ALBERT REX BERGSTROM: 1925–2005

BY

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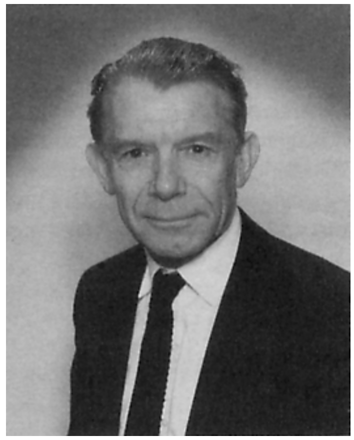

Albert Rex Bergstrom
1925–2005

A. R. Bergstrom, universally known as Rex, was born on 9 July 1925 in Christchurch, where he spent his childhood and attended Christchurch Boys High School. He was the first of four children to mother Lily and father Albert Victor Bergstrom, a mechanic. His grandfather, Sten Gustaf Bergström, had migrated to New Zealand from Sweden in 1875. Bergstrom studied at Christchurch University College (1942-1947) part-time while holding accountancy posts and serving with the RNZAF (1945-1946). He gained an M.Com (University of New Zealand) with first class honours in 1948 and won a Travelling Scholarship in Commerce in 1950, which he took up two years later to do his doctoral work at the University of Cambridge in 1952, completing his Ph.D in 1955. He was Emeritus Professor of Economics at the University of Essex when he died in London on 1 May, 2005.

Rex Bergstrom was New Zealand's first econometrician and the second New Zealander (after Bill Phillips) to be elected a Fellow of the Econometric Society. During his career, he published five articles in the Econometric Society journal *Econometrica,* some of these turning out to be landmark papers which made his name in the international community and earnt him professional distinction as New Zealand's leading quantitative economist. His most notable research contributions were to continuous time modeling in econometrics, a field that he helped to establish and nurture and with which he will always be identified. As a teacher, his influence on New Zealand econometrics was foundational and profound. His impact continues to this day in the traditions he established among his many students.

Bergstrom started his professional career as an Assistant Lecturer in Economics at Massey College (1948-1949) where the department comprised only two people. He moved to Auckland University College in 1950, making up a department of four people as a Junior Lecturer. The Auckland department was headed by Colin Simkin, who had a great appreciation of the importance of econometrics and had acquired all the back issues of *Econometrica* and the Cowles Commision research papers. One of the other lecturers in the Auckland department was Malcolm Fisher, who had completed his Auckland MA in 1948 and whose interests also included applied econometrics. Bergstrom rose through the ranks at Auckland to Associate Professor of Economics until he left New Zealand to take up a Readership at the London School of Economics (1962-1964) joining Bill Phillips, Jim Durbin and later Denis Sargan to make the LSE the leading centre for econometric research in the UK. He subsequently returned to the University of Auckland as Professor of Econometrics (1964-1971) and left New Zealand again in 1970 to become Keynes Visiting Professor at the University of Essex. He then remained at Essex as Professor of Economics until his formal retirement in 1992, becoming the University's first Professor Emeritus of Economics.

In retirement, Bergstrom continued his academic research with undiminished devotion. At the time of his death, he had just completed his latest work [5][1], *A Continuous Time Econometric Model of the United Kingdom with Stochastic Trends.* This book, which is co-authored with Ben Nowman (a former student from the University of Essex), develops and estimates the latest version of his econometric model of the UK economy. His intention was to stay in London to see the book in print at the LSE bookshop before returning permanently to New Zealand to be with his family.

Auckland and the Early Research

While working at the University of Auckland in the 1950s, Bergstrom became recognized as New Zealand's foremost empirical researcher. He published his first applied econometrics article [6] in the *Economic Record* in 1949 and several other papers [7, 8, 9, 12, 13] on empirical aspects of the New Zealand economy over this period. His second *Economic Record* paper

[1] References to Bergstrom's articles are given in square brackets [ ] and refer to the bibliography of his published works at the end of this paper.

[7] developed and estimated an export supply function for the New Zealand economy and was the precursor to his famous model of supply and demand for New Zealand exports [9] that was published by *Econometrica* in 1955, which appears to be the first article in *Econometrica* to be published by a New Zealand economist.

Bergstrom's study [9] was based on his doctoral dissertation at Cambridge, which was completed while he was on leave from Auckland during 1952-4. The research was conceptualized and commenced before Bergstrom arrived in Cambridge and the dissertation was supervised by Richard Stone. The objective of the empirical work was to model supply and demand equations for New Zealand's main exported food products - dairy products, lamb and mutton - and to apply new econometric methodologies for the estimation of dynamic structural equations. Since almost all these exported food products were destined for the UK, the model comprised UK demand equations, NZ supply equations and additional equations for the NZ labour market and the NZ income determination process. The formulation of the equations was guided by consumer demand theory and intertemporal profit maximisation. Overall, the model involved 27 equations and 55 parameters, making it the largest system of simultaneous equations ever formulated for empirical work up to that time, larger even than the famous Klein-Goldberger (1955) model of the US economy, which was published the same year. The model was estimated by the new limited-information maximum likelihood (LIML) methodology which had been recently devised by the Cowles Commission and which involved more complex calculations than least squares. Bergstrom did most of the numerical work by hand on an electric desk machine, including some 10×10 matrix inversions, and also used the EDSAC, one of the two electronic computers in the UK at that time, when it was available.

