

Zvi Griliches, 1930 - 1999: A Critical Appreciation¹

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"Discovery consists of seeing what everybody has seen and thinking what nobody has thought."

Albert Szent-Györgyi, *The Scientist Speculates*, 1962

1. Prologue

Zvi Griliches was born in Kaunas, Lithuania, on September 12, 1930, and died on November 4, 1999, in Cambridge, Massachusetts. The story of how he got from there to here is a long one with a harrowing beginning. It has been told by Griliches himself in a talk presented on the eve of Yom Hashoah (Holocaust Remembrance Day) at the Harvard-Radcliffe Hillel Foundation (Griliches, 1992) and in an interview given Alan Krueger and Timothy Taylor about four months before his death (Krueger and Taylor, 2000). The beginning was harsh: In 1940, the Soviet Union annexed Lithuania and the other Baltic Republics. The Nazis occupied the country in 1941. Griliches and his family were confined to the Ghetto in Kaunas in August of that year. He managed to evade the periodic roundups for transport to the concentration camps until sometime during the summer of 1944. After that, he was moved, often by foot, from one camp to another until he was liberated from Dachau by the American advance in May, 1945. He lost all his immediate family, except for a sister, in the Holocaust. Eventually, Griliches made his way via a British internment camp on Cyprus to what was then Palestine. After working on a *kibbutz*, participating in the War of Independence, and despite his lack of formal education, Griliches managed to pass what we would call a high school equivalency exam and spent a year studying history and languages at the Hebrew University, 1950-1951, before matriculating in the College of Agriculture at the University of California, Berkeley, where he obtained a bachelor's degree, 1953, and a master's degree, 1954, both in agricultural economics. While most people's subsequent intellectual development, ideas and perspective in a social science such as economics would be expected to have been affected profoundly by the horrific experiences through which Griliches lived in the decade before he emigrated to the United States, I find remarkably little evidence that his subsequent work and contributions were. As he himself once remarked: "After we came out of the Holocaust, we did not look back. We had too much trouble re-establishing some kind of life and getting going. Besides, there was no point in dwelling. People like me were a dime a dozen. Lots of people, everyone had a story. No one out there was interested in our stories."² He was surely not one of a "dime a dozen," but the story of his life and work I want to tell here begins at the University of Chicago in the Fall of 1954, when he matriculated in the Ph.D. program there.

¹ The writing of this essay was supported by the Maryland Agricultural Experiment Station. I am indebted to Bruce Gardner, Anke Sofia Meyer and Tim Breshnahan for helpful comments and criticism. John Chipman, Jacques Mairesse and Mark Schankerman have commented extensively on an earlier drafts, and I have had the benefit of correspondence with several of Griliches's former students, Pascal Mazodier, Tor Jakob Klette, Vidar Ringstad, and Clint Cummins. The opinions expressed are my own and do not necessarily reflect those of Griliches's former students and colleagues I have consulted.

² Quoted in Michael Weinstein's obituary in the *New York Times*, November 5, 1999.

The intellectual atmosphere and ferment at Chicago in the fifteen years Griliches was there, first as a graduate student 1954-56 and subsequently on the faculty, 1957-69, were heady. I have described the milieu and cast of characters in some detail in a previous paper (Nerlove, 1999) and need not repeat it here. Perhaps the greatest influence on his subsequent work was T. W. Schultz. But also important to his intellectual development were Gregg Lewis, D. Gale Johnson, Al Harberger, and Carl Christ. (The Cowles Commission, along with such luminaries such as Tjalling Koopmans and Jacob Marschak, among others, left formally in 1955 but had largely gone by 1954.) Hans Theil visited that year and his lectures provided a neat framework which Griliches adapted in his paper on specification bias in the estimation of production functions (1957b). Trygve Haavelmo visited during the academic year 1957-58. His work on the theory of investment (1960) completed that year played a pivotal role in Griliches's development of his ideas on capital heterogeneity and, more importantly, in accounting for economic growth and productivity change. I think though that it was Schultz's influence that was really formative, and a strong interaction between the two continued until Schultz's death in 1998, only a year and a half before Griliches's.³

