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# ABSTRACT

# Contributions of Zvi Griliches

In this article, I summarize Griliches' contributions to economics and to applied econometrics.

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## I. Griliches Major Contributions to Economics

In this section of the article, I focus on three major contributions of Zvi Griliches to the understanding of the economics of technical change:

1. His work on the social rates of return to research activity and the role of economic incentives in determining the benefits from, and the diffusion of, new technologies;

2. His work on developing and extending the "hedonic framework" for adjusting prices for changes in the quality of products; and

3. His work on the sources of productivity growth.

His work on (1) laid the foundation for rigorous empirical studies of the private and social returns to research activity, and hence for the role of formal research activity in generating growth. His work on (2) provided a way of comparing new to old goods, and thus enabled both researchers and the statistical agencies to correct quantity and price indices for improvements in the quality of the goods consumed. His work on (3) transformed the study of productivity growth from the study of a residual to a study of the measurable factors that caused increases in the output available from given configurations of inputs, and in so doing changed both official statistical procedures, and our understanding of how productivity improvements occur.

Griliches' work on each of these topics has had a major impact on research in economics and on the practices of statistical agencies of governments. As a result he is one of the most influential empirical analysts in the history of economics. I review his contribution to these three topics in the approximate chronological order in which Griliches started working on them.

In addition to these contributions, Professor Griliches has made major contributions to the development of both the data sources and the econometric tools that underlie much of the applied empirical work done today (especially empirical work on "micro" data sources). I include a separate section on Griliches' contributions to econometrics and to micro applied work more generally.

## *1. Rates of return and economic incentives for research activity*

As a student, Griliches recognized that technical change was a major source of measured productivity growth. This was the message emerging from the agricultural data developed by the USDA and the national data constructed by the NBER (see, e. g., Barton and Cooper 1948, Schmookler 1952, Fabricant 1954, Abramovitz 1956). It was also clear in this early research that such technological changes are not purely "exogenous". They are the result of economic activity, especially where the main purpose is to generate such changes, as in organized public and private research. His teacher, Theodore Schultz, attributed all the productivity growth in agriculture to public investments in agricultural research (Schultz 1953). While the idea that the rate and direction of technical change were influenced by economic incentives was not new, there were almost no quantitative measures of the impacts of these incentives at the time Griliches began his career.

His early empirical work on the social rate of return to research activity (*JPE* 1958b), and on the role of economic incentives in determining the distribution of benefits from new technologies (*Econometrica* 1957a), laid the foundations for scientific study of these topics. Their profound effect on both our profession and on government agencies was a result of two aspects of his study.

By going to a lower level of aggregation than had been used in previous studies he was able to establish a direct link between research activity and the output the economy could produce from its inputs (or its “productivity”), and to quantify the benefits from that research. The data he gathered and analyzed on the development, diffusion, costs and benefits of hybrids and hybridization techniques, and his use of a direct consumer surplus measure of the benefits from hybrids, generated a lower bound to the national benefits from innovations that transformed agriculture.

This work showed that economic logic can be used to empirically quantify the impacts of the incentives which determine the distribution of benefits from research activity and, by implication, the social and private returns from investing in that research. His papers demonstrated how the diffusion of hybrid corn was related to the profitability from employing it, and how the benefits from the research investments in different hybrids varied with the extent of their markets and the cost conditions at the time of their development which in turn depended on prior development of hybridization techniques.

This work, and subsequent work by Griliches and his coauthors on related topics, were the direct antecedents to

- modern growth theory(which emphasizes the role of the production and transmission of knowledge in determining growth and structural change in the economy),

- modern productivity analysis and its embodiment in the productivity statistics produced by the federal government (which attempts to quantify the role of various factors in determining the output that can be produced from given quantities of inputs),

- demand analysis in characteristics space, and its embodiment, through hedonic analysis, in the price statistics of the federal government.

His subsequent work established additional empirical frameworks for determining the impacts of knowledge-producing activities in the economy. It also provided initial estimates of relevant empirical magnitudes, almost always qualified by the author's own list of possible problems with his conclusions. The frameworks, and his list of problems, were taken up and expanded upon, first by the profession and then often by statistical agencies (initially in "experimental" procedures, but later as part of official statistical procedures). Relevant contributions by Griliches in approximate chronological order (with partial reference to his publications on these topics) include:

1. Developing quality adjusted input measures, as in

- a series of articles in the *JFE* 1958b 1959 1960 1963 and the *JPE* 1963, focusing on the impacts of quality change and innovation in inputs on agricultural productivity,

- his joint work with Dale Jorgenson, *AER* 1966, and the *Survey of Current Business* 1967, on accounting for productivity growth in the U.S. economy, and

- his work on the returns to schooling and the adjustment of labor input for quality change. This includes his work in the Hansen volume 1970, with Mason in the *JPE* 1972, with Chamberlain in the *IER* 1975, the papers in the *JPE* 1976 and 1979, and *Econometrica* 1977.

2. Determining the biases (and their correction) in various econometric estimates of productivity; this includes the role of left-out variables, errors in measurement, and distributed lags (see the articles in the *JFE* 1958a 1959, and 1961, *Review of Economics and Statistics* 1960, and 1969,

*Econometrica* 1961 1967a, and 1970);

3. Establishing the hedonic framework for analyzing the relationship between prices and quality, and hence for adjusting quantity and price data (and consequently productivity) for "quality" change (Government Price Statistics Hearings 1961, with Irma Adelman in *JASA* 1961, with Kaysen and Fisher in *JPE* 1962, *Proceedings of the Business and Economics Statistics Section of the American Statistical Association* 1967, *AER* 1996),

4. Integrating formal research activity into productivity analysis and separating the influence of basic versus applied research, as well as privately versus federally funded research activity (*AER* 1964, articles in the Williams 1973, and Kendrick 1980, volumes, Bell Journal of Economics 1979, *AER* 1986, and with Adams 1996, 1997).

I will return to (1) and (3) below. Much of the work in (2) is now standard in applied econometrics more generally (both in course work and in judging applied articles), and I come back to it in my discussion of Griliches' impact on modern applied work. I conclude this section with a brief review of (4) in conjunction with his earlier work on hybrid corn. The focus of this work is on the role of research activity in generating growth and structural change.

Shortly after writing his seminal pieces on the diffusion and rates of return to hybrids, Griliches began to question the generality of case studies on the returns to successful innovations and their use in calculating social rates of return on investments in research programs more generally. It was in this context that he developed an analysis of the contribution of public expenditures on agricultural research to the overall productivity in agriculture using state data in the U.S. (*AER* 1964). By the mid-1960's, he had presented more general analyses of the productivity growth puzzle in manufacturing and in the economy at large (Griliches 1967b and Jorgenson and

Griliches 1967). At the same time he began his search for micro data with the twin hopes that; i) the structure of the processes underlying productivity growth could be better studied at lower levels of aggregation (see, e.g., Griliches and Ringstad 1971), and ii) by comparing returns at different levels of aggregation one might learn something about the difference between the private and social rates of return to research activities. This latter point was made explicitly in his 1979 *Bell Journal* essay, an essay which was an up-to-date accounting of the empirical progress and problems in the research and development literature.

