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REX BERGSTROM'S CONTRIBUTIONS TO CONTINUOUS TIME MACROECONOMETRIC MODELING

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This paper reviews the contributions of Rex Bergstrom to the development of continuous time dynamic disequilibrium macroeconomic modeling since the early 1960s. The models provide an elegant integration of economic theory with analysis of steady state and stability properties. The subsequent contributions of his Ph.D. students, spawned by Bergstrom's work over the years, is also reviewed. It was Bergstrom's early pioneering vision 40 years ago of formulating and estimating continuous time models that underlies much of the research in that area of econometrics and finance today.

DEDICATION

This paper is dedicated to the memory of Rex Bergstrom, who since 1982 was my teacher, Ph.D. supervisor, co-author, and colleague, and who always supported me in personal matters and in my continuous time econometric research.

1. INTRODUCTION

One of the many major contributions of Albert Rex Bergstrom was in the development of theoretical continuous time economic models and dynamic disequilibrium macroeconometric modeling over 40 years. The econometric estimation of continuous time models in economics and more recently in finance has also been a major ongoing development since his pioneering work in the 1960s (see P.C.B.

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Phillips, 1988, 1993, 2005). Given that the economy is made up of millions of agents making decisions continuously, the use of a continuous time macroeconometric model that allows for these interactions to be incorporated will be a more realistic description of the underlying phenomena we are trying to model compared to discrete time macroeconomic modeling. This was the Rex Bergstrom's view of how the economy should be modeled. A recent extensive overview of Bergstrom's life and research in different areas is presented in Phillips (2005). In this paper, we discuss Bergstrom's contributions to continuous time macroeconometric modeling since the 1960s and describe work that he has spawned through his Essex Ph.D. students. As his principal collaborator since 1992, I have also included some discussion of what it was actually like to work with Bergstrom.

This paper is structured as follows. Section 2 discusses early theoretical models of the trade cycle and cyclical growth. Section 3 reviews the continuous time macroeconometric models. Section 4 discusses the Ph.D. students from the University of Essex since the early 1980s. Section 5 presents concluding comments.

2. EARLY TRADE CYCLE AND CYCLICAL GROWTH MODELS

Bergstrom's (1962, 1966a, 1967) early research was concerned with linear and nonlinear continuous time models of the trade cycle and cyclical growth. This period of work was inspired by the pioneering work of the New Zealand economist Bill Phillips (see A.W. Phillips, 1954, 1961; Bergstrom, 2000) and the work of Solow (1956) and Swan (1956). Building on the model of Phillips (1961) which provided, in a single system, a synthesis of real and monetary quantities with cycles and growth, Bergstrom (1962) developed the influence of the price mechanism from microeconomic theory more explicitly with the use of a pseudo-production function. Over this period he also worked on developments of the neoclassical growth model (Bergstrom (1966a)), building on the work of Solow (1956) and Swan (1956). These different models and the major neoclassical-Keynesian cyclical growth model, which provided a synthesis of neoclassical and Keynesian theory, were brought together masterfully in his classic monograph in Bergstrom (1967).

3. CONTINUOUS TIME MACROECONOMETRIC MODELS

The next major contribution in the early 1970s was to use the prototype neoclassical-Keynesian cyclical growth model (Bergstrom, 1966a, 1967) as the basis for the development of the first continuous time macroeconometric model of the United Kingdom by Bergstrom and Wymer (1976). The Bergstrom-Wymer (BW) model has been used as the prototype for similar models for many other leading industrialized countries (see references in Bergstrom and Nowman, 2007). A key feature of these models is that most equations have the form of a partial adjustment (error correction) equation, in which the dependent variable is adjusting, continuously, in response to the deviation of its current level from its partial

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equilibrium level, which is a function of other variables in the model. These partial adjustment equations are typically of first- or second-order differential equation form. Following Bergstrom and Nowman (2007) the first-order equations are generally of the form

$$\frac{dx(t)}{dt} = \lambda + \gamma\{f(z(t)) - x(t)\}, \tag{1}$$

where $x(t)$ is the dependent variable to be explained, $z(t)$ is a vector of other variables in the model that directly influence $x(t)$, $f(z(t))$ (a function of $z(t)$) is the partial equilibrium level of $x(t)$ at time t, γ is a speed of adjustment parameter, and λ is a parameter representing the expected rate of increase in $f(z(t))$, which depends on the expected rates of increase in the elements of $z(t)$. The second-order equations are generally of the form