The empirical results gave strong support to the new econometric methodology in terms of the plausibility of the LIML coefficient estimates and the performance of the fitted equations in post-sample predictions in comparison with least squares. The sample size was small - only 17 annual observations - so it was of considerable interest to see the outcome of the new econometric methods in comparison with least squares and to assess the empirical effects of the well-known asymptotic bias in such small samples. Residuals on the equations were assumed to be autoregressive with a unit root, so that all the core variables in the system had stochastic trends and the model was estimated in log differences. These many features combined to give the paper an extraordinary quality of cutting-edge mastery in applied research. The work was accordingly cited by many leading econometricians, and its skilful mix of economic theory, econometric methodology, and painstaking empirical implementation became the hallmark of Bergstrom scholarship.

By the close of the decade of the 1950s, Bergstrom's interests in and knowledge of econometrics had widened well beyond empirical research. One particularly ambitious contribution stands out. In search of a more complete understanding of the properties of the LIML procedure that he used successfully in his empirical work on New Zealand exports, Bergstrom set about finding the exact finite-sample distributions of the maximum likelihood estimator (MLE) and ordinary least squares (OLS) estimator of the propensity to consume in a simple stochastic income determination model. The Indian econometrician Nagar (1959) had earlier developed moment approximations for simultaneous equations estimators and his study provided a precursor to Bergstrom's research. Another catalyst was the belief, well articulated in Malcolm Fisher's (1954) review of the Cowles Commision research, that new simultaneous equations estimators like LIML may not have good small sample performance. Bergstrom's work specifically addressed this question and, in doing so, turned out to be very different from Nagar's approach. Bergstrom derived exact mathematical forms for the density functions of the MLE and OLS estimators (under Gaussian innovations), graphed the densities and computed probabilities of concentration about the true value of the parameter for the two estimators. The results were conclusive and provided clear support for the use of simultaneous equations estimators like LIML. Bergstrom's results were published in his 1962 *Econometrica* paper [14]. Remarkable as a first piece of technical research, this paper helped to usher in a new era of mathematical sophistication in econometrics. Independently, Basmann (1961) had published some related work on the exact density of the two-stage least squares estimator and together their articles are recognized as having opened up this new research field.

Later research has reinforced the conclusions reached by Bergstrom on the superiority of the LIML procedure in small samples. It is interesting that this is so, in spite of the fact that the distribution of the LIML structural estimator is known to have heavy tails (Phillips, 1984) and can be bimodal. Indeed, the same distribution that was originally derived by Bergstrom was considered decades later by Nelson and Startz (1990) and Maddala and Jeong (1992) in two subsequent *Econometrica* articles that brought the bimodal property of certain structural equation estimators into prominence. Interestingly, the bimodality is present but does not show up in Bergstrom's sketches - it becomes apparent in different parameter configurations and over a wider domain. The topic is of ongoing interest and relates in important ways to the recently studied and practically important phenomenon of weak instrumentation in structural estimation. Phillips (2006) provides some further discussion, analysis and references.

The London School of Economics 1962-64

In 1962 Bergstrom left Auckland for the London School of Economics to take up a Readership in Economics. His arrival coincided with the time when the LSE was rising to prominence in the field of econometrics and overtaking Cambridge as the leading centre of econometric research in the UK. Bergstrom joined a burgeoning group of econometricians that included the New Zealand born economist Bill Phillips, the statistician Jim Durbin and, somewhat later, Denis Sargan, as well as a larger team of economists such as Dick Lipsey, Chris Archibald and Morris Peston all of whom were working vigorously in applied econometrics. The initiatives established during this period at the LSE were to put the School at the forefront of econometric research in the UK, a position that it has retained ever since.

During his period at the LSE from 1962-1964, Bergstrom's own research on econometric modeling moved in decisive new directions. Influenced primarily by the work of Bill Phillips, he had embarked on a research agenda concerned with the development of economic models of cyclical growth that synthesized real and monetary phenomena in a growing economy. These models, which were published in *Economica* in 1962 [15] and *Economic Studies Quarterly* in 1966 [18], incorporated a neoclassical production technology, Keynesian-type feedbacks involving prices and interest rates to the real sector, and adjustment mechanisms to accommodate market disequilibrium. As economic models, they represented an important advance over earlier trade cycle models which set out to explain cyclical behaviour in real variables through the multiplier-accelerator mechanism alone. In addition, the new models had particular solutions that corresponded to the steady state paths of the earlier neoclassical growth models of Solow (1956) and Swan (1956). The Bergstrom cyclical growth models therefore provided a synthesis of two earlier strands of research and were the first truly disequilibrium models of neoclassical growth.