Over the years Griliches garnered many honors and awards for his work: The prestigious John Bates Clark Medal of the American Economic Association in 1965, Presidencies of the Econometric Society and American Economic Association in 1975 and 1993, respectively, and an honorary degree from the Hebrew University, Jerusalem, in 1991. He was elected to fellowships in the Econometric Society, 1964, the American Academy of Arts and Sciences and the American Statistical Association, 1965, the American Association for the Advancement of Science, 1966, the American Agricultural Economics Association, 1991, and the American Economic Association, 1994. In 1975 he was elected to the National Academy of Sciences. He served on many Academy and national committees, the most notable being the so-called Boskin Commission to Study the Consumer Price Index, 1995-97, and had an important and far-reaching influence on economic statistics in the U. S., a part of which I deal with in section (3) below. Much of his contribution was through his interaction with students and research associates, particularly over the thirty years, he spent at Harvard University and the National Bureau of Economic Research, and not merely through his published work. I will try to deal with these influences *ad passim*.⁴ Many in the profession thought he should have been awarded a Nobel Memorial Prize in Economics for his work. But, although the selection committee for the prize was aware that he was terminally ill, they did not choose to grant him that distinction before his death in 1999.

I knew Griliches since we were together at the University of Chicago in the years 1954 - 56. I followed his work closely over the years. I would share with you, in this essay on his work, my appreciation and assessment, not uncritical however, of his contribution to the science of economics. Much of his work was of profound and far-reaching significance for economics. But his contributions were many and diverse and some of his work was of lesser importance and long-run significance than the more central core. In his obituary, *New York Times*, Friday, November 5, 1999, Michael Weinstein characterized Griliches as one of "...the world's leading authorities on the statistical analysis of economic data." And states that he "...develop[ed] techniques of statistical estimation, including methods for analyzing 'panel' data that trace the behavior of many individuals or companies over time." Indeed, much of our profession

³ The interaction between the two began rather early: His 1956 paper, "Reflections on Agricultural Production and Supply," Schultz lays out the idea that the "unexplained growth in agricultural output should be explained by expanding the concept of inputs to account for their quality and to treating new knowledge and the contribution of public investments in such knowledge as inputs." If inputs were correctly measured, he argued a "correct" index of output per unit of input ought to remain roughly constant. In a footnote (1956, p. 758), Schultz credits this idea to Griliches, then a second-year graduate student (!). Such interaction and openness between a senior professor and a graduate student only in his second year is a tribute to them both. See also Griliches (1960d). Griliches's important work on the economics of technical change was also motivated by this view of the stock of knowledge as a form of capital, in which it was possible to invest. The idea that technology is endogenous appears earlier in Schultz's *The Economic Organization of Agriculture* (1953).

⁴ One of Griliches's former students, Iain Cockburn, has put together two formidable lists of Griliches's former students, postdocs and research associates, listing also their students and students' students, in the manner of genealogical tree. These can be accessed at http://people.bu.edu/cockburn/tree_of_zvi.html

regarded Griliches as pre-eminently an econometrician. Griliches's own assessment of his contributions to econometric methodology, however, was somewhat different. He later said (Krueger and Taylor, 2000): "Much of the stuff I did was empirical. I did some econometric theory, but the econometric theory was by and large theory I needed to develop for the problems I was working on, not because it was out there. By today's standard, I was woefully under prepared to be an econometrician." I would argue, however, that although statistical and econometric methodology were not at the central core of his contribution, he was an empirical economist in the best sense, perhaps the best his generation of economists produced. This is econometrics in its best sense, which blends theory and application. Many of the areas in econometrics which he opened up because they were relevant to the substantive work he was doing later proved to be methodologically seminal, perhaps in part because they were relevant to real economic problems. I hope that what follows may provide a guide and assessment of what he accomplished, albeit a personal one, and a delineation of the central core of his contribution, which was, in my view, principally a fuller and more quantitative understanding of the process of economic growth.⁵