$$\frac{d^2x(t)}{dt^2} = \gamma_1\left\{\lambda - \frac{dx(t)}{dt}\right\} + \gamma_2\{f(z(t)) - x(t)\}, \tag{2}$$

in which γ_1 and γ_2 are speed of adjustment parameters. An important feature of nearly all existing continuous time macroeconometric models, starting with the model of BW, is that they are designed in such a way as to permit a rigorous mathematical analysis of their steady state and stability properties, thus providing a valuable check on the capacity of the model to generate plausible long-run behavior. The general methodology used in this analysis was developed in Bergstrom (1966a, 1967) and applied in BW, where it was shown that, when the exogenous variables satisfy certain conditions, the model has a steady state solution in which all variables grow at constant exponential rates (possibly zero). Moreover, for these models, it was possible to obtain an explicit differential equation system in the logarithms of the ratios of the variables to their steady state paths, so that the nonlinear part satisfies the Poincaré-Liapounov-Perron conditions (see Bergstrom and Nowman, 2007). The asymptotic stability of the steady state solution can then be deduced from the eigenvalues of the linear part of this system. Another general feature of these models is that they make intensive use of economic theory to obtain parsimonious parametrizations and cross-equation restrictions. Also, the role of expectations and long-run rational expectations are used in various ways for cross-equation restrictions and identification of key parameters.

The BW model was a closed system of 13 interdependent differential equations (10 structural equations and 3 identities). The model had 35 key parameters: 16 long-run elasticities and propensities, 16 speed of adjustment parameters, and 3 trend parameters. The model was estimated on quarterly United Kingdom data over 1955–1966 using an exact discrete model and produced impressive dynamic forecasts over a two-year period and plausible long-run behavior. Overall, the BW study was very successful and has become a classic seminal work on modeling the economy in continuous time.

In the 1980s, Bergstrom (1983, 1986, 1990) derived the exact discrete models for general second-order continuous time models, which allow for richer dynamic

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adjustments, and developed associated Gaussian estimation procedures, which under appropriate conditions yield exact maximum likelihood estimates of the structural parameters from a sample of mixed stock and flow data. In particular, the general case of Bergstrom (1986) formed the basis of Bergstrom's next stage on modeling the economy. Following a suggestion in Bergstrom (1986) to form a second-order version of the BW model, I returned to Essex to work as Bergstrom's research officer on a major continuous time macroeconomic modeling project and to complete my Ph.D. under his supervision. The first second-order continuous time macroeconometric model of the United Kingdom was reported in Bergstrom, Nowman, and Wymer (1992). The model known as the Bergstrom-Nowman-Wymer (BNW) model provided a much richer dynamic specification than the predominantly first-order continuous time macroeconometric models that had been developed over the previous 15 years and also had a much more elaborate financial sector. It was a system of 14 second-order differential equations with 63 structural parameters. A preliminary set of estimates were obtained by Clifford Wymer by the application of FIML to an approximate discrete model. These estimates were then used as starting values in the iterative procedure for obtaining the exact Gaussian estimates of the model on a Cray X-MP/48 supercomputer on United Kingdom quarterly data over the period 1974–1984, with the predictive performance tested over 1985–1986. It presented the first application in the literature of the exact Gaussian estimation method to an economy-wide model and provided the first set of continuous lag distributions and coefficient matrices of the exact discrete model in its VARMAX form satisfied by discrete stock and flow data. Further extensions to the model were carried out by Nowman (1996, 1998).

One of the main conclusions from the BNW study, Bergstrom argued, was that some equations with fast speeds of adjustment should be modeled as first-order equations, and the investment equation should also be disaggregated. Bergstrom also became convinced that the replacement of deterministic trends by stochastic trends could significantly improve the forecasting performance of most macroeconometric models, formulated in either discrete or continuous time, that include deterministic trends or segmented trends as discussed by Nowman (1998). This resulted in Bergstrom further developing exact Gaussian estimation methods for the complicated case of a mixed first- and second-order continuous time system with unobservable stochastic trends in Bergstrom (1997).