The formulation of cyclical growth models as ordinary differential equations with a continuous time parameter leads naturally to an econometric specification in terms of systems of stochastic differential equations. Apart from some isolated early research by Bartlett (1946), Quenouille (1957), Phillips (1959), and Durbin (1961), econometric methodology for estimating systems of stochastic differential equations was completely undeveloped at this time. Indeed, the mathematics of stochastic Ito calculus had only recently been worked out, statisticians had not yet confronted the issues of likelihood-based inference using discretely observed data, including the thorny aliasing problem, and few econometricians were aware of the subject and its potential. An early, but largely ignored, reference on the latter was Koopmans (1950), who had pointed to some of the advantages of working with continuous systems in econometrics.

Stimulated by earlier work of Bill Phillips (1959), Bergstrom commenced while at LSE an ambitious research program that was complementary to his work on economic models of cyclical growth. This research program explicitly addressed the estimation of econometric models in continuous time with discrete data. Bergstrom's research on this topic was motivated by concerns of practical implementation and this led him to propose a new empirical procedure based on a nonrecursive discrete approximation to a continuous-time system. The approximation was constructed in the form of a simultaneous equations model and the proposal had the natural advantage of making available the by-then well-established simultaneous equations methodology for estimation and inference in continuous-time models formulated as systems of differential equations. The discrete approximation is especially interesting because it shows the precise sense in which a system of (nonrecursive) simultaneous interdependent equations may be regarded as an approximation to a recursive differential equation system. In effect, when a continuous time record of a process is not available (as is the case with economic data), but observations are made at discrete points in time (such as quarterly), it is natural to think that a recursive structure (arising for instance from individual or representative agent decision making) that may operate in continuous time will be lost over a discrete interval when there is temporal aggregation. The outcome is a form of simultaneous interdependent system. This approach was systematically explored in Bergstrom's article [16] which was published by *Econometrica* in 1966 and became the foundation stone for much further work on the econometrics of continuous time models. Later on, Sargan (1974) and Phillips (1974) provided further mathematical analysis which studied the impact of the specification error involved in such non-recursive approximations.

The twin themes of modeling of cyclical economic growth and econometric estimation in continuous time remained a major force in Bergstrom's thinking during the 1960s and for the rest of his career. In 1964 he returned to Auckland University as Professor of Econometrics, where he completed his monograph [1] *The Construction and Use of Economic Models*, published by the English University Press in 1967. This monograph was planned and commenced when he was at LSE. It is a masterful synthesis of earlier developments in trade cycle and cyclical growth models and it gives full expression to the disequilibrium modeling methodology that forms the basis of Bergstrom's later research. In fact, the monograph develops and analyzes a single-sector disequilibrium growth model that is the prototype for his subsequent empirical work on modeling the UK economy. In its final chapter, the monograph provides a beautifully succinct description of simultaneous equations econometric methodology and its application to the estimation of nonrecursive discrete approximations to stochastic differential equation systems, thereby summarizing much of Bergstrom's own research to this point.

Continuous Time Econometrics

Following the publication of his 1966 *Econometrica* paper and the 1967 monograph, Bergstrom's career became caught up in a deep fascination with the prospects and problems of empirically modeling the macroeconomy in continuous time. A singular fascination of this kind involving a decades-long research agenda is rare in the modern economics research community. But Bergstrom came from a different tradition, he had a tenacity that was unusual even among high-level researchers, and he held with great conviction his own views about how best to model macroactivity. As he put it in his interview in *Econometric Theory* (Phillips, 1988):

> This reflects my general approach to econometrics and to some extent I think I was influenced in this way back in Cambridge by Stone. This was very much his approach: to formulate a 12-year project, develop a model, devise methods of estimating it, then set about estimating it and so on. I think this is very much what I have done in terms of my continuous-time modeling work right from the theoretical model to the development of the estimation techiniques and through to the application.

In Bergstrom's case, the paradigm of a 12 year project evolved into a research agenda that slowly but surely took over the remainder of his career.

It was during his period back at Auckland over 1964-1970 that Bergstrom launched the first phase of this agenda. The initiating project entailed an ambitious study that took up half a decade. The work involved the construction of a complete macroeconomic model of the UK economy in continuous time, the development of econometric methodology for estimating this new system, the empirical implementation of the model on post war data, an empirical stability analysis of its long term properties, and the use of the model in forecasting and policy analysis. Much of the modeling work, data preparation and analysis of the model's properties was done in Auckland. Then, during 1970, Bergstrom returned to the UK as Keynes Visiting Professor at the University of Essex and took up a permanent Professorship there the following year. By this time his model of the UK economy was developed, its properties analyzed and most of the econometric methodology completed. The empirical implementation was conducted with the help of Clifford Wymer, a former student from the University of Auckland who was on the faculty of the LSE. When the work was completed, they jointly authored a paper [24] reporting the model, its analytical properties, the econometric methods and the empirical results, including projections and policy experiments.