The *Bell Journal* paper exposits the "R&D Capital Model" which has become a standard tool in this field. It outlines the "spillovers" problem and suggests several approaches to its solution, some of which were taken up later by his students (e.g., Jaffe 1986) and/or reinvented (Romer 1990). Two related Griliches papers (Griliches 1979 and 1980) report the results of a major, two-decades long effort to gain access to the detailed individual firm-level data on R&D collected by the Census for the NSF and match them to parallel company data in the Censuses of Manufacturers and Enterprise Statistics. I will come back to his work on spillovers after a brief review of his work on the micro data.

The first paper on micro data was started in the mid-1960's, reported at the Conference on Research in Income and Wealth in 1975, but not published until 1980. It is important for two reasons. It is one of the first attempts at integrating and accessing the micro data bases collected through U.S. government firm surveys. Over the 1990s, the work done by Griliches and a few others has helped to make such data available to researchers through the RDC's (the regional census data centers of the U.S. Bureau of the Census), and this in turn has had major impacts on empirical work. This work also provided the first broad-based analysis of the returns to formal research activity on micro level data.

The main conclusion of this line is of work is that various estimates "indicate an overall elasticity of output with respect to R&D investments of about .07, which can be thought of as an as average of .1 for the more R&D-intensive industries such as chemicals and .05 for the less intensive rest of the universe. [It implies]...0.27 as the overall estimate of the average gross excess rate of return to R&D in 1963...It is 'gross' because neither measure allows for any depreciation of past R&D, and it is "excess" because the conventional labor and fixed capital measures already include the bulk of current R&D expenditures once." Although these numbers are large, they are not large enough to account for most of the productivity growth in the U.S. economy. On the other hand since they were based on micro data, they were more clearly interpreted as measures of private returns, and spillovers of various forms were a possible explanation for the productivity growth not yet accounted for.

After much labor, a new micro data set was created. It allowed him to update and extend this work (Griliches 1986). The major advance in this study was the ability to distinguish between basic and other R&D expenditures, and between privately and federally financed R&D expenditures. The interesting findings were: (1) R&D contributed positively to productivity growth and seemed to have earned a relatively high rate of return. Moreover, there was no evidence of a decline in returns between the two studies, the first covering 1957-65, and the second 1966-77. (2) Basic research appeared to be more important as a productivity determinant than other types of R&D, and (3) Privately financed R&D expenditures were more effective, at the firm level, than federally financed ones. The analysis of these data was updated in the 1980's by Lichtenberg and Siegel (1991) and has stood up to the test of time. Additional work using this database has been done recently by Adams and Jaffe (1996).

The difficulties and long delays involved in working with confidential Census data led him to

look at other, more “open” data sources. In the 1970’s, detailed firm income and balance sheet data became available in machine-readable form as part of the Compustat tapes. He initiated a large, NSF-sponsored research project at the NBER in 1978 to study this data. This project generated an easily accessible and widely used data set on manufacturing firms. A central part of the project consisted of matching data for U.S. manufacturing firms in the various Compustat tapes (including those on the over-the-counter market) with the records of their patenting activity. The effort to analyze these data brought together a number of first-rate students and collaborators. Much of the first round results of this work was summarized in a series of papers presented at a 1981 NBER conference at Lenox, MA, and published subsequently in Griliches (1984). His work on patents, summarized in “Patent Statistics as Economic Indicators” (Griliches 1981), explained how the newly computerized patent indicator of knowledge-producing activity could be used, and discussed both the potential and the weaknesses of the variable. Importantly, it also pointed his students to the additional information on patent documents (citations, ownership rights, geographic location, etc.) and encouraged them to use it to trace possible externalities in the knowledge-generating process (e.g., Trajtenberg 1990, Jaffe 1990, and Jaffe, Henderson and Trajtenberg 1993 and 1997).

Always aware of the potential importance of knowledge spillovers in the generation of technological change (see the lengthy discussion in the 1979 “Issues” paper), he had already sent a number of his students down the path of looking for such spillovers and some of them were able to produce evidence of their existence (Evenson 1968, Evenson and Kislev 1973, Schankerman 1979, Pakes and Schankerman 1984,and Jaffe 1986). In 1992, he surveyed the accumulated literature on spillovers and the conceptual and econometric problems associated with their estimation. The evidence that had accumulated since his 1979 paper was actually quite

impressive and, if taken at face value, would assign a greater role to R&D in the generation of productivity growth and possibly also in its slowdown. More recently, he has investigated the third aspect of this puzzle: the role of science and the productivity of the social resources invested there (Adams and Griliches 1996 and 1997).

Thus, early on, several components of the new growth theories were integrated into his research: the emphasis on "endogenous" technical change, the emphasis on R&D spillovers, and the importance of imperfect competition in the R&D context. That technical change was endogenous was not "news" to him. That is what he had been studying all along in his work on diffusion (Griliches 1957a), on the role of purposive R&D expenditures as generators of such change (Griliches 1964), and the impact of the economy on inventive output (Griliches and Schmookler 1963). The other main component of this literature was the emphasis on the importance of R&D spillovers and their incorporation into aggregate growth models. Here there was a congruence of later theoretical and empirical research, especially at the aggregate level (Coe and Helpman 1995, is a leading example of such work). What the new theories of growth added was the explicit integration of the R&D process with market equilibrium in imperfectly competitive markets. While the older literature discussed the "appropriability" problem due to the "nonrivalrous" nature of R&D output, the problem had not been fully integrated into the earlier growth models or reflected adequately in empirical work (though there is some discussion of it in Griliches and Mairesse 1984). In so doing, the new growth theory also revived interest in "creative destruction" (see, e.g., Aghion and Howitt 1992) of knowledge-based quasi-rent positions, though these topics had been discussed earlier by Griliches and his students under the label of "depreciation" of knowledge or R&D stocks (see Pakes and Schankerman 1984). The new combination of theory and empirical work gave impetus to a whole new range of studies

(such as Caballero and Jaffe 1993, and Putnam 1997).

Griliches' work is still central to clarifying exactly what economists can learn from these endeavors and what needs to be done to sharpen conclusions. A major theme of his AEA Presidential address (1994) was the difficulty of estimating the productive impacts of R&D in a world of imperfect output measurement, the problem of data sets that do not produce sharp parameter estimates, and aggregation difficulties emanating (in part) from the spillover problem. The address calls for a review and expansion of the national income accounts to include more and broader measures of economic welfare, especially those that would bring the value and quality of human time into this framework, and a plea for a lowering of expectations as to what economics can deliver in this area. Griliches' qualified, honest analysis of the fundamental problems in determining how formal R&D activity effects our economy has converted a theoretical problem into an empirical one, and has greatly advanced our knowledge.