Economics is an empirical science and thus concerned with the real economic world and with understanding economic behavior and the implications of such behavior for economic policy. However, economic research, in common with research in other academic disciplines, is largely driven by its own internal logic and structure in the sense that most work is on problems which flow from previous work rather than from any attempt to understand reality. The sub discipline of econometrics is no exception in this respect. Griliches's contributions invariably had their origin in a serious attempt to resolve some real economic problem and to understand some real economic phenomenon rather than to solve some outstanding methodological issue. Griliches was pre-eminently an empirical scientist. Recall the story of Hercules: One of Hercules' twelve tasks was to rid the neighborhood of the giant Antaeus who was terrorizing all and sundry. Antaeus was born of Mother Earth and drew sustenance and renewal from her whenever cast down. Hercules, realizing this, lifted Antaeus high in the air, cracked his ribs, and held him aloft until he died. Griliches was from the beginning virtually consumed with the desire to understand and modify the real world. Such methodological conclusions of more general applicability as he may have made draw their inspiration and strength from the substantive issues with which he was concerned. If his ideas have been held aloft, away from contact with economic reality, it is by others who have followed in his footsteps but not in his lead. It has not been his methodological contributions divorced from their substantive context which constitute Griliches's principal contribution to economic knowledge but rather his answers to the substantive questions themselves. More importantly, raising the questions themselves in the right way is his lasting legacy to our discipline.

In his Presidential Address to the American Economic Association (1994a), Griliches wrote: "The major message that I will be trying to convey is that we often misinterpret the available data because of inadequate attention to how they are produced and that the same inattention by us to the sources of our data helps to explain why progress is so slow [in this instance in understanding the process of economic growth]. It is not just the measurement of productivity that is affected. Other fields of empirical economics are also struggling against limitations imposed by the available data. Great advances have been made in theory and in econometric techniques, but these will be wasted unless they are applied to the right data." For most of his professional life and in the great bulk of his papers, Griliches attempted to deal with such data problems and with issues related to the appropriate ways to measure the relevant variables of economic theory. Framing the issues in this way was the key to his contribution.

Much of Griliches's substantive work dealt with the process of technological change and its interpretation as an economic phenomenon. In the introduction to a collection of early papers (1988a), covering the period of his work through 1971, he wrote: "...measurement frameworks can be expanded to bring more aspects of technological change into the domain of 'standard' economics, removing thereby some of the mystery from this range of topics. This kind of work, however, takes much effort, is heavily data dependent, and is rarely definitive. At best it opens up new subjects rather than providing closure. It shows by example, what can be done and what it might be interesting to do more of; and often the question

⁵ At the time of his death, Griliches was revising his Kuznets Lectures on economic growth, to be published by Harvard University Press. I have not had access to these lectures and thus to Griliches's most definitive statement on the subject.

is as interesting as the possible answers." The tentative and incomplete nature of much of Griliches's work is indicated by the many papers which he titles "Notes on" But this hesitancy should not blind us to the importance or significance of the contributions made. If one broadly construes econometrics as dealing with problems of appropriate measurement in addition to problems of inference, as I think should be the case, Griliches's contributions have been of immense and far-reaching significance. His contributions to the methodology of econometric inference *per se*, derive largely from his more substantive work and his concern with measurement.⁶

Griliches's bibliography is very large; my review of his work can, at best, be highly selective. His opera can be roughly sorted into five main categories, although some work falls in more than one category and almost all are related to the theme of appropriate measurement to a greater or lesser degree: (1) Technological innovation and diffusion, R&D, and patents; (2) Hedonics, including proper measurement and adjustment of input and output measures in the analysis of economic growth and productivity measurement; (3) Production functions, growth accounting, and supply and derived demand; (4) Unobserved or latent variables and specification errors, including substantial substantive research on the relation among income, education or schooling, and ability, and with important implications for panel data econometrics; and (5) Other econometric issues, particularly those connected with distributed lags and dynamics. Of the five, the second and third are most central to the theme of measurement. I provide a selective bibliography at the end of this essay.