The Bergstrom-Wymer (BW) model, as it became known, was a 13-equation continuous-time stochastic system that was based on a formal one-sector model of a macroeconomy. It was heavily constrained by cross-equation restrictions delivered from an underlying neoclassical growth theory, so that the production function parameters, for example, entered many different equations of the model in complex nonlinear ways. The model was estimated with postwar quarterly data for the UK by Gaussian techniques (that is by maximizing a Gaussian likelihood), its long-run properties were examined analytically, a stability analysis was conducted, and impressive out-of-sample forecasting performance was demonstrated. This model is distinguished from other empirical macromodels in many ways, not the least of which is the fact that it was formulated in continuous time but estimated with discrete time series data. A notable practical difference with other macromodels was that the system had only one exogenous variable (a simple time trend) and yet the model performed well in empirical exercises in spite of this simplification. The paper is a showpiece of careful applied econometrics and has become a classic study in empirical econometric research. Taking the Bergstrom-Wymer model as a prototype, similar economy-wide models have since been constructed for many of the world's leading industrialized nations, including the USA, Italy, Germany, Sweden and the Netherlands.

Following this major empirical undertaking, Bergstrom commenced a second phase of research involving the theoretical study of Gaussian methods of estimation in continuous-time systems. This research was started at Essex during the late 1970s and continued through the next two decades. During the 1980s, the research matured, as had his earlier work on discrete approximations to continuous systems, into a complete econometric methodology that involved a body of theory for estimation and inference, computational algorithms, and computer programs. Several doctoral students who worked under Bergstrom's supervision at Essex during these two decades helped in the completion of this phase of his research agenda.

The first step in the new program was the econometric theory. Some earlier work by the present author (Phillips, 1972) that was done under Bergstrom's supervision at the University of Auckland over 1969-70 had shown how the exact discrete vector autoregressive model (extracted from the solution of the stochastic differential equation system) could be used for estimation and inference using nonlinear regression methods. This study revealed that structural equation restrictions eliminated the aliasing problem and that there were major asymptotic gains (in terms of consistency and efficiency) relative to the use of the discrete approximation. Moreover, these advantages were sustained in finite samples, leading to major reductions in coefficient standard errors. This exact approach was extended to stochastic differential equation systems with exogenous variables and stock and flow data in Phillips (1974, 1978). Following this approach in 1983, Bergstrom published in *Econometrica* an extensive study [26] of exact discrete-time models corresponding to stochastic differential equation systems. His paper broke new ground by allowing for higher order systems of equations with both stock and flow variables. The form of the exact discrete-time model that accommodated these complexities was found to be a vector autoregressive moving average model (a VARMA(2,2) for a second-order stochastic differential equation system) whose coefficient matrices were highly nonlinear transcendental functions of the original system parameters. Gaussian estimation involved the construction and optimization of the Gaussian likelihood for this discrete-time model. The statistical properties of the resulting estimates then followed from existing asymptotic theory for the estimation of stationary vector time-series models in discrete time, such as that developed earlier by Dunsmuir (1979). Bergstrom's 1983 paper set the stage for subsequent empirical research with more complex and realistic continuous time systems.

It is interesting to reflect that this work was published at a time when there was much focus, following Sims (1980), on the use of vector autoregressions (VARs) in applied macroeconomic research. VAR models are typically agnostic, with no economic theory design inputs or design inputs only on the error structure (in structural VARs), and their dynamic structures that are no more complex than the VARMA models considered by Bergstrom. By embodying systematic theory restrictions in their formulation, Bergstrom's VARMA models enabled the restrictions to be implemented and tested empirically, leading to tightly parametrized systems that were far better suited to forecasting exercises and more fundamental policy analysis than unrestricted VAR models.

The next stage in the program to implement these enhancements was computation. In practical work, the principal difficulty in the use of full Gaussian maximum likelihood methods for continuous systems is the construction of the likelihood. The problem is acute when there are data irregularities such as mixed stock and flow variables, missing observations, or initialization on a state vector with unknown elements. The problems can be even more severe in the event of variable nonlinearity, as the most recent research in financial econometrics has discovered (e.g., see Ait Sahalia, 2002,.Nowman 1997, Phillips and Yu, 2001 and references therein). Unfortunately, these problems arise regularly in practical work with continuous-system estimation. At least for linear models there are some convenient solutions. One general approach to the construction of the likelihood is the Kalman filter. The use of this method in continuous-system estimation had been studied in work by Harvey and Stock (1985, 1988a, 1988b). In two papers [30, 31] published in 1985 and 1986, Bergstrom explored another approach that does not rely on the Kalman filter but makes explicit use of the exact discrete model for the observable variables, including the functional dependence of the error covariance matrix (Ω) on the system parameters. The likelihood can then be constructed readily from the conventional Gaussian form, given an initialization of the state vector, by using the Choleski factorization of Ω.The resulting algorithm involves computations that are on the order of Tn^3, where n is the dimension of the system and T is the sample size. Computations of this order in a general algorithm to maximize a likelihood function are well within the capability of modern computing equipment, at least for moderate values of n and T.