## ***2.*** *Hedonics*

Hedonic price functions are empirical summaries of the relationship between the prices and the characteristics of goods sold in differentiated product markets. They were introduced by Court (1931) and revived by Griliches (1961) as a way of accounting for quality change in the prices of new goods. He reasoned that since newer models of goods (in his case automobiles) often had more desirable characteristics, the difference between the prices of the newer and the older models should not be entirely attributed to inflation. On the other hand, if we build price indices entirely from interperiod price comparisons of goods sold in both periods, that is, if we never compare "old" to "new" goods directly, we will never capture the effect that switching to new goods has on welfare, and this will bias price index calculations upward. Griliches suggests

estimating a surface which relates prices to characteristics, and then using the estimated surface to obtain estimates of "quality adjusted" price changes for products with given sets of characteristics.

A brief digression on the importance of the problem and of Griliches' solution to it is in order. Except in rare instances (and in most of those instances it is because Griliches' hedonic procedures have been incorporated into the official statistics), current price indices are built from data provided by enumerators on price changes of a particular good at a particular outlet (both of which are chosen by a sampling process). The good is defined by a detailed list of (physical, and often brand name) characteristics. Identical goods sold at different outlets are not compared, and even more importantly, newer versions of a good are not directly compared to older versions, even if both versions perform precisely the same tasks.

No matter how fast new goods are incorporated into the index, without some direct comparison between the new goods and old goods, the price change for the commodity group will be just a weighted average of the price changes in the new and old goods. The subindices for the new and old goods may both be increasing rapidly, even though consumers are transferring to the newer and incurring a (quality adjusted) price which is only a fraction of the price they previously paid for the old good. This can produce striking anomalies in the official price indices. For example, the U.S. had a "flat" computer price index for a very long time, despite the fact that the price of a "unit of computing power" had declined dramatically. Similarly, until recently, the Producer Price Index (the PPI) never compared prices of generic drugs to the prices of the patented drugs to which they were (FDA certified to be) bioequivalent. Thus the lapse of patents and the introduction of generics never caused a fall in the drug index (this despite the fact that in many cases most people were paying 30 to 40% of the original price of the patented drug). Only after

Cockburn and Griliches (1994) pointed out the empirical implications of this procedure was the official PPI revised to make such a comparison.

There are many ways of comparing new to old goods, but most involve estimating utility or production functions, and this in turn, requires a host of questionable assumptions discussed in Pollak (1989), and later elaborated by Pakes (1998).[1] So the rationale for using hedonics is the same as that for using a standard index (originally given by Konus 1924), though one has to accept the switch from goods space to characteristics space. More importantly, the outpouring of empirical work using hedonics, some of it by Griliches and his coauthors (see the work with Irma Adelman in 1961, with Kaysen and Fisher in 1962, the American Statistical Association 1967, with Ohta in 1976 and 1986 , with Berndt 1993, with Berndt and Rappaport 1995, with Berndt and Cockburn in1996, with Fisher in 1995, with Cockburn in 1994, and the *AER* in 1996), but much of it by others (see Triplett 1971; Gordon 1990 and the articles in the Foss, Manser and Young 1993, and the Bresnahan and Gordon 1997, volumes ), and the experiments with the use of hedonic indices at the Bureau of Labor Statistics (BLS), made it clear to all involved that hedonic techniques provided price series that were often much more believable than those developed using standard procedures.

As a result of this work, the Bureau of the Census adopted hedonics for their housing indices in the late 1960's, hedonics were adopted for use in deflating computer prices in the National Income Accounts in the 1980's, and subsequently the BLS adopted them for the apparel and computer components of the CPI. Hedonic procedures are at various stages of development for

[1] Using the characteristics of goods, the hedonic index is the Laspeyre's lower bound to the ideal price index in characteristic space.

several other items in the U.S. and in several other countries. Much of the difficulty in applying hedonic procedures more generally is that use of hedonics requires different data gathering and data analysis procedures that will take time to implement.

The Boskin Commission, - set up by the U.S. Senate to investigate possible biases in the BLS's Consumer Price Index (CPI) - concluded that a bias of 0.7 per cent per year, out of a total bias of 1.1 per cent a year, was caused by one form or another of new good bias.[2] The CPI is used to determine cost of living increases for all entitlement programs (social security, veterans benefits, and the like), all federal employees, tax brackets and a myriad of contracts in the private economy. The implications of an annual bias of this magnitude are enormous. Moreover, similar new goods and quality-adjustment problems arise in other price indices (notably the PPI). Further, since quantity indices are generally obtained from dividing sales data by a price index, and productivity is constructed by subtracting an output quantity index from one for inputs, any bias in the price index transfers immediately into biases (of the opposite sign) in output indices and subsequently in productivity indices. Thus the wider application of hedonics can be expected to have further major impacts of policy, research, and descriptive importance.

Finally one should not ignore the intellectual debt applied work in economics owes to hedonics. The empirical hedonic work made it clear that hedonic functions fit prices quite well. As a result Griliches, and the others who had been working on hedonics, encouraged a range of researchers, several of them Griliches students, to take Lancaster's (1971) characteristic theory seriously, and build empirical characteristic based models of demand (see Berry, Levinsohn, and Pakes 1995 and the literature they cite). The result has been a notable improvement in our ability to estimate

[2] The commission consisted of Boskin, Dullberger, Griliches, and Jorgenson and issued its report in 1996.

demand systems in a range of markets, and, as a result, improvements in our ability to analyze both price competition and the advantages of new goods in those markets (e.g., see Davis 1997; Nevo 1996; and Petrin 1997.)

## ***3.*** *The sources of productivity growth*

Technical change is usually measured by changes in "Total," or more precisely, "Multi-Factor Productivity" (TFP, or MFP) at the firm, industry, or economy-wide level. Changes in total productivity are either constructed as a difference between a change in an index of outputs and a change in an index of inputs, or obtained as a residual from estimating a production function relationship between those outputs and inputs.

Recall that Griliches' early work on the returns to investment in hybridization documented that the social returns to the investments in hybrid corn had been enormous. In addition, it analyzed the relationship between the characteristics of the markets for different hybrids and the rates of return to their successful development, partially answering the question of where successful innovation is likely to be more socially profitable. On the other hand, it also led him to question the ability of economists to generalize from case studies on the returns to successful innovations to the social rates of return on investments in research program more generally.

As a result he started working on the direct measurement of "technological change" in more aggregated data bases, using both output over input indexes and production function estimation. This was based on the earlier work in agriculture summarized by Schultz (1953; see also Ruttan 1954 and 1956), which had been applied also to other sectors of the U.S. economy (see Abramovitz 1956, and Solow's 1957, elegant formulation). The stylized facts that had emerged

from this research were quite troublesome to Griliches. The major empirical result was that the lion's share of the observed growth in output was attributed to "technical change" rather than to the then existing measures of capital and labor input. However technical change in this context was no more than an unexplained "residual", and both his background in econometrics, and his quality as a social scientist, made him uncomfortable with basing conclusions on a residual, even when it was renamed "technical change" and thereby implicitly given some explanatory power.