2. Technological innovation and diffusion, R&D, and patents.

Griliches's paper (1957a), arguably his best known, is essentially a summary of his Ph.D. dissertation, "Hybrid Corn: An Exploration in the Economics of Technological Change." The ideas presented in this paper foreshadow much of Griliches's subsequent work in this area. "A unifying thread that runs through ...is the view that technological change is itself an economic phenomenon and hence also an appropriate topic for economic analysis." (1988, p. 1.) But appropriate measurement of inputs and outputs is essential to this goal. Looking at the differential geographical spread of hybrid corn in the U. S., Griliches (1957a) sought to interpret it in terms of both the supply of the new technology in the form of specific hybrids adaptable to specific areas and the speed of adoption by farmers (i.e., their demand for the new technology). Using a logistic growth curve to summarize the spread of hybrid corn in the various states of the U. S., Griliches is able to parameterize the process by three parameters: origin, slope and ceiling.⁷ Origins are interpreted in terms of the supply of hybrid varieties by the various state experiment stations. Slopes and ceilings are interpreted in terms of farmers' incentives to adopt. But differences in ceilings are inadequately explained. The framework Griliches developed has been the basis for many studies of technological diffusion (see, for example, Feder, Just and Zilberman, 1985; Thirtle and Ruttan, 1987). Several studies by Griliches related to agricultural research flowed directly from this study: (1958a), "Research Cost and Social Returns: Hybrid Corn and Related Innovations," and (1960a), "Hybrid Corn and the Economics of Innovation." The former had a wide influence in the agricultural economics profession

⁶ In *The Role of Measurement in Economics* (1951), Richard Stone wrote: "Measurement is concerned with finding an expression for the degree of difference in distinguishable qualities or characteristics. It is possible if a means can be found for bringing the amount of any characteristic under investigation into a certain relationship with a set of numbers." Concern with data and appropriate measurement of the relevant variables is necessarily prior to inference, as Griliches would argue and as I would agree. Definitive boundaries are difficult to draw, and this is the case particularly in the context of Griliches's work, because one of the things he did was to introduce economic models and inferential issues into the problem of appropriate measurement.

⁷ The model which Griliches used is as follows: $P = \frac{K}{1 + e^{-(a+bt)}}$, where P is the percentage of total corn acreage planted with hybrid seed, K is the ceiling or equilibrium value, t is time, and b is the rate of growth coefficient. a is a location parameter. The proportional rate of growth is $\frac{1}{P} \frac{dP}{dt} = b \frac{P}{K}$.

and led to many subsequent studies by Evenson (e.g., 1968), Huffman (e.g., 1972), Griliches (1980), and others. (See also Evenson and Kislev, 1975, and Huffman and Evenson, 1993.) Perhaps (1957a) has been even more influential outside economics; see Rogers (1983).

Less directly but more importantly, Griliches's interest in hybrid corn led to a concern with the other major changes that were occurring in U. S. agriculture, principally mechanization and the spectacular growth in fertilizer use (1958b, 1959a, 1959c, 1960b, 1960d, 1963a) and to his concern, which I regard as central to his work, with appropriate measurement of inputs and output and thus to his pioneering resurrection of hedonic analysis. These early studies of agricultural inputs employed econometric tools sophisticated for their time and led to Griliches's papers on distributed lags and aggregation, to be discussed in (5) below. I will take up hedonics in the next section and Griliches's work on production function estimation in (3). His concern with appropriate measurement of inputs and estimation of production functions is also reflected in his work on measurement of labor inputs and thus to that on the relation among education or schooling, ability and income as a way of adjusting labor input in studies of productivity and total factor productivity.