With the development of a theory of Gaussian estimation of continuous systems and a computational algorithm to implement it, Bergstrom turned to address issues of forecasting, control, and statistical testing. In [34], Bergstrom showed how to generate optimal forecasts for a continuous system in a simple way from the discrete VARMA model using the Gaussian estimates of the matrix Choleski factorization of the full error covariance matrix. Recursive formulas were provided for the generation of k-period ahead forecasts. A related article [32] dealt with optimal control and provided the solution of a quadratic cost functional optimization problem given stochastic differential equations of motion for the system. This work extended earlier certainty equivalence theory and allowed for weaker conditions on the innovation processes by relaxing the requirement that they be increments of

Brownian motion.

To this point in time, virtually all work on continuous system estimation had assumed the validity of the underlying specification. By contrast and in recognition of the fact that models are misspecified, much attention in other areas of econometrics had been devoted to specification testing and model evaluation exercises. Indeed, one of the arguments that attracted empirical researchers to unrestricted VAR modeling was the agnostic nature of their dynamic specification and their presumed compatibility with a very wide class of generating mechanisms. In comparison, continuous system modeling seemed less flexible, given the direct links that bound the exact discrete model to the underlying continuous system with its many prior parameter restrictions. To address such concerns, Bergstrom initiated in [35] the study of statistical model evaluation testing for continuous systems, developing practical statistical tests of the models and the explicit parameterizations that arise in discrete versions of continuous systems. For example, discrete data generated from a continuous system with mixed stock and flow variables satisfy a VARMA model with heavily restricted coefficient matrices. For a second-order system of stochastic differential equations, the VARMA model is of order (2,2). The VARMA(2,2) class is capable of providing approximations to a very wide class of spectra, so that an unrestricted VARMA model of this type might be regarded as plausibly competitive with an unrestricted VAR with many more lags. Thus, the starting point in testing is to assess the adequacy of this unrestricted specification by means of conventional time series model selection procedures; next the explicit form of the coefficient matrices in the VARMA(2,2) that are implied by an underlying continuous system can be tested by likelihood ratio procedures; and finally, the explicit parameterization of the coefficient matrices that are implied by economic theory can be tested by conventional Wald test procedures. These tests permit an investigator to assess the adequacy of the maintained hypothesis (i.e. a VARMA(2,2) model) within which the continuous system's discrete model is embedded, to test the validity of the restrictions implied by the presence of an underlying continuous time system, and, finally, to test any restrictions delivered by economic theory on the coefficients in the continuous systems.

This article on statistical testing completed Bergstrom's decade-long study of the econometric methodology of higher order continuous-time systems. The empirical implementation of the refined methodology was the next phase of the research and this succeeding line of research was conducted during the decade of the 1990s and onwards into the 2000s with two of his former Ph.D students at the University of Essex – Marcus Chambers and Ben Nowman.

The empirical research program began with a joint article with Chambers [36] on the demand for durable goods in the UK using data over 1973-84, studying dynamic responses of consumer purchases to changes in disposable income and evaluating the post-sample predictive performance of the model against simpler models. This study was followed by an ambitious empirical application [37] by Bergstrom, Nowman and Wymer of the Bergstrom methodology to a new continuous-time macroeconometric model of the UK. The primary innovation in this work was the use of higher order continuous time dynamics, issuing in a new era in applied econometric continuous time modeling with richer dynamic structures. The model also incorporated a more developed financial sector than models of the earlier Bergstrom-Wymer generation, involving international capital flows, exchange rate adjustments and long-run rational expectations. The fitted model, now known as the BNW model, was a 14-equation second order differential equation system with 63 structural parameters and 11 exogenous variables. The complexity in estimating a system of this type is evident in the fact that the corresponding exact discrete system used in estimation (a type of time varying VARMAX system) involved 1477 reduced form components which were highly complicated transcendental functions (delivered by partitioned matrix exponential series) of the system's basic 168 parameters (comprising the 63 structural parameters and 105 parameters of the error covariance matrix). This huge reduction in parameter dimension shows the enormous parsimony achieved by introducing restrictions from economic theory. The model was estimated and tested using quarterly UK data over 1974-1986 and subsequently employed in multi-period forecasting exercises and stability analysis. Estimation of the model took 23 hours of CPU time on a CRAY X-MP/48 supercomputer, indicating that implementation of the new econometric methodology pushed computational capability close to its limits at that time.