This led him to a research program designed to explain, or at least account for, the residual in terms of processes which economists could understand and analyze. It had two broad components;

1. development of procedures for constructing input and output indexes that accounted for the improvements in both that were generated by growth processes,

2. a deeper look at the model used to connect the input and output indexes.

Research on (2) led him to develop the econometrics of specification analysis including questions of appropriate functional forms (with Ringstad 1971), of left-out variables (Griliches ba), of distributed lags (*JFE* 1959, XLI(1), *Econometrica* 1961, *Econometrica* 1967a, and with A. Pakes in the *Review of Economic Studies* in 1984), and of errors in variables (with V. Ringstad in *Econometrica* 1970, *Econometrica* 1974, with G. Chamberlain in the *IER* 1975). These are all topics which were central to developments in modern applied econometrics, and which Griliches made substantial contributions to (see the next section). Work on (1) led to the ingredients, the data, used in the model's implementation. It directed him to the measurement of the services of capital equipment, "left out" variables such as R&D, and corrections for; quality change in material and capital inputs, deflation, quality change in outputs, depreciation, and the

education of the labor force.

This program of research, which was announced, implicitly, in “Measuring Inputs in Agriculture” (Griliches 1960), and found its fullest expression in his two papers on agricultural productivity (Griliches 1963 and 1964), are basic contributions to knowledge. In certain aspects, this line of research was similar to the line of research pursued by Denison (1962) at about the same time, and in retrospect it is easy to see the debate between Denison, and Griliches and Jorgenson in the *Survey of Current Business* (1967) taking shape. Perhaps the biggest difference between the conventional growth accountants and Griliches was that Griliches often stopped to consider the broader implications of his findings on economics. Thus he was heavily involved in the debates on understanding the relationship between education, productivity and wages (see the next section), and, as documented above, on the interaction between various forms of scientific activity and productivity.

Griliches' productivity work also had a direct impact on statistical agencies. Productivity statistics are produced separately from national income accounts by the Division of Commerce. Official agencies gradually produced a multi-factor, as well as a labor, productivity measure, adopted the weighting scheme for capital proposed by Jorgenson and Griliches, and recently integrated an education-based weighting scheme for labor input based on work by the same authors.

## II. The Griliches approach to applied econometrics

A review of Griliches’ contributions would not be complete without a section on his contributions to econometrics and to applied work more generally. Griliches started his research

in agricultural economics, a field that took both data and econometrics seriously and used it to attack substantive problems. Econometrics was a tool, not an end in itself. All of Griliches' econometric work has been stimulated by economic questions. Still, because he was so careful about the interpretation of his estimates, that he often uncovered problems that had more general import and provided detailed analysis of them. As a result, many of his insights have now been incorporated into the "standard" of what constitutes good empirical work.

## *1. Specification bias*

His paper on specification bias (1957b) was motivated by the contradiction between farm accounting studies which indicated increasing returns to farm size and production function estimates which showed no such results. Both the methodology of specification analysis and the question were pursued by Griliches in a series of papers leading, among other works, to the book on *Economies of Scale* with Vidar Ringstad (1971) and continuing to date in his work with Tor Jacob Klette and Jacques Mairesse. This work is widely used by applied economists. The piece with Ringstad (1971) extends specification analysis to errors-in-variables and simultaneity contexts.

In joint work with Yehuda Grunfeld (1960), he raised the question, "what was the gain from using micro data instead of the then more readily available industry level aggregates?" They showed that in the context of incomplete and misspecified micro-models, the gain from disaggregation could be illusory. That work is extended in joint work with Neil Wallace (1965). The Griliches-Grunfeld paper was quite controversial and led to a small, but important literature. It discusses the important problem of how much error, or rather, irrelevant variation, there is in the micro data and how incomplete are micro models as descriptions of actual individual

behavior.

His paper on “Cost Allocation” (1972) started out as a consulting report and an analysis of alternative ways of dealing with heteroskedasticity but turned quickly into another example of specification analysis where the answer depends largely on the question one wants to answer. The issue was economies of scale, but the methodology did not produce a unique answer to it. Since the resulting function was nonlinear, the answer depended on the level at which the scale elasticity was evaluated. It mattered whether the question was asked for the average railroad or the average ton-mile, since the railroads in the sample differed greatly in size.

## ***2.*** *Distributed lags*

In his Ph.D. thesis research (Griliches 1957a), Griliches used logistic curves to analyze the diffusion of a new technology (hybrid corn). The central fact studied there was the delay in adjustment to such an event and the slow diffusion of this technology across farmers, space, and time.

Griliches analyzed the specification problems raised by the presence of lagged dependent variables in such models (1959). He considered a range of issues. It is difficult to distinguish the source of the apparent slowness in response to adoption of the technology. Are the actors slow because they face high adjustment costs? Are they slow because they are uncertain about the information available to them and are waiting for more evidence for a move? Or are they only apparently slow because the empirical models omit many factors?

Pondering the latter question led him to write an important paper on serial correlation bias (1961), which suggested a way of distinguishing between the first and last interpretation of what

appeared to be rather low adjustment coefficients estimated by OLS. The simple idea was to nest the first in the third, by adding lagged regressors to the equation and testing the pure serial correlation interpretation. This suggestion became popular in the UK literature under the "Comfac Test" name and has also been attributed to the late Denis Sargan. Sargan visited Chicago at about the time Griliches was conducting this research so the allocation of the credit for this work is ambiguous.

Working with distributed lag models, one quickly wants to move beyond the simple geometric form introduced by both Cagan and Koyck. A number of efforts were made to generalize the available functional forms, most notably by Almon (1965) and Jorgenson (1966). What Griliches did in his "Survey" (1967a) paper was to connect both the functional form and identification issues in an applied context. There is much useful material there, though the field has moved away from such models to the estimation of unconstrained VARs at one extreme and an emphasis on "cointegration" at the other. The increased availability of panel data has made possible the estimation of more general models but also confronted analysts with new problems. Estimating distributed lag models requires a history of the relevant influences but, because of the shortness of such panels, much of the relevant history is pre-history and is absent from the data. His joint paper with Ariel Pakes (1984) assumes a relatively simple pattern for such "pre-histories" which allows it to estimate the "visible" part of the lag structure even in the absence of earlier data.

## ***3.*** *Errors in variables and panel data*

Griliches' move towards the analysis of micro data forced him to confront a new set of problems, primarily in the form of erroneous or missing data. The paper with Vidar Ringstad (1970), uses a

very simple model to show that there is a sense in which random errors-in-variables lead to even greater biases in nonlinear models than in linear ones. His Fisher-Schultz lecture (1974) surveys the field more generally and discusses issues of specification associated with left-out "unobservable" variables, such as "ability," common to several equations or observations, and introduces the work on siblings. His paper on brothers is joint with Chamberlain (1975) and represents his effort to solve the left-out "ability bias" problem in the estimation of returns to education, a topic he had previously worked on, and which I discuss further below. (Griliches 1970 and Griliches and Mason 1972).

