analysis for some time. Spectral analysis provided new tools and yielded fundamental new insights into this phenomenon. Today, macroeconomists often refer to business cycle *frequencies*, and a primary starting point for the analysis of business cycles is still the application of frequency domain methods. In fact, advanced textbooks in macroeconomics, such as Sargent (1987), devote an entire chapter to spectral analysis. The dominant feature of the spectrum of most economic time series is that most of the power is at the lower frequencies. There is no single pronounced business cycle peak; instead there are a wide number of moderately sized peaks over a large range of cycles between four and eight years in length. Granger (1966) dubbed this shape the "typical spectral shape" of an economic variable. A predecessor to Granger's 1966 paper entitled "The Typical Spectral Shape of an Economic Variable" is his joint paper with Morgenstern published in 1963, which is entitled "Spectral Analysis of New York Stock Market Prices." Both papers are representative of Granger's work in the area of spectral analysis and are reproduced as the first set of papers following the ET Interview.

The paper with Morgenstern took a fresh look at the random walk hypothesis for stock prices, which had been advanced by the French mathematician M. L. Bachelier (1900). Granger and Morgenstern estimated spectra of return series of several major indices of stocks listed on the New York Stock Exchange. They showed that business cycle and seasonal variations were unimportant for return series, as in every case the spectrum was roughly flat at almost all frequencies. However, they also documented evidence that did not support the random walk model. In particular, they found that very long-run movements were not adequately explained by the model. This is interesting because the random walk hypothesis was associated with definitions of efficiency of financial markets for many years (e.g., see the classic work of Samuelson 1965 and Fama 1970). The Granger and Morgenstern paper is part of a very important set of empirical papers written during the early part of the 1960s, which followed the early work of Cowles (1933). Other related papers include Alexander (1961, 1964), Cootner (1964), Fama (1965), Mandelbrot (1963), and Working (1960). Today, the long-term predictability of asset returns is a well-established empirical stylized fact, and research in the area remains very active (e.g., see Campbell, Lo, and MacKinlay 1997 for recent references).

SEASONALITY

Seasonal fluctuations were also readily recognized from the spectrum, and the effect of seasonal adjustment on economic data was therefore straightforward to characterize. Nerlove (1964, 1965) used spectral techniques to analyze the effects of various seasonal adjustment procedures. His approach was to compute spectra of unadjusted and adjusted series and to examine the cross spectrum of the two series. Nerlove's work took advantage of the techniques Granger and Hatanaka had so carefully laid out in their monograph. Since then, many papers that improve these techniques have been written. They apply the techniques to the study of seasonal cycles and the design of seasonal adjustment filters. For example, many significant insights have been gained by viewing seasonal adjustment procedures as optimal linear signal extraction filters (e.g., see Hannan 1967; Cleveland and Tiao 1976; Pierce 1979; and Bell 1984, among others). At the same time, there has been a perpetual debate about the merits of seasonal adjustment, and since the creation of the X-11 program, many improvements have been made and alternative procedures have been suggested. The Census X-11 program was the product of several decades of research. Its development was begun in the early 1930s by researchers at the National Bureau of Economic Research (NBER) (see, for example, Macaulay 1931), and it emerged as a fully operational procedure in the mid 1960s, in large part due to the work by Julius Shiskin and his collaborators at the U.S. Bureau of the Census (see Shiskin et al. 1967). During the 1960s and 1970s, numerous papers were written on the topic of seasonality, including important papers by Sims

(1974) and Wallis (1974). Granger's (1979) paper, "Seasonality: Causation, Interpretation and Implications," is the first of two papers on the topic of seasonality included in this volume. It was written for a major conference on seasonality, which took place in the late 1970s, and appeared in a book edited by Zellner (1979). In this paper, he asks the pointed question, "Why adjust?" and gives a very balanced view of the merits and drawbacks of seasonal adjustment. The paper remains one of the best reflections on the issue of seasonality and seasonal adjustment. The second paper in this subsection, "Is Seasonal Adjustment a Linear or a Nonlinear Data-Filtering Process?," written with Ghysels and Siklos (1996), also deals with a pointed question that was initially posed by Young (1968). The question is: Are seasonal adjustment procedures (approximately) linear data transformations? The answer to this question touches on many fundamental issues, such as the treatment of seasonality in regression (cf. Sims 1974; Wallis 1974) and the theory of seasonal adjustment. The paper shows that the widely applied X-11 program is a highly nonlinear filter.