The Later Years

Bergstrom retired from the University of Essex in 1992 and became the University's first Emeritus Professor of Economics. His research was still far from complete and in retirement over the next decade Bergstrom went on to publish seven papers [38-44], all dealing with continuous time systems, including a history [38] and a survey [40] of continuous time econometrics. These articles complemented and updated earlier overviews that Bergstrom had written in [2] and [33], as well as his article published in the Handbook of Econometrics [27].

The BNW model discussed above represented the state of the art in continuous time modeling in the early 1990s. Whilst the work on this model was under way, time series econometrics was in the midst of a major transformation that had already affected both theory and practice. This transformation arose from the new methodology of unit root econometrics, the limit theory for stochastic trends and the concept of cointegration. These developments in nonstationary time series affected nearly all empirical econometric applications in macroeconomics, including both estimation methodology and approaches to testing, and by the early 1990s had led to near universal changes in empirical practice. Recognizing how important these developments were for applied research because of the additional generality of allowing stochastic nonstationarity in the system, Bergstrom sought to extend the continuous time modeling methodology to allow for the presence of unit roots in the system. A paper by the present author (Phillips, 1991) had already explored some of the implications of error correction and cointegration in continuous time systems. In a continuous system, the unit root hypothesis corresponds to the presence of zero eigenvalues, so that processes have a continuous martingale component. Earlier empirical work in the Bergstrom-Wymer model had indicated that some such roots were indeed likely in applications, underscoring the need for this generalization.

Accordingly, in the 1990s, Bergstrom set about making the necessary generalizations to the model formulation, the econometric methodology of estimation, and the computational algorithms for implementation of continuous systems with stochastic nonstationarity. The project involved a major undertaking. It was more like an ambitious research agenda for a young Ph.D than a project for one's later years. Nonetheless, it soon became Bergstrom's intellectual opus for his retirement years, crowning off decades of his own earlier work.

His 1997 article in *Econometric Theory* outlined the results of the theoretical study. The paper developed the exact discrete model for the observed variables in the form of a VARMAX system analogous to earlier work in [26] as a basis for estimation and projection, allowing for mixed first and second order stochastic differential equations in the structural continuous system, a mixture of stock and flow observed data, and an unobserved stochastic trend vector with drift. These generalizations involved substantial algebraic complications over earlier work and were systemic in the sense that the stochastic trends (which in applications typically relate to technical progress) were deeply embedded in the system as random forcing functions on the continuous system, rather than simply additive trends in a component representation. The paper showed how to set up the Gaussian likelihood for the observed data and gave asymptotic properties for the corresponding estimates, which involved changes in the rates of convergence of some parameters because of the presence of stochastic trends and cointegrating effects. This paper moved the continuous time econometric methodology into line with modern developments in the treatment of nonstationarity in time series econometrics.

The new research agenda would be completed by an empirical application, showing the feasibility of the new methods and assessing their performance characteristics. This final phase of the opus took 7 years and a joint effort with Ben Nowman to finish, leading to Bergstrom's final work [5], the manuscript of a jointly authored book reporting a new model of the UK economy that implemented his new methodology. The book (BN) was completed a few months before Bergstrom's death in May, 2005, and published posthumously in 2006.

The principal goal of the BN book was to describe a new continuous time model of the UK economy in which the mechanism of trending behaviour that accommodates slowly moving drifts in economic activity is made stochastic. In particular, the assumption of deterministic trends used in the BNW model and all earlier empirical continuous time models to represent technical progress is replaced by an assumption that the trends are unobservable and stochastic but have deterministic drift. The model comprised a mixture of 18 first and second order nonlinear differential equations with 63 structural parameters that comprised 33 long-run parameters and 27 speed of adjustment parameters and 3 deterministic drifts parameters. Like the earlier BW and BNW models, most equations of the new model represented behavioural adjustment mechanisms describing how a dependent variable adjusted in a continuous way towards a partial equilibrium level, functionalized on other variables and involving many of the same parameters across equations. A distinguishing feature of the new model is that the adjustment mechanisms include both first and second order equations, the latter involving adjustments in the derivatives toward their equilibrium levels. These continuous adjustment mechanisms can be derived by way of a dynamic optimization problem that takes into account adjustment costs. Like BNW, the new model involves long-run rational expectations, whereby agents are assumed to know the trend parameters involved in productivity, the model can be solved analytically and its properties analyzed, including its dynamic adjustment, stability and steady state behaviour. The model was estimated using the Gaussian likelihood and quarterly UK data over 1975-1994 and the two year post-sample period 1995-1996 was used for prediction.

All the empirical coefficient estimates turned out to be realistic and the fitted model results showed evidence of trade cycle behaviour with a period of around 9 years and a much longer (possibly demographic) cycle of around 40 years. The model's forecasting performance was satisfactory, but not impressive when measured against that of a benchmark VARX (VAR model with exogenous variables) system, so it seems that there are residual issues of model specification and room for model improvements. Like other modeling endeavours, the empirical results raised new questions for exploration. With Bergstrom's passing, these issues are left for a new generation to ponder. Bergstrom's personal effort is complete and the BN project is the culmination of an extraordinary research program of continuous time econometrics and practical implementation that occupied, almost completely, the last 40 years of his working life.