## ***4.*** *Production functions*

Griliches wrote extensively on the methodology of estimating production functions. His work on production functions set forth a large agenda, investigating functional form issues and largely accepting Cobb-Douglas, looking for economies of scale, and discussing labor and capital measurement issues (1967c). He also developed a sequel paper on the estimation of CES-type functions based on manufacturing data by states (1967b). He used micro data on firms directly instead of on state aggregates in his joint work with Vidar Ringstad published in *Economies of Scale and the Form of the Production Function* (North Holland 1971).

His paper with Mairesse, "Heterogeneity in Panel Data" (1990), takes the heterogeneity issue seriously and tries to estimate, a separate production function for each of the firms in his samples. It finds too much heterogeneity in the estimates, much more than can be explained by sampling variability alone, and concludes, along the lines of the Grunfeld-Griliches paper, that the simple model then in use must be severely misspecified at the micro level. His warnings against the uncritical use of "twins" data in this context have, unfortunately, not been heeded.

Whether that matters at the more aggregate levels and in what contexts remains an open question.

Other work with Mairesse (1998) surveys the state of production function estimation at the micro, firm or plant level. It discusses the "search for identification" in such models and the trend to estimate them from smaller slices of the data in an attempt to guard oneself against various sources of simultaneity bias. Griliches shows how errors in variables may defeat such attempts and discusses a variety of alternative approaches, including methods based on the Generalized Method of Moments and the more complex alternative approaches.

## ***5.*** *Automobile prices and hedonic regressions*

Griliches has also done important work on the measurement of quality change. Two joint papers written with Makoto Ohta are of special importance (1976, 1986). Besides the substantive interest of the results, the first paper cite introduces the concept of "economic significance" in hypothesis testing and suggests a relevant metric for it, while the second generalizes the usual hedonic regression by making the parameters of some of the characteristics functions of prices (gasoline), producing thereby relative stability in the estimated coefficients across both the OPEC-induced oil price shocks. Griliches continued to be active in this field, working with a number of coauthors on the measurement of computer and pharmaceutical prices (Berndt and Griliches 1993; Berndt, Griliches, and Rappaport 1995; Berndt, Cockburn, and Griliches 1996; Fisher and Griliches 1995; and Griliches and Cockburn 1994) and serving on the U.S. Senate Finance Committee Advisory Commission on the CPI (see Boskin et al. 1996). I note that the "hedonic" techniques which he revived and turned into an empirical tool, have already been incorporated into the construction of some of the component indices that form the basis of the

Consumer and Producer Price Indices in the U.S. and in several other countries. Moreover since use of hedonics has been shown to reduce various biases in the construction of those indices, we can expect hedonics to be used more generally by the statistical agencies in the future.

## ***6.*** *Estimating the returns to education*

Griliches has also done influential research on the measurement of the returns to education and the attempts to unravel them from the other forces that affect the observed wages of individuals. The first paper in this section (1976) continues the work he started with Mason (Griliches and Mason 1972). It uses NLS data with IQ scores on individuals and largely supports his earlier conclusions. His Econometric Society Presidential Address, surveys this whole field (as of that time) and concludes that if anything, the returns to education have been under, rather than over, estimated (1977). This conclusion has largely stood the test of time (see the recent work and surveys by Angrist and Krueger 1991; Card 1995; Ashenfelter and Krueger 1992; and others). The next two papers deal with more specific aspects of this field; the first surveying the then still-developing field of sibling data analysis (1979) and the second, with Bound and Hall (1986), pursuing an intricate missing data methodology, trying to use many of the available pairs and individuals in the underlying data set (the NLS) to test the hypothesis that the unobserved "ability" is priced differentially in the market for women than men. The latter paper is based on the interesting contrast between brother-sister pairs and single sex brother-brother and sister-sister sibling pairs.

## References

Adams, J. D. and Griliches, Z., "Measuring Science: An Exploration," *Proceedings of the National Academy of Sciences* 93, November 1996 12664-70.

Berndt, E., Cockburn, I. and Griliches, Z., "Pharmaceutical Innovations and Market Dynamics: Tracking Effects on Price Indexes for Antidepressant Drugs," *Brookings Papers on Economic Activity: Microeconomics* 1996 133-88.

Berndt, E. and Griliches, Z., "Price Indexes for Microcomputers: An Exploratory Study," in *Price Measurement and Their Uses*, M. F. Foss, M. E. Manser and A. H. Young, eds. 1993, NBER Studies in Income and Wealth, Vol. 57, 63-93, Chicago: University of Chicago Press.

Berndt, E., Griliches, Z. and Rappaport, N., "Econometric Estimates of Prices Indexes for Personal Computers in the 1990s," *Journal of Econometrics* 68(1) 1995, 243-268.

Boskin, M., Dulberger, E., Gordon, R. J., Griliches, Z. and Jorgenson, D., *Final Report of the Advisory Commission to Study the Consumer Price Index*, December 1996, Washington, DC: U.S. Government Printing Office, S. Prt. 104-72.

Bound, J., Hall, B. H. and Griliches, Z. "Wages, Schooling and IQ of Brothers and Sisters: Do the Family Factors Differ?" *International Economic Review*, 27(1), Feb. 1986, 77-105.

Chamberlain, G. and Griliches, Z. "Unobservables with a Variance-Components Structure: Ability, Schooling and the Economic Success of Brothers", *International Economic Review* 16(2), June 1975, 422-49.

Cockburn, I. and Griliches, Z., "Industry Effects and Appropriability Measures in the Stock

Market's Valuation of R&D and Patents," *American Economic Review*, 78(2) 1988, 419-23.

Eden, B. and Griliches, Z., "Productivity, Market Power, and Capacity Utilization When Spot Markets Are Complete," *American Economic Review Papers and Proceedings* 83(2) 1993, 219-223.

Fisher, F. and Griliches, Z., "Aggregates Price Indices, New Goods, and Generics," *The Quarterly Journal of Economics* 110(1), no. 440, February 1995, 229-244.

Griliches, Z., "Hybrid Corn: An Exploration in the Economics of Technological Change," Ph.D. dissertation, University of Chicago 1956.

Griliches, Z., "Hybrid Corn: An Exploration in the Economics of Technological Change," *Econometrica*, 25(4) 1957a, 501-522.

Griliches, Z., "Specification Bias in Estimates of Production Functions," *Journal of Farm Economics*, 39(1) 1957b, 8-20.

Griliches, Z., "The Demand For Farm Fertilizer: An Econometric Interpretation of a Technical Change," *Journal of Farm Economics*, XL(3) 1958a, 591-606.

Griliches, Z, "Research Cost and Social Returns: Hybrid Corn and Related Innovations," *Journal of Political Economy*, LXVI(5) 1958b, 419-431.

Griliches, Z. "Distributed Lags, Disaggregation, and Regional Demand Functions for Fertilizer," *Journal of Farm Economics*, Feb. 1959, XLI(1), 90-102.

Griliches, Z., "The Demand for a Durable Input: U.S. Farm Tractors 1929-1957," in A. C. Harber (ed.) *The Demand for Durable Goods*, Chicago: University of Chicago Press 1960a 181-

207.