Much of Griliches's more recent work dealt with productivity growth in the U. S., Israel, Japan and France. To a great extent this work is related to production function estimation, but there is one very large group of papers more directly related to the source of technical change and its explanation by economic factors, namely, those papers on R & D and patents (1963c, 1979a, 1980a-c, 1981b, 1982, 1984a-f, 1986a-b, 1988b-c, 1989b, 1990a-c, 1991, 1994a, 1995a). These studies started the microeconomic study of patents as an indicator of innovation. He initiated the creation of a very large panel data set in which patent data were linked to other firm data available from Standard and Poor's Compustat tapes. Central to this work is the idea that technical change, and more generally knowledge, is produced. The late Jacob Schmookler pioneered in the study of patents as an indicator of inventive activity and technical change (1954), but the link has proved elusive (see especially Griliches, 1990b). In his Presidential Address to the American Economic Association (1994a), he characterizes patents as "a shrinking yardstick," but nonetheless valuable.⁸ Moreover, the relationship between patents and R & D is also problematic (1994f). A more rewarding direction of research has been the study of the relation between productivity growth and R & D expenditures, particularly at the level of the individual firm. In (1979a), Griliches lays out the production function approach to the estimation of returns to R & D, the issues associated with output measurement in R & D intensive industries, the problem of defining the stock of R & D capital as a factor of production. In this work, he continues a *leitmotiv* from the part of his work on hybrid corn dealing with the supply of hybrids. One of Griliches's most important, if not the most important, contributions in this area was to link Census of Manufactures data on firms and industries with National Science Foundation data on R & D expenditures, no mean accomplishment in a country obsessed with privacy and maintaining confidentiality, and which required considerable managerial and administrative skill.⁹ A collaborator, Bronwyn Hall, was instrumental in these studies, as she was in the collection and collation of the patent data. In this connection, mention should also be made of Griliches's collaborators in France, Israel and Norway: Jacques Mairesse (Institut National de la Statistique et des Études Économiques), Tor Jakob Klette (Central Bureau of Statistics, Norway), and Haim Regev (Central Bureau of Statistics, Israel).¹⁰ Work on these data was certainly facilitated by a more open tradition of academic research. Many of Griliches's

⁸ "In spite of all of the difficulties, patents statistics remain a unique resource for the analysis of the process of technical change. Nothing else even comes close in the quantity of available data, accessibility, and the potential industrial, organizational, and technological detail. ... the currently available patent data can be used to study longer-run interfirm differences in levels of inventive activity and as a substitute for R & D data where they are not available in the desired detail." (1990b, p.1702.) Subsequent work, notably Schankerman and Pakes (1986), Pakes (1986), Lanjouw (1998), Jaffe, *et al.*, (1993, 2000), has focused on attempts to measure the "quality" of patents rather than simple patent counts and show that patent data more generally are much more useful than patent count data alone. (I am indebted to Mark Schankerman for these references.)

⁹ Indeed, the difficulties in dealing with the U. S. Census data were so great that much of Griliches's later work made use of the Standard and Poor Compustat data base. See especially (1984b).

¹⁰ Griliches's first collaboration using Norwegian microdata at the firm level was with Vidar Ringstad on production function estimation. See section 5 below.

subsequent papers and those of numerous co-investigators at the National Bureau of Economic Research rest on these data. Several appear in the 1984 volume edited by Griliches. The papers in this volume deal, *inter alia*, with the following questions: "What is the relationship of R & D investments at the firm and industry level to subsequent performance indicators such as patents, productivity, and market value? How does one formulate and estimate such relationships? What makes them vary across different contexts and time periods? To what extent can one use patent counts as indicators of R & D output? Can one detect the output of R & D in the market valuation of the firm as a whole? What determines how much R & D is done and how many patents received?" (Griliches, 1984, p. 2.) In a paper published posthumously, Klette and Griliches (2000) develop a sophisticated model of the growth of heterogeneous firm in which R&D and stochastic innovation are the engines of firm growth and apply this model to a panel of Norwegian firms. Although there are no great breakthroughs in econometric method to be found in this work, there are many innovations (nonstochastic!) in application of panel data methods in this work on micro firm data more generally. (I have more to say about Griliches's contribution to panel data econometrics below in section 5.)

A widely cited paper of Griliches, is joint with D. W. Jorgenson, "The Explanation of Productivity Change" (1967a). This paper has, in my view, provided a sound basis for the field of growth accounting, despite the fact that its major finding has often been misinterpreted, and has been of major influence in the study of economic development in general and of great significance in recent debates over the supposed slowdown in U. S. productivity growth. This work is foreshadowed in (1963c) in some detail (indeed, the basic structure is already in place there) and, earlier, by Abramovitz (1950, 1962) and Denison (1962); it is more properly treated as an aspect of production function analysis in section (4) below.¹¹

3. "Hedonics." Proper measurement of prices and adjustment of input and output measures