This biography has not discussed every paper that Bergstrom wrote. There were additional papers on theory and some empirical applications outside the continuous time framework. For instance, working with Brownlie in [16] and [22], he developed a small demand driven model of the New Zealand economy and used this in forecasting exercises. This work was later continued by Phillips and Yeabsley (1975) to assist in calibrating the first exercises in empirical macroeconomic modeling by the Reserve Bank of New Zealand. Even during the last 4 decades when Bergstrom was so preoccupied with continuous time econometrics, he made some forays away from his main agenda. Perhaps most notable of these was his work [29] on an approach to nonparametric estimation in Hilbert space using polynomial approximants. This study constituted an early econometric contribution to a subject that has since become a major field of econometric research with strong wings of ongoing work in both theory and empirical application.

University Administration

When Bergstrom moved to the University of Essex in 1970 it was a young campus having received its Royal Charter only a few years earlier in 1965. There were burgeoning administrative needs for the new institution and a relatively small professoriate. As a member of the senior faculty, Bergstrom was naturally called upon to participate in the administration of the university. This he did willingly even though it undoubtedly reduced his time for research. In consequence, he spent a decade in administration at Essex, serving a 3-year term as Dean of the School of Social Studies over 1972-1975, a term as chairman of the Department of Economics over 1976-1979 and a term as Pro Vice Chancellor over 1982-1985.

Bergstrom was a focused administrator. People frequently claimed that meetings chaired by Bergstrom were the shortest they had ever been at Essex, no quarter being given for small talk or self indulgent academic monologues. As Pro Vice Chancellor he was on all the main committees that dealt with the financial planning of the university and he seemed to enjoy the work. He was proud of the fact that Essex ran a healthy financial surplus during his tenure as Pro Vice Chancellor, when so many other universities were "close to insolvency" during the difficult financial period of the early 1980s. When questioned about this administrative work in his ET Interview (Phillips, 1988), his response was upbeat, indicating that there were positive externalities to the work, such as meeting senior managers and chief executives from outside of academia who had gained first class academic qualifications in their youth and were now on the council of the university. Nonetheless, having served Essex well in this capacity, Bergstrom was keen to return to his research and did so with a passion when his term ended.

A Legacy of Students

Almost a half of Bergstrom's working academic life was spent in New Zealand and his impact on quantitative economics and the training of economists in New Zealand was enormous. Over the period 1950-1970, he trained many successive generations of New Zealand economists. Bert Brownlie, former Vice Chancellor of the University of Canterbury, Hugh Fletcher, the Chancellor of the University of Auckland, Alastair MacCormick, the past Dean of the School of Business and Economics, and former acting Vice Chancellor of the University of Auckland, Viv Hall, Professor of Economics and former Head of the School of Economics at Victoria University, and the present author were among Bergstrom's many students at the University of Auckland during the 1950s and 1960s. Viv Hall was Bergstrom's first Ph.D student, graduating from Auckland in 1971. A list of the students at Auckland whom he supervised and influenced in their research beginnings is given at the end of this article.

During his time at the University of Auckland, Bergstrom taught econometrics, money and banking, public finance, and all the economic theory courses offered by the department. In the 1960s, the econometrics sequence that he developed at Auckland was the equal of the best Ph.D courses offered in North America and Europe and far more rigorous than most. His masters econometrics course, in particular, took students to the research frontier in linear and nonlinear estimation and simultaneous equations modeling. A feature of this course from 1968 was that it followed Malinvaud's (1966) text in its first English edition – a book that Bergstrom greatly admired – and provided a careful mathematical development of the asymptotic theory of multivariate nonlinear regression. In addition to this tough theory course, Bergstrom encouraged his students to do empirical research on various aspects of the New Zealand economy. In conjunction with this empirical research, students at Auckland during the 1960s developed a suite of departmental regression software that included least squares, two-stage and three-stage least squares, a multivariate nonlinear regression program, and various prediction and simulation routines. This work was done concurrently with similar developments overseas and further details are provided in Phillips and Hall (2004). With this background of experience, many of Bergstrom's Auckland students went on to become academics in economics, accounting, marketing, and econometrics

At the University of Essex, Bergstrom supervised 9 Ph.D students over the period 1971-1993. These students and their theses are listed at the end of the article. Many of these former students have gone on to work in econometrics, some of them making their own research contributions to the field of continuous time econometrics. In particular, Marcus Chambers, a former student and co-author, has made many contributions to the field and continues the Bergstrom tradition of econometrics teaching, research and supervision at the University of Essex. Ben Nowman, another former Essex Ph.D student, has taken the Bergstrom methodology on continuous time econometrics into the field of interest rate modeling and financial econometrics. Nowman was Bergstrom's last co-author and worked to complete Bergstrom's final research project and jointly author his final manuscript [5].