Griliches, Z., “Measuring Inputs in Agriculture: A Critical Survey,” *Journal of Farm Economics*, XLII(5) 1960b 1411-1427.

Griliches, Z. “A Note on Serial Correlation Bias in Estimates of Distributed Lags,” *Econometrica***,** 29(1), Jan. 1961, 65-73.

Griliches, Z., “Production Functions, Technical Change, and All That,” Netherlands School of Economics, Econometric Institute, Report #6328 1963a.

Griliches, Z., “The Sources of Measured Productivity Growth: U.S. Agriculture 1940-1960,” *Journal of Political Economy*, LXXI(4) 1963b, 331-346.

Griliches, Z., “Research Expenditures, Education and the Aggregate Agricultural Production Function,” *American Economic Review*, LIV(6) 1964, 961-974.

Griliches, Z. “Distributed Lags: A Survey,” *Econometrica* 35(1), Jan. 1967a 16-49.

Griliches, Z. “More on CES Production Functions,” *Review of Economics and Statistics* XLIX(4), Nov. 1967b, 608-10.

Griliches, Z., “Production Functions in Manufacturing: Some Preliminary Results,” in M. Brown, ed., *The Theory and Empirical Analysis of Production*, vl. 31 of NBER, *Studies in Income and Wealth*, New York: Columbia University Press 1967c, 275-340.

Griliches, Z., “Production Functions in Manufacturing: Some Additional Results,” *Southern Economic Journal*, October 1968, Vol. XXXV(2) 151-156.

Griliches, Z., "Notes on the Role of Education in Production Functions and Growth Accounting," in W. Lee Hansen, editor, *Education, Income and Human Capital*, NBER Studies in Income and Wealth, Vol. 325, New York: Columbia University Press 1970.

Griliches, Z. "Cost Allocation in Railroad Regulation," *The Bell Journal of Economics and Management Science* 3(1), Spring 1972, 26-41.

Griliches, Z. "Errors in Variables and Other Unobservables," *Econometrica* 42(6), Nov. 1974, 971-98.

Griliches, Z. "Wages of Very Young Men," *Journal of Political Economy* 84(4) pt 2 1976, S69-S85, combined refs at S239-S47.

Griliches, Z. "Estimating the Returns to Schooling: Some Econometric Problems," *Econometrica*, 45(1), Jan. 1977 1-22.

Griliches, Z. "Sibling Models and Data in Economics: Beginnings of a Survey," *Journal of Political Economy* 87(5) pt. 2 1979, S37-S64.

Griliches, Z., "Returns to Research and Development Expenditures in the Private Sector," in J. W. Kendrick and B. Vaccara, eds., *New Developments in Productivity Measurement*, NBER Studies in Income and Wealth, Vol. 44 1980, 419-454, Chicago: University of Chicago Press.

Griliches, Z., "Market Value, R&D and Patents," *Economics Letters*, 7 1981 183-187.

Griliches, Z., *R&D, Patents and Productivity*, Z. Griliches, ed. Chicago: University of Chicago Press 1984.

Griliches, Z., "Productivity, R&D, and Basic Research at the Firm Level in the 1970s,"

*American Economic Review* 76(1), March 1986 141-154.

Griliches, Z., *Technology, Education and Productivity: Early Papers with Notes to Subsequent Literature*, New York: Basil Blackwell 1988a.

Griliches, Z., "Productivity Puzzles and R&D: Another Nonexplanation," *The Journal of Economic Perspectives*, 2(4) 1988b, 9-21.

Griliches, Z., "R&D and Productivity: Econometric Results and Measurement Issues," in P. Stoneman, ed., *Handbook of the Economics of Innovation and Technological Change*, Oxford, UK and Cambridge, MA: Basil Blackwell 1995, 52-89.

Griliches, Z., *R&D and Productivity: The Econometric Evidence*, Chicago: University of Chicago Press 1998.

Griliches, Z. and Cockburn, I., "Generics and New Goods in Pharmaceutical Price Indexes," *American Economic Review* 84(5) 1994 1213-32.

Griliches, Z. and Grunfeld, Y. "Is Aggregation Necessarily Bad?" *Review of Economics and Statistics*, Feb. 1960, 42(1) 1-13.

Griliches, Z. and Mason, W., "Education, Income, and Ability," *Journal of Political Economy* 80(3), Part II, May 1972, S74-S103.

Griliches, Z. and Mairesse, J., "Productivity and R&D at the Firm Level," in Z. Griliches, ed., *R&D, Patents and Productivity*, Chicago: University of Chicago Press 1984, 339-374.

Griliches, Z. and Mairesse, J. "Heterogeneity in Panel Data: Are There Stable Production Functions?" in Paul Champsaur et al., ed., *Essays in Honor of Edmond Malinvaud*, vol. 3,

*Empirical Economics*, Cambridge, MA: MIT Press 1990 192-231.

Griliches, Z. and Mairesse, J., "Production Functions: The Search for Identification," NBER Working Paper No. 5067, Cambridge, MA, March 1995.

Griliches, Z. and Mairesse, J. "Production Functions: The Search For Identification," in Steinar Strom, ed., *The Ragnar Frisch Centennial Symposium*, Econometric Society Monograph Series, Cambridge University Press 1998.

Griliches, Z. and Ohta, M. "Automobile Prices Revisited: Extensions of the Hedonic Hypothesis," in N. Terleckyj, ed., *Household Production and Consumption*, Studies in Income and Wealth Vol. 40, New York: Columbia University Press for National Bureau of Economic Research 1976, 325-390.

Griliches, Z. and Ohta, M. "Automobile Prices and Quality: Did the Gasoline Price Increases Change Consumer Tastes in the U.S.?" *Journal of Business and Economic Statistics* 4(2), April 1986 187-198.

Griliches, Z. and Pakes, A. "Estimating Distributed Lags in Short Panels with an Application to the Specification of Depreciation Patterns and Capital Stock Constructs," *Review of Economic Studies,* LI(2), No. 165, April 1984, 243-62.

Griliches, Z. and Ringstad, V. "Error-in-the-Variables Bias in Nonlinear Contexts, *Econometrica* 38(2), March 1970, 368-70.

Griliches, Z. and Ringstad, V., *Economies of Scale and the Form of the Production Function*, Amsterdam: North Holland 1971.

Griliches, Z. and Ringstad, V. “Various Bias Formulae,” Appendix C from Z. Griliches and V. Ringstad, *Economies of Scale and the Form of the Production Function: An Econometric Study of Norwegian Manufacturing Establishment Data* 1971, Amsterdam: North Holland 194-98.

Griliches, Z. and Schmookler, J., “Inventing and Maximizing,” *American Economic Review*, September 1963, Vol. LIII(4), 725-729.

Griliches, Z. and Wallace, N. “The Determinants of Investment Revisited,” *International Economic Review*, Sept. 1965, 6(3), 311-329.

Hall, B. H., Griliches, Z. and Hausman, J. A., “Patents and R&D: Is There a Lag?” *International Economic Review*, 27(2) 1986, 265-283.