This would provide the basis for Bergstrom's last major contribution to continuous time macroeconometric modeling in the development of the first mixed-order continuous time macroeconometric model of the United Kingdom incorporating internally embedded stochastic trend elements. The model was based on the BNW model, and the study was presented at the Cowles Foundation Conference on New Developments in Time Series Econometrics at Yale University in 1999. It is fully discussed in his final research monograph in Bergstrom and Nowman (2007), which took seven years to complete. The monograph represents an accumulation of research on a United Kingdom macroeconometric model

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over 40 years; such dedication by an econometrician is truly exceptional by modern standards. The Bergstrom-Nowman model is an 18-equation mixed first- and second-order model with 63 structural parameters. The model was estimated using the exact Gaussian estimation method for stochastic trends in Bergstrom (1997) on quarterly United Kingdom data over the period 1974–1994 and dynamic forecasts obtained over 1995–1996. All the structural parameters and the time lag distributions derived from the speed of adjustment parameters were very plausible. An examination of the steady state and stability properties of the estimated model showed that it generated fluctuations about the steady state neoclassical growth path, including both a trade cycle with a period of about nine years and a longer (Kondratieff) cycle with a period of about 40 years.

Working with Bergstrom over the period 1987–1991 on the BNW model was exciting and inspiring. Our weekly meetings to discuss progress were a highlight of my week. Rex was also very generous outside these times, where he kindly devoted long hours in London to discussing the estimation and analysis of his model. Bergstrom always used his fountain pen to write notes on the next step of the analysis or to present examples of his work to help understanding in a precise and clear way. The data used in the model were carefully collected and constructed by him from the national statistics books and handwritten in careful columns over many months. This was the Bergstrom approach to doing research. Many times the phone would ring and it would be Rex on the line with another idea for me to check and analyze on his model. Sitting next to him in his large darkened office with the table lamp on, watching him while he was in deep thought about his model, was a true privilege. His frame was engulfed by his executive chair and yet, backed by an imposing stock of books behind him, he conveyed a Napoleonic presence to all who knew him. Working with him on his final monograph in his retirement was also exciting and challenging, from the planning of the book structure to the checking of numerous handwritten derivations of complicated formulas that Rex would send me. Long hours were spent discussing our work and empirical results and how to present complicated analysis to a wider audience of econometricians and economists.

4. BERGSTROM AND HIS STUDENTS

Bergstrom had a number of Ph.D. students over the years who worked on a range of areas; a full list with titles is provided in P.C.B. Phillips (2005). Figure 1 presents a summary of them and those of Marcus Chambers, a distinguished student, who continues the Bergstrom traditions of research and supervision at the University of Essex to this day. Since the early 1980s, Bergstrom supervised a number of Ph.D. students building on his general Gaussian estimation methods at Essex. Before discussing these, we mention the very prominent master's student, Peter C.B. Phillips, who suggested and explored in early important work the use of the exact discrete model to estimate first-order continuous time models (Phillips, 1972). This was based on his master's thesis, supervised by Bergstrom over 1969

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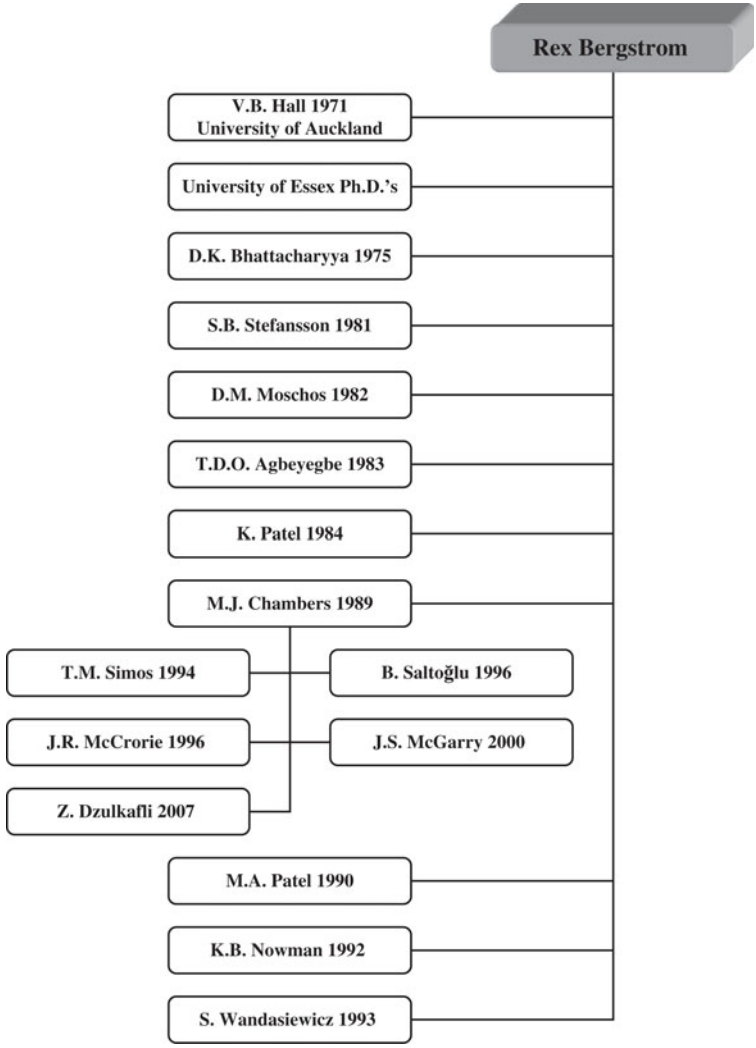