NONLINEARITY

The book by Box and Jenkins (1970) pushed time series analysis into a central role in economics. At the time of its publication, the theory of stationary linear time series processes was well understood, as evidenced by the flurry of textbooks written during the late 1960s and the 1970s, such as Anderson (1971), Fuller (1976), Granger and Newbold (1977), Hannan (1970), Nerlove et al. (1979), and Priestley (1981). However, many areas of time series analysis fell beyond the scope of linear stationary processes and were not well understood. These areas included nonstationarity and long memory (covered in Volume II) and nonlinear models. Four papers on nonlinearity in time series analysis are reproduced in Volume I and are representative of Granger's important work in this area. Because the class of nonlinear models is virtually without bound, one is left with the choice of either letting the data speak (and suffering the obvious dangers of overfitting) or relying on economic theory to yield the functional form of nonlinear economic relationships. Unfortunately, most economic theories provide only partial descriptions, with blanks that need to be filled in by exploratory statistical techniques. The papers in this section address the statistical foundations of nonlinear modeling some of the classical debates in the literature of nonlinear modeling.

The first paper, "Non-Linear Time Series Modeling," describes the statistical underpinnings of a particular class of nonlinear models. This paper by Granger and Andersen predates their joint monograph on bilinear models (Granger and Andersen 1978). This class of models is not as popular today as it once was, although bilinear models are connected in interesting ways to models of more recent vintage, such as the class of ARCH models introduced by Engle (1982). One of the classical debates in the literature on nonlinear models pertains to the use of deterministic versus stochastic processes to describe economic phenomenon. Granger has written quite extensively on the subject of chaos (a class of deterministic models) and has expressed some strong views on its use in economics, characterizing the theory of chaos as fascinating mathematics but not of practical relevance in econometrics (see Granger 1992, 1994). Liu, Granger, and Heller (1992), in the included paper entitled "Using the Correlation Exponent to Decide Whether an Economic Series Is Chaotic," study the statistical properties of two tests designed to distinguish deterministic time series from stochastic white noise. The tests are the Grassberger-Procacia correlation exponent test and the Brock, Dechert, and Scheinkman test. Along the same lines, Lee, White, and Granger (1993), in the paper entitled "Testing for Neglected Nonlinearity in Time Series Models" examine a battery of tests for nonlinearity. Both papers are similar in that they consider basic questions of nonlinear modeling and provide useful and practical answers.

The fourth paper in this section, "Modeling Nonlinear Relationships Between Extended-Memory Variables," is the Fisher-Schultz lecture delivered at the 1993 European Meetings of the Econometric Society in Uppsala. The lecture coincided with the publication of the book by Granger and Teräsvirta (1993) on modeling nonlinear economic relationships. This book is unique in the area because it combines a rich collection of topics ranging from testing for linearity, chaos, and long memory to aggregation effects and forecasting. In his Fisher-Schultz lecture, Granger addresses the difficult area of nonlinear modeling of nonstationary processes. The paper shows that the standard classification of $I(0)$ and $I(1)$ processes in linear models is not sufficient for nonlinear functions. This observation also applies to fractional integration. As is typical, Granger makes suggestions for new areas of research, advancing the notions of short memory in mean and extended memory, and relates these ideas to earlier concepts of mixing conditions, as discussed for instance in McLeish (1978), Gallant and White (1988), and Davidson (1994). At this point, it is too early to tell whether any of these will give us the guidance toward building a unified theory of nonlinear nonstationary processes.