Jorgenson, D. W. and Griliches, Z., “The Explanation of Productivity Change,” *Review of Economic Studies*, 34(3) 1967, 249-83.

Klette, T. J. and Griliches, Z., “The Inconsistency of Common Scale Estimators when Output Prices Are Unobserved and Endogenous,” *Journal of Applied Econometrics* 11(4) 1996, 343-361.

Mairesse, J. and Griliches, Z., “Heterogeneity in Panel Data: Are There Stable Production Functions?” in P. Champsaur et al., eds, *Essays in Honor of Edmond Malinvaud*, vol. 3 193-231, Cambridge, Mass.: MIT Press 1990.

*Other References*

Abramovitz, M., "Resource and Output Trends in the U.S. Since 1870," *American Economic Review*, 46(2) 1956, 5-23.

Adams, J. D. and Jaffe, A. B., "Bounding the Effects of R&D: An Investigation Using Matched Establishment-Firm Data," NBER Working Paper No. 5544, Cambridge, MA, April 1996.

Aghion, P. and Howitt, P., "A Model of Growth through Creative Destruction," *Econometrica* 60(2) 1992, 323-51.

Aigner, D. and S. Goldfeld, "Estimation and Prediction from Aggregate Data when Aggregates are Measured More Accurately than Their Components," *Econometrica* 42(1), Jan. 1974 113-34.

Almon, S., "The Distributed Lag Between Capital Appropriations and Expenditures," *Econometrica*, 33(1) 1965.

Angrist, J. and Krueger, A. B., "Does Compulsory School Attendance Affect Schooling and Earning?" *Quarterly Journal of Economics* ***1***06 1991, 979-1014.

Ashenfelter, O. and Krueger, A., "Estimates of the Economic Return to Schooling from a New Sample of Twins," NBER Working Paper No. 4143 1992.

Australian Industry Commission, *Research and Development*, Report no. 44, Canberra: Australian Government Publishing Service 15 May 1995.

Barker, T. and Pesaran, M. H., "Disaggregation in Econometric Modeling–An Introduction," in T. Barker and M. H. Pesaran, eds., *Disaggregation in Econometric Modelling*, Routledge 1990 1-14.

Bartelsman, E. J. and Gray, W.B., Manufacturing industry productivity database, NBER Technical Working Paper, Cambridge, MA, forthcoming 1996.

Basu, S. and Kimball, M., "Cyclical Productivity with Unobserved Input Variation," Working Paper 5915, Cambridge, MA: NBER, February 1997.

Berry, S., J. Levinsohn, and A. Pakes (1995): "Automobile Prices in Market Equilibrium", *Econometrica*, Vol.63, No.4, pp.841-90.

Biorn, E., "Panel Data with Measurement Errors," in L. Matyas and P. Sevestre, eds., *The Econometrics of Panel Data: A Handbook of the Theory with Applications*, 2nd ed. Dordrecht: Kluwer 1996, Chap. 10, 236-79.

Bresnahan, T. and Gordon, R (eds), *The Economics of New Products*, the University of Chicago Press 1997.

Brown, M. and Conrad, A., "The Influence of Research on CES Production Relations," in M. Brown, ed., *The Theory and Empirical Analysis of Production***,** vol. 31 of *Studies in Income and Wealth*, New York: Columbia University Press for NBER 1967, 275-340.

Burnside, C., Eichenbaum, M. and Rebelo, S., "Capital Utilization and Returns to Scale," in B. Bernanke and J. Rotemberg, eds., *NBER Macroeconomics Annual*, Vol. 10, Cambridge: NBER 1995, 67-109.

Caballero, R. J. and Jaffe, A. B., "How High Are The Giants Shoulders?" in *NBER Macroeconomics Annual 1993*, Cambridge, MA 1993.

Cagan, P., "The Monetary Dynamics of Hyper Inflations," in M. Friedman, ed., *Studies in the*

*Quantity Theory of Money*, Chicago: University of Chicago Press 1956.

Card, D., "Earnings, Schooling, and Ability Revisited," *Research in Labor Economics* 1995.

Cockburn, I. and Henderson, R., "Public-Private Interaction and the Productivity of Pharmaceutical Research," NBER Working Paper 6018, April 1987, Cambridge, MA.

Coe, D. and Helpman, E., "International R&D Spillovers," *European Economic Review* 39(5), May 1995, 859-87.

Cummins, C., "Efficient Estimation of Regression Coefficients with Missing Data," Ph.D. thesis, Harvard University 1989.

Davis, P. (1997): "Spatial Competition in Retail Markets: Motion Theaters", *mimeo,* M.I.T.

Denison, E. F., *The Sources of Economic Growth in the United States*, Supplementary Paper No. 13, New York: Committee for Economic Development 1962.

Evenson, R. E., "The Contribution of Agricultural Research and Extension to Agricultural Productivity," Ph.D. Dissertation, University of Chicago 1968.

Evenson, R. E. and Kislev, Y., "Research and Productivity in Wheat and Maize," *Journal of Political Economy*, 81(6) 1973 1309-1329.

Ezekiel, M. *Methods of Correlation Analysis*, 2nd ed., New York: Wiley 1941.

Foss, M., M. Manser and A. Young, *Price Measurements and Their Uses*, the University of Chicago Press (*Studies in Income and Wealth,* Volume 57) 1993.

Friedman, M., *The Theory of the Consumption Function*, National Bureau of Economic Research

General Series No. 63, Princeton University Press 1957.

Gordon, R., *The Measurement of Durable Goods Prices*, Chicago, the University of Chicago Press (the NBER) 1990.

Grunfeld, Y., "The Determinants of Corporate Investment," in A. C. Harberger, ed., *The Demand for Durable Goods*, Chicago: University of Chicago Press 1960.

Grossman, G. M. and Helpman, E., *Innovation and Growth in the Global Economy*, Cambridge, MA: MIT Press 1991.

Hall, B. H., "The Private and Social Returns to Research and Development," in B. Smith and C. Barfield, eds., *Technology, R&D, and the Economy*, Washington, DC: Brookings Institution and AEI 1996 140-162.

Hall, B. H., Cummins, C., Laderman, E.S. and Mundy, J., "The R&D Master File: Documentation," NBER Technical Working Paper 72, Cambridge, MA 1988.

Hall, R. E., "The Relation Between Price and Marginal Cost in U.S. Industry," *Journal of Political Economy*, 96(5) 1988, 921-47.

Heckman, J. J., "Sample Selection as a Specification Error," *Econometrica*, 47(1) 1979 153-161.

Henderson, R. and Cockburn, I., "Scale, Scope, and Spillovers: Determinants of Research Productivity in the Pharmaceutical Industry," *RAND Journal of Economics*, 27(1) 1996, 32-59.

Jaffe, A., "Technological Opportunity and Spillovers of R&D: Evidence from Firm's Patents, Profits and Market Value," *American Economic Review*, 75(6) 1986, 984-1002.

Jaffe, A., Trajtenberg, M. and Henderson, R., "Geographic Localization of Knowledge Spillovers as Evidenced by Patent Citations," *Quarterly Journal of Economics* 108(3) 1993, 577-98.