Bergstom's lectures were models of clarity. He came to lectures extremely well-prepared, carrying a folder of notes that he usually left unopened on the front desk, presumably for reference should he need it. He then proceeded to develop all the material on the blackboard with great precision and economy of presentation without consulting his notes and usually with little class interaction, students simply watching in wonderment at what transpired at the board. Although he taught many different courses over his career, he is most remembered at Auckland and Essex for his lectures in microeconomic theory and econometrics. Many economists, accountants and other professionals in New Zealand and in the UK attended his courses, and those that have continued in academe aspire to the pedagogical traditions he established.

In Remembrance

Rex Bergstrom was an extraordinary individual. He channelled his great intellectual gifts in pursuit of a particular research agenda that gave him a truly exceptional career. For some forty years from the mid 1960's, he was recognized as the world's leading proponent of continuous-time econometric modeling and he took the field forward from its beginnings to a level of technical sophistication that was virtually unmatched in other areas of applied econometric endeavour. Few econometricians have ever shown such tremendous dedication to a field of research. Nowadays the subject and its people seem forever to be on the move: much shorter time horizons are evident in econometric research, as the subject of econometrics grows rapidly wider, research directions continue to multiply, and funding agencies encourage research diversification and interdisciplinary research. This new world of econometrics is very different in character from that of Rex Bergstrom.

As an econometrician, Bergstrom developed his own paradigm for applied research. He loved mathematics and the economy and precision of mathematical formulations of economic problems and econometric methods shines through in all his research. He believed fervently in the value of economic theory restrictions in modeling and the importance of endogeneity as a distinguishing characteristic of econometrics. Bergstrom brought this sunshine of economic theory into his empirical applications to guide the formulation of econometric models, to achieve parsimony in parametric forms, and to light up a roadway for interpreting empirical findings. All of his applied work attests to the success of this paradigm.

Bergstrom's work has not had the professional impact he wished for it in applied macroeconomics. Continuous time econometrics is a difficult field that is mathematically and computationally demanding and it has remained just a niche market in empirical macroeconomics. Since the early 1970s, time series macroeconomics has moved primarily in other directions, led by agnostic VAR methods, real business cycle modeling, and cointegration methods which concentrate on long-run relations. But Bergstrom's conviction of the importance of the continuous time approach has been truly vindicated in the world of finance, where ultra-high frequency, second-by-second transactions data are now widely available and used to price options and other financial derivatives, to measure market volatility, and to fit nonlinear stochastic differential equations. In this rapidly expanding field, continuous time methods play a significant role in asset pricing theory, which is now heavily dependent on continuous time stochastic process theory, and these methods have become an integral part of the growing apparatus of financial econometrics.

No description of Rex Bergstrom is complete without mention of his unworldliness, which those who knew him remember so fondly. Rex Bergstrom was so caught up in his own world of econometric research that the trivia of modern life frequently passed him by, leading to many stories of eccentricities that his students shared in testimony to his total engagement in research. These tales range from his walking unfazed in his jacket, collar and tie on a hot summer's day on a New Zealand nudist beach, to mistaking a bank for a bakery and asking the teller for a loaf of bread, through to innocently enquiring what 'Watergate' meant after listening to an academic dinner conversation about politics in the midst of that crisis.

Bergstrom was a man of small stature (5' 4" tall) and extraordinary intellect. He had sharp penetrating eyes and a small crop of blond hair which turned grey as he grew older. He had a distinctive bearing and physical signature that made him instantly recognizable and almost ageless over time. He always wore a plain charcoal savile row suit, charcoal tie, white shirt and polished black leather shoes. In the winter he wore a black overcoat and scarf. This was his uniform for half a century and it presented an unmistakable image of academic gravitas. Most of the time he was indeed serious, avoiding small talk and seemingly in constant meditation about his research. Yet this image concealed the kind, gentle and very generous man that he was beneath. In fact, he was not as formal as he so often seemed and he loved to laugh. I once told him the Chinese saying that a happy man is one who already has enough. He joked that he would have enough when he could afford to fly first class everywhere. This is the way Rex Bergstrom was. The man so many of us greatly admired and loved.

Bergstrom's passing is a great loss for the profession of economics and the loss is particularly felt by the close community of scholars that knew him personally. It is fitting that on the day of his funeral, the University of Essex flew the flag at half mast in his memory. Rex Bergstrom's students formed the core of Bergstrom's inner community and they occupied a special place in his heart - he cared for them, helped them begin their careers, lobbied for them as they matured, thought about them, and wrote to them in his characteristically flowing long hand with the fountain pen that was his signature in personal correspondence. In return, his students over many generations in New Zealand and the UK were devoted to him, some becoming co-authors, others becoming colleagues and one, Christine, becoming his wife. These students carry his memory, pedigree and traditions forward. They form the human accompaniment to the enduring legacy of his academic research.

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Cowles Foundation for Research in Economics, Yale University
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