The final paper in this section is entitled "Semiparametric Estimates of the Relation Between Weather and Electricity Sales." This paper with Engle, Rice, and Weiss is a classic contribution to the nonparamentric and semiparametric literature and stands out as the first application of semiparametric modeling techniques to economics (previous work had been done on testing). Other early work includes Robinson (1988) and Stock (1989). Recent advances in the area are discussed in Bierens (1990), Delgado and Robinson (1992), Granger and Teräsvirta (1993), Härdle (1990), Li (1998), Linton and Neilson (1995), and Teräsvirta, Tjostheim, and Granger (1994), to name but a few. In this classic paper, Granger and his coauthors use semiparametric models, which include a linear part and a nonparametric cubic spline function to model electricity demand. The variable that they use in the nonparametric part of their model is temperature, which is known to have an important nonlinear effect on demand.

METHODOLOGY

The title of this subsection could cover most of Granger's work; however, we use it to discuss a set of six important papers that do not fit elsewhere. The first paper is Granger and Morris's 1976 paper "Time Series Modeling and Interpretation." This is a classic in the literatures on aggregation and measurement error. The paper contains an important theorem on the time series properties of the sum of two independent series, say ARMA(p,m) + ARMA(q,n), and considers a number of special cases of practical interest, like the sum of an AR(p) and a white noise process. A key insight in the paper is that complicated time series models might arise from aggregation. The paper also contains the seeds of Granger's later paper (Granger 1987) on aggregation with common factors, which is discussed later.

The next paper, Granger and Anderson's "On the Invertibility of Time Series Models," also deals with a fundamental issue in time series. Invertibility is a familiar concept in linear models. When interpreted mechanically, invertibility refers to conditions that allow the inverse of a lag polynomial to be expressed in positive powers of the backshift operator. More fundamentally, it is a set of conditions that allows the set of shocks driving a stochastic process to be recovered from current and lagged realizations of the observed data. In linear models, the set of conditions is the same, but in nonlinear models they are not. Granger and Anderson make this point, propose the relevant definition of invertibility appropriate for both linear and nonlinear models, and discuss conditions that ensure invertibility for some specific examples.

The third paper in this section is Granger's "Near Normality and Some Econometric Models." This paper contains exact small sample versions of the central limit theorem. Granger's result is really quite amazing: Suppose x and y are two independent and identically distributed (i.i.d.) random variables and let z be a linear combination of x and y. Then the distribution of z is closer to the normal than the distribution of x and y (where the notion of "closer" is defined in terms of cumulants of the random variables). The univariate version of this result is contained in Granger (1977), and the multivariate generalization is given in the paper included here. The theorem in this paper shows that a bivariate process formed by a weighted sum of bivariate vectors whose components are i.i.d. is generally nearer-normal than its constituents, and the components of the vector will be nearer-uncorrelated.

The fourth paper, "The Time Series Approach to Econometric Model Building," is a paper joint with Paul Newbold. It was published in 1977, a time when the merits of Box-Jenkins-style time series analysis versus classical econometric methods were being debated among econometricians. Zellner and Palm (1974) is a classic paper in the area. Both papers tried to combine the insights of the Box-Jenkins approach with the structural approach to simultaneous equations modeling advocated by the Cowles Foundation. The combination of time series techniques with macroeconomic modeling received so much attention in the 1970s that it probably seems a natural approach to econometricians trained over the last two decades. Work by Sims (1980) on vector autoregression (VAR) models, the rational expectation approach in econometrics pursued by Hansen and Sargent (1980), and numerous other papers are clearly a result of and in various ways a synthesis of this debate. Of much more recent vintage is the next paper in this subsection, entitled: "Comments on the Evaluation of Policy Models," joint with Deutsch (1992). In this paper, the authors advocate the use of rigorous econometric analysis when constructing and evaluating policy models and note that this approach has been largely neglected both by policy makers and by econometricians.