FIGURE 1. Ph.D. students of Rex Bergstrom

and 1970 at the University of Auckland, and he found there were major asymptotic gains compared to using the discrete approximation approach pioneered by Bergstrom (1966b). Phillips went on to make many important contributions to the continuous time econometrics literature (see, for example, Phillips, 1973, 1974, 1978, 1991; Yu and Phillips, 2001; Bandi and Phillips, 2003).

Agbeyegbe (1983) looked at the derivation of the exact discrete models for a first-order mixed sample system and a mixed-order system. Issues of estimation

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were considered and the properties of several estimators for estimating mixed sample systems were studied using a Monte Carlo study (Agbeyegbe, 1984, 1987, 1988). Chambers' (1989) thesis was concerned with the derivation of exact discrete models for single and multi-equation models of consumer demand and with the Gaussian estimation of these models. Methodological advances were made for consumer stocks not being directly observable. A comparison of the forecasting performances with discrete-time models showed clear gains for the continuous time models (see also Bergstrom and Chambers, 1990; Chambers, 1992, 1993). Since completing his thesis, Chambers has made extensive contributions in continuous time econometrics and has also brought wider issues in time-series econometrics to bear on Bergstrom's approach. Chambers' (1999a) paper on exact discrete time representation theory is now the standard reference for applied workers using higher-order models with stationary, nonstationary, and explosive systems with mixed stock and flow data. He has extended Bergstrom's basic framework to the estimation of a class of univariate fractional ARIMA models with a continuous time parameter to the modeling of long-memory time series (Chambers, 1996, 1998a) and to differential-difference equations (Chambers, 1998b). He has also offered a contribution to the study of seasonal processes from the perspective of continuous time (Chambers, 1999b). In recent years, he has adopted the continuous time framework to address issues in temporal aggregation. Specifically, he has shown that the efficiency of estimators of the asymptotic variances in cointegrated systems depend on whether the variables are stock variables or flow variables, and he showed that estimators based on the latter type of variable are as efficient as if the data were recorded continuously (Chambers, 2003). He shows in Chambers (2004) a related result, that it is possible consistently to test for a unit root in a flow variable even when the span of the data is not increasing. In other work he has offered an explanation of how to ameliorate the problem of temporal aggregation bias in estimating the half-lives of shocks to real exchange rates, thereby contributing to an explanation of the purchasing power parity puzzle (Chambers, 2005).

Nowman's (1992) thesis was concerned with the application of the Gaussian estimation approach to second-order continuous time models with mixed stock and flow data for the general case of Bergstrom (1986). A Monte Carlo study using a second-order version of an extended trade cycle model based on the model of A.W. Phillips (1954; see also P.C.B. Phillips, 1972; Nowman, 1993) showed that the Gaussian estimates performed well. An extension of the model of Bergstrom (1986) to include the derivatives of the exogenous variables was also given using interpolation formulas (Nowman, 1991; see also Chambers, 1991, who independently provided an alternative approach via deriving the exact discrete model). The final part of his thesis was concerned with the Gaussian estimation of the BNW model discussed above. The exact discrete model of Phillips (1972) was earlier used by Brennan and Schwartz (1979) to estimate their two-factor interest rate model in finance. Nowman (1997) moved Bergstrom's Gaussian estimation methods into financial econometrics with a modified exact discrete model

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of Phillips (1972) to estimate a range of single-factor interest rate models that were currently being used by practitioners in the financial markets on trading floors. Babbs and Nowman (1999) developed a general multifactor model of interest rates and estimated the model using the Kalman filter. This model was also estimated using Bergstrom's Gaussian estimation methods in Bergstrom and Nowman (1999), where they derived the exact discrete model and exact Gaussian likelihood function. Wandasiewicz's (1993) thesis investigated monetary and fiscal policy feedbacks in the BW and BNW models using advanced optimal control theory developed in Bergstrom (1987; see also, Bergstrom, Nowman and Wandasiewicz, 1994).