In (1964, p. 382), Griliches wrote: "Economists use price series for two main purposes: (1) to deflate expenditures and receipts for the purpose of arriving at some conclusions about either changes in welfare (in the case of consumption expenditures and earning receipts) or productivity (in the case of sales receipts, wage bills, and investment expenditures); and (2) to explain and predict changes in quantities used or purchased. In either case we are likely to have a broader concept of 'price' in mind than just one of the particular numbers recorded during a transaction." Thus stated, the problem of constructing an appropriate price index for a multitude of different transactions involving different commodities of differing qualities or efficacies is basically an aggregation problem (Frisch, 1936). On the consumer side, appropriate aggregation weights by marginal utilities or marginal rates of substitution; on the producer side, weighting is by marginal productivities, marginal rates of transformation, or marginal rates of substitution.¹² Under certain circumstances, these marginal rates of substitution or transformation can be treated as given prices, actual or implicit.¹³ A central problem, for both consumer and producer prices, is how to treat new commodities and quality changes. (Griliches's collaborations with Ernst R. Berndt, 1993 a-b, on personal computers, and with Iain Cockburn, 1994c, on pharmaceuticals should be mentioned in this connection.)

In two papers published in the same year (1961a, 1961b), one with Irma Adelman, Griliches resurrected the earlier work of Waugh (1929), Court (1939) and Stone (1954, 1956), although he did not acknowledge Waugh's work until much later (1988a, p. 122).¹⁴ Griliches's own earlier work on measuring

¹¹ For Griliches's own view of the history of this subject see (1996b). He viewed the paper as an attempt to get at an attribution of the relative sources of growth and not as an explanation of growth. Thus, growth accounting is a setting of a research agenda. More on this in section 4, below.

¹² For a good discussion of consumer price indices see Frisch (1936) and Fisher (1972); the problem of producer price indices is a great deal more complicated, and "Only in the simplest cases is the theory fully isomorphic to that of the cost-of-living index because of interlinkages among the various production units." The definitive work on the problem of producer price indices is Fisher and Shell (1998).

¹³ For consumer theory, Muellbauer (1974) presents several models of utility maximizing behavior which justify such an interpretation in terms of underlying consumer preferences, but he is quick to admit that his analysis neglects the other, producer, side of the market.

¹⁴ In the section of his classic study of consumer behavior dealing with the consumption of beer (1954, p. 388), Stone clearly enunciates the basis of hedonic analysis and, moreover, recognizes the identification

inputs in agriculture (1960d) also foreshadows his later contribution. The central idea probably originated independently in his work on the demand for tractors in U. S. agriculture (1960b). It is that a commodity can be decomposed into a bundle of attributes and was later theoretically developed by Lancaster (1966) and, independently, both theoretically and empirically by Ironmonger (1961 pub. 1972).¹⁵ This idea has had a great impact on official statistical measurement of price changes, largely through Griliches efforts, and in a variety of other fields, for example in the valuation of environmental amenities.¹⁶ Griliches himself wrote massively on this subject (1961a-b, 1964, 1967, 1976a, 1986c, 1989a, 1990d, 1993a-b, 1994b-c, 1995b-c, 1996a, c, e, 1997a-b).

The traditional method of adjusting for quality changes over time in the measurement of prices is to "match models," that is, to use only prices for varieties of a commodity which are unchanged in specification between two adjacent periods, chaining pairs of periods over time. Difficulties arise for commodities the varieties of which are changing rapidly over time or for totally new commodities. The hedonic technique (Waugh, 1929; Court, 1939) involves regressing unit prices for different varieties on measures of quality characteristics or attributes; if the varieties are distinguished by time periods, a simple technique for obtaining a quality-adjusted price index is to introduce dummy variables for periods in a multiple regression framework (Court, 1939). Griliches's contribution to hedonics was largely to resurrect and to promote, with great vigor and effect, Court's formulation. And, of course, he used the technique very effectively in work on productivity growth and its sources.