The final paper in this section is Granger's 1987 paper, "Implications of Aggregation with Common Factors." This paper concerns the classic problem of aggregation of microeconomic relationships into aggregate relationships. The paper deals almost exclusively with linear microeconomic models so that answers to the standard aggregation questions are transparent. (For example, the aggregate relationship is linear, with coefficients representing averages of the coefficients across the micropopulation.) The important lessons from this paper don't deal with these questions but rather with the implications of approximate aggregation. Specifically, Granger postulates a microeconomic environment in which individuals' actions are explained by both idiosyncratic and common factors. Idiosyncratic factors are the most important variables explaining the microeconomic data, but these factors are average out when the microrelations are aggregated so that the aggregated data depend almost entirely on the common factors. Because the common factors are not very important for the microdata, an econometrician using microdata could quite easily decide that these factors are not important and not include them in the micromodel. In this case, the aggregate model constructed from the estimated micromodel would be very misspecified. Because macroeconomists are now beginning to rely on microdatasets in their empirical work, this is a timely lesson.

FORECASTING

By the time this book is published, Granger will be in his sixth decade of active research in the area of forecasting.[1] In essence, forecasting is based on the integration of three tasks: model specification and construction, model estimation and testing, and model evaluation and selection. Granger has contributed extensively in all three, including classics in the areas of forecast evaluation, forecast combination, data transformation, aggregation, seasonality and forecasting, and causality and forecasting. Some of these are reproduced in this section.[2]

One of Granger's earliest works on forecasting serves as a starting point for this section of Volume I. This is his 1959 paper, "Estimating the Probability of Flooding on a Tidal River," which could serve as the benchmark example in a modern cost-benefit analysis text because the focus is on predicting the number of floods per century that can be expected on a tidal stretch. This paper builds on earlier work by Gumbel (1958), where estimates for nontidal flood plains are provided. The paper illustrates the multidisciplinary flavor of much of Granger's work.

The second paper in this section is entitled "Prediction with a Generalized Cost of Error Function" (1969). This fundamental contribution highlights the restrictive nature of quadratic cost functions and notes that practical economic and management problems may call instead for the use nonquadratic and possibly nonsymmetric loss functions. Granger illuminates the potential need for such generalized cost functions and proposes an appropriate methodology for implementing such functions. For example, the paper discusses the importance of adding a bias term to predictors, a notion that is particularly important for model selection. This subject continues to receive considerable attention in economics (see, for example, Christoffersen and Diebold 1996, 1997; Hoffman and

[1] His first published paper in the field was in the prestigious *Astrophysical Journal* in 1957 and was entitled "A Statistical Model for Sunspot Activity."

[2] A small sample of important papers not included in this section are Granger (1957, 1967); Granger, Kamstra, and White (1989); Granger, King, and White (1995); Granger and Sin (1997); Granger and Nelson (1979); and Granger and Thompson (1987). In addition, Granger has written seven books on the subject, including *Spectral Analysis of Economic Time Series* (1964, joint with M. Hatanaka), *Predictability of Stock Market Prices* (1970, joint with O. Morgenstern), *Speculation, Hedging and Forecasts of Commodity Prices* (1970, joint with W. C. Labys), *Trading in Commodities* (1974), *Forecasting Economic Time Series* (1977, joint with P. Newbold), *Forecasting in Business and Economics* (1980), and *Modelling Nonlinear Dynamic Relationships* (1993, joint with T. Teräsvirta). All these books are rich with ideas. For example, Granger and Newbold (1977) discuss a test for choosing between two competing forecasting models based on an evaluation of prediction errors. Recent papers in the area that propose tests similar in design and purpose to that discussed by Granger and Newbold include Corradi, Swanson, and Olivetti (1999); Diebold and Mariano (1995); Fair and Shiller (1990); Kolb and Stekler (1993); Meese and Rogoff (1988); Mizrach (1991); West (1996); and White (1999).