Simos (1994, 1996) investigated the Gaussian estimation of a first-order continuous time system driven by an observable vector of exogenous common stochastic trends and derived the exact discrete model and the Gaussian likelihood function. He also looked at an efficient estimation method for the class of first-order continuous time systems characterized by the saddle path stability property. Another aspect of his thesis looked at the class of linear quadratic rational expectations models whose foundations lie in the optimal control literature. He provided prediction formulas and suggested a spectral estimation method. Recently, Simos (2005) derived closed formulas for the exact discrete model of a third-order continuous time system under different data assumptions. Saltoğlu (1996) applied Gaussian estimation methods to the Brennan and Schwartz (1979) interest rate model using the exact discrete model they used of Phillips (1972). It was shown that the forecasting performance of the continuous time model performed well compared to discrete time models. He also considered a continuous time portfolio selection model that was estimated via continuous time methods (see also Saltoğlu, 2000, 2003). In later work, he compared the forecasting performance of nonparametric methods and multifactor continuous time interest rate models estimated by Bergstrom's Gaussian estimation methods (Nowman and Saltoğlu, 2003).

McCrorie (1996) developed a method of deriving the exact discrete analog (and so the exact Gaussian likelihood) that did not rely on restrictions on the data that previous authors imposed, which were capable of being rejected by a statistical test. The method used a nonstandard integral interchange that gets around the usual steady state assumption that can rule out unit root processes. It allowed for weak assumptions on the disturbances and also for a mixture of stock and flow data. Furthermore, he developed a data-based method of selecting an optimum interpolant to address the problem that the exogenous variable component in the exact discrete analog of an open continuous time model depends on a continuous record of the exogenous series (see also McCrorie, 2000, 2001). More recently, Chambers and McCrorie (2006) looked at important issues of model identification, specification, and estimation in exchange rate models with unobservable fundamentals. In another contribution, Chambers and McCrorie (2007) developed the asymptotic theory for the joint estimation of long-run equilibrium coefficients and parameters governing the short-run dynamics of a fully-parametric co-integrated

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system formulated in continuous time. They derived an exact discrete analogue and discussed issues of estimation.

McGarry (2000) considered ways in which continuous time models can account for seasonal fluctuations in economic processes. The exact discrete time model was derived for a fourth-order system of stochastic differential equations that included seasonal dummies, and the time paths of the exogenous variables are approximated using a quartic interpolant. Such a model is useful for quarterly data. The thesis also considered the role of differential-difference equations, in which particular lag values may be included to represent seasonal behavior, but the lags can also be treated as unknown and included in the vector of estimable parameters. A frequency domain maximum likelihood estimator is proposed, and the properties of an approximation to the spectral density function of the process was analyzed (see also McGarry, 2003). Two papers related to this work are Chambers and McGarry (2002), in which estimation methods are developed for a univariate first-order differential-difference equation containing a single (not necessarily integer) lag within a continuous-time unobserved components model, and, more recently, Ercolani and Chambers (2006), in which the estimation of more general systems of differential-difference equations is considered. These models provide an exciting scope for empirical applications in the future, especially in the estimation of business cycles. Finally, Dzulkafli (2007) investigated the impact of oil prices on interest rates, exchange rates, and prices using discrete and continuous time models. He derived an exact discrete model and applied Bergstrom's Gaussian estimation methods.

5. CONCLUDING COMMENTS

Rex Bergstrom was one of the great econometricians, teachers, and supervisors, and his contributions to the development of econometrics and econometricians in the United Kingdom, New Zealand, and beyond have been considerable. His impact on his close group of students has been important, and his traditions and pedigree are carried forward with great pride. This issue is a great tribute to Rex Bergstrom and will inspire further generations to work on continuous time modeling and econometrics in the years to come.

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