Jaffe, A., Trajtenberg, M. and Henderson, R., "Universities as a Source of Commercial Technology: A Detailed Analysis of University Patenting," *Review of Economics and Statistics* 1998.

Jorgenson, D., "Rational Distributed Lag Functions," *Econometrica*, 34(1) 1966.

Kendrick, J.W., *Productivity Trends in the U.S.*, Princeton, NJ: Princeton University Press for NBER 1961.

Klette, T. and Willassen, Y., "Errors in Variables and Parameter Bounds: An Application to the Estimation of Production Relationships," mimeo, Oslo: Central Bureau of Statistics of Norway 1993.

Konus, A.A., "The Problem of the True Cost of Living," translated in *Econometrica* 10-29 1939 (original article published in 1924).

Kortum, S., "Equilibrium R&D and the Patent R&D Ratio: U.S. Evidence," *American Economic Review*, 83(2) 1993, 450-457.

Kortum, S. and Lerner, J., "Stronger Protection or Technological Revolution: What Is Behind the Recent Surge in Patenting?" mimeo, Boston University and Harvard Graduate School of Business 1997.

Koyck, L.M., *Distributed Lags and Investment Analysis*, Amsterdam: North Holland 1954.

Lancaster, Kelvin, *Consumer Demand: A New Approach*, Columbia University Press, New York 1971.

Lanjouw, J., Pakes, A. and Putnam, J., "How To Count Patents and Value Intellectual Property: Uses of Patent Renewal and Application Data," NBER Working Paper 5741, Cambridge, MA 1996.

Lichtenberg, F. and Siegel, D., "The Impact of R&D Investment on Productivity: New Evidence Using Linked R&D-LRD Data," *Economic Inquiry*, 29(2) 1991, 203-29.

Mairesse, J. and Mohnen, P., "Research & Development and Productivity: A Survey of the Econometric Literature," Universite du Quebec a Montreal and CIRANO, December 1995.

Mairesse, J. and Sassenou, M., "R&D and Productivity: A Survey of Econometric Studies at the Firm Level," *STI Review*, 8 1991, 9-43, Paris: OECD.

Mansfield, E., "Rates of Return from Industrial R&D," *American Economic Review*, 55 1965, 863-873.

Minasian, J., "The Economics of Research and Development," in R. R. Nelson, ed., *The Rate and Direction of Inventive Activity*, NBER Special Conference Volume 13, New Jersey: Princeton University Press 1962.

Nadiri, M. I., "Innovations and Technological Spillovers," WP No. 4423, Cambridge, MA.: National Bureau of Economic Research 1993.

Nelson, R. R., "The Simple Economics of Basic Scientific Research," *Journal of Political Economy*, 67(June) 1959, 297-306.

Nelson, R. R. ed., *The Rate and Direction of Economic Activity*, Princeton, NJ: Princeton University Press for NBER 1962.

Nevo, Aviv; "Measuring Market Power in the Ready-to-Eat Cereal Industry," NBER Discussion Paper, No. 6387 1997.

Olley, S. and Pakes, A., "The Dynamics of Productivity in the Telecommunications Equipment Industry," *Econometrica*, 64(6) 1996 1263-97.

Orcutt, G. and Edwards, J., "Should Aggregation Prior to Estimation Be the Rule?" *Review of Economics and Statistics* 51(4) 1969, 409-20.

Pakes, A. and Schankerman, M., "The Rate of Obsolescence of Knowledge, Research Gestation Lags, and the Private Rate of Return to Research Resources," in Zvi Griliches, ed., *R&D, Patents and Productivity*, Chicago: University of Chicago Press 1984, 73-88.

Pakes, A. "Hedonic Bounds to Ideal Price Indices", mimeo, Yale University 1997.

Pesaran, H. and Smith, R., "Estimating Long Run Relationships from Dynamic Heterogeneous Panels," *Journal of Econometrics* 65(1) 1995, 79-113.

Petrin, A.; "Quantifying the Benefits of New Products: The Case of the Mini Van", mimeo, University of Chicago, Graduate School of Business 1997.

Pollak, R., *The Theory of the Cost-of-Living Index*, Oxford University Press 1989.

Putnam, J., "The Value of International Patent Rights," Boston: Charles River Associates 1997.

Ringstad, V., *Estimating Production Functions and Technical Change from Micro Data*,

Economic Studies No. 21, Oslo, Bureau of Statistics 1971.

Romer, P. M., "Increasing Returns and Long-Run Growth," *Journal of Political Economy*, 98(5) 1990, S71-S102.

Ruttan, V. W., *Technological Progress in the Meat Packing Industry 1919-47*, Washington, D.C.: USDA: Marketing Research Report 1954.

Ruttan, V. W., "The Contribution of Technological Progress to Farm Output 1950-75," *Review of Economics and Statistics*, 38(1) 1956, 61-69.

Schankerman, M., "Essays on the Economics of Technical Change: The Determinants Rate of Return and Productivity Impact of Research and Development," Harvard Ph.D. thesis 1979.

Schankerman, M., "How Valuable Is Patent Protection: Estimates by Technology Field," mimeo, London School of Economics 1997.

Scherer, F. M., "Corporate Inventive Output, Profits, and Growth," *Journal of Political Economy*, 73 1965, 290-97.

Scherer, F. M., "Interindustry Technology Flows and Productivity Growth," *Review of Economics and Statistics* 1982, 627-634.

Scherer, F.M., "Using Linked Patent and R&D Data to Measure Interindustry Technology Flows," in Z. Griliches, ed., *R&D, Patents and Productivity*, Chicago: University of Chicago Press 1984.

Scherer, R. M., "The Size Distribution of Profits from Innovation," ZEW Discussion Paper, 96-13, Mannheim, Germany 1996.

Schmookler, J., "The Changing Efficiency of the American Economy 1869-1938," *Review of Economics and Statistics*, 34(3) 1952, 214-231.

Schmookler, J., "Economic Sources of Inventive Activity," *Journal of Economic History*, 22(March) 1962 1-20.

Schultz, T. W., *The Economic Organization of Agriculture*, New York: McGraw-Hill 1953.

Solow, R. M., "Technical Change and the Aggregate Production Function," *Review of Economics and Statistics*, 39(3) 1957, 312-320.

Terleckyj, N., "Factors Underlying Productivity: Some Empirical Observations," *Journal of the American Statistical Association* 1958.

Trajtenberg, M., "A Penny for Your Quotes", the *Rand Journal of Economics* 1990.

Triplett, J. (1971): "Quality Bias in Price Indexes and New Methods of Quality Measurement" pp. 180-214, in Z. Griliches, op. cit.

Van Reenen, J., "The Creation and Capture of Rents: Wages and Innovation in a Panel of U.K. Companies," *Quarterly Journal of Economics* 111(1) 1996 195-226.

Woolridge, J., "Distribution-Free Estimation of Some Nonlinear Panel Data Models," unpublished, MIT 1990.