Rasche 1996; Leitch and Tanner 1991; Lin and Tsay 1996; Pesaran and Timmerman 1992, 1994; Swanson and White 1995, 1997; Weiss 1996). A related and subsequent paper entitled "Some Comments on the Evaluation of Economic Forecasts" (1983, joint with Newbold) is the third paper in this section. In this paper, generalized cost functions are elucidated, forecast model selection tests are outlined, and forecast efficiency in the sense of Mincer and Zarnowitz (1969) is discussed. The main focus of the paper, however, is the assertion that satisfactory tests of model performance should require that a "best" model produce forecasts, which cannot be improved upon by combination with (multivariate) Box-Jenkins-type forecasts. This notion is a precursor to so-called forecast encompassing and is related to Granger's ideas about forecast combination, a subject to which we now turn our attention.

Three papers in this section focus on forecast combination, a subject that was introduced in the 1969 Granger and Bates paper, "The Combination of Forecasts." This paper shows that the combination of two separate sets of airline passenger forecasts yield predictions that mean-square-error dominate each of the original sets of forecasts. That combined forecasts yield equal or smaller error variance is shown in an appendix to the paper. This insight has led to hundreds of subsequent papers, many of which concentrate on characterizing data-generating processes for which this feature holds, and many of which generalize the framework of Granger and Bates. A rather extensive review of the literature in this area is given in Clemen (1989) (although many papers have been subsequently published). The combination literature also touches on issues such as structural change, loss function design, model misspecification and selection, and forecast evaluation tests. These topics are all discussed in the two related papers that we include in this section – namely, "Invited Review: Combining Forecasts – Twenty Years Later," (1989) and "The Combination of Forecasts Using Changing Weights" (1994, joint with M. Deutsch and T. Teräsvirta). The former paper has a title that is self explanatory, while the latter considers changing weights associated with the estimation of switching and smooth transition regression models – two types of nonlinear models that are currently receiving considerable attention.

The literature on data transformation in econometrics is extensive, and it is perhaps not surprising that one of the early forays in the area is Granger and Newbold's "Forecasting Transformed Series" (1976). In this paper, general autocovariance structures are derived for a broad class of stationary Gaussian processes, which are transformed via some function that can be expanded by using Hermite polynomials. In addition, Granger and Newbold point out that the Box and Cox (1964) transformation often yields variables that are "near-normal," for example, making subsequent analysis more straightforward. (A more recent paper in this area, which is included in Volume II, is Granger and Hallman

1991). The sixth paper in this part of Volume I is entitled "Forecasting White Noise." Here, where Granger illustrates the potential empirical pitfalls associated with loose interpretation of theoretical results. His main illustration focuses on the commonly believed fallacy that: "The objective of time series analysis is to find a filter which, when applied to the series being considered, results in white noise." Clearly such a statement is oversimplistic, and Granger illustrates this by considering three different types of white noise, and blending in causality, data transformation, Markov chains, deterministic chaos, nonlinear models, and time-varying parameter models.

The penultimate paper in this section, "Can We Improve the Perceived Quality of Economic Forecasts?" (1996), focuses on some of the fundamental issues currently confronting forecasters. In particular, Granger espouses on what sorts of loss functions we should be using, what sorts of information and information sets may be useful, and how forecasts can be improved in quality and presentation (for example, by using 50% rather than 95% confidence intervals). The paper is dedicated to the path-breaking book by Box and Jenkins (1970) and is a lucid piece that is meant to encourage discussion among practitioners of the art. The final paper in Volume I is entitled "Short-Run Forecasts of Electricity Loads and Peaks" (1997) and is meant to provide the reader of this volume with an example of how to correctly use current forecasting methodology in economics. In this piece, Ramanathan, Engle, Granger, Vahid-Araghi, and Brace implement a short-run forecasting model of hourly electrical utility system loads, focusing on model design, estimation, and evaluation.

Volume II

CAUSALITY

Granger's contributions to the study of causality and causal relationships in economics are without a doubt among some of his most well known. One reason for this may be the importance in so many fields of research of answering questions of the sort: What will happen to Y if X falls? Another reason is that Granger's answers to these questions are elegant mathematically and simple to apply empirically. Causality had been considered in economics before Granger's 1969 paper entitled "Investigating Causal Relations by Econometric Models and Cross-Spectral