The basic formulation in hedonic analysis is to obtain observations on the unit prices of varieties of a differentiated commodity, units of which embody varying amounts of different attributes or qualities -- be these clean air, greenness of stalk, or speed of multiplication. A regression, possibly nonlinear, is then used to estimate the so-called hedonic price function, the gradients of which are the implicit prices of the attributes, the ratios of which, in turn, are supposed to reflect consumers' marginal rates of substitution among attributes or producers' marginal rates of substitution or transformation, as the case may be. Unfortunately, just as in the case of ordinary demand analysis, using data on prices and quantities, there is an unresolved identification problem involved in trying to draw inferences about consumers' preferences or producers' production possibilities from such hedonic price functions. As Working (1927) pointed out long ago, price-quantity observations represent equilibria of demand and supply and only under special circumstances can regressions of price on quantity or of quantity on price be used to infer anything about the underlying supply and/or demand functions. The classic paper by Rosen (1974) shows that essentially the same identification problem exists for hedonic price functions (see the Appendix). Observations on variety prices and on quantities of attributes associated with each variety and the number of units sold are, in general, jointly determined by supply and demand. The demand for attributes in various combinations is determined by consumer preferences, but the supplies of these attributes depend on the costs of producing them in various combinations and on producers' access to markets for the scarce resources used in production. A large and statistically significant coefficient for a particular quality attribute in an estimated hedonic price function, for example, may reflect not consumers' high valuation of that attribute, but rather the difficulties that producers have in achieving that attribute per se or in combination with other attributes. In general, the coefficients in the estimated hedonic regression reflect both supply and demand considerations, both producers' costs and consumers' preferences. There is a further problem: in hedonic analysis it is generally assumed that only one variety of each commodity is available, whether or not that is actually the case; all information about the quantities exchanged, if it exists, is suppressed. If indeed true, and if availability is exogenously determined, then the traditional hedonic regression is justified, but not otherwise (see the Appendix). In my view, there is no excuse for discarding valuable information if you have it.¹⁷

problem inherent in the now common-place hedonic regressions of prices on quality attributes. See my Appendix to this essay. Griliches cites only Stone (1956); I assume he was unaware of Stone's even earlier work.

¹⁵ Even earlier by Brems (1951).

¹⁶ See, for example, Cropper and Oates (1992, pp 706 - 708).

¹⁷ I think this was the substance of the argument between Griliches and Dhrymes (1971). See also Gorman (1956) who emphasizes the importance of quantity information. Gorman's paper, although it enjoyed a wide circulation in *samizdat*, was not actually published until 1980.

Griliches's response to the fundamental identification problem raised by Rosen and others was remarkable for one so concerned with appropriate measurement as he was. He essentially agreed and then moved on in the manner of the Scottish preacher, who is reported to have said, "Ay lads, there's a grave difficulty; let us look it in the eye and pass on." He wrote (1988a, p. 120): "My own view is that what the hedonic approach tries to do is to estimate aspects of the budget constraint facing consumers, allowing thereby the estimation of 'missing' prices when quality changes. It is not in the business of estimating utility functions *per se*, though it can also be useful for these purposes. ... What is being estimated is actually the locus of intersections of the demand curves of different consumers with varying tastes and supply functions of different producers with possibly varying technologies of production. One is unlikely, therefore to be able to recover the underlying utility and cost functions from such data alone, except in very special circumstances. Nor can theoretical derivations at the individual level really provide substantive constraints on the estimation of such 'market' relations." And further (1986, p. 326): "...the hedonic hypothesis can be viewed as asserting the existence of a reduced form relationship [*sic*] between prices and the various characteristics of the commodity. That relationship need not be 'stable' over time, but changes that occur should have some rhyme and reason to them, otherwise one would suspect that the observed results are a fluke and cannot be used in the extrapolation necessary for the derivation of the missing prices...." We have learned from Haavelmo (1944) and Frisch (1934) the importance of structural estimation and inference as a basis for *understanding* behavior and policy formulation; such cannot be obtained from confluent relationships. Hedonic regressions are not even that when varying quantities of each variety are available. That being said, however, it may always be possible to make a case for hedonic regression of price on quantity and attributes, or of quantity on price and attributes, along the lines suggested by Working (1927). And the "bracketing theorem" might be usefully employed to set bounds on the implicit hedonic prices.¹⁸ This being said, however, it is doubtless true that Griliches and others would have got nowhere in the development and application of hedonic analysis had careful attention been paid to the formidable identification problem involved. Economic statistics, particularly with respect to price indices, would certainly have been poorer for it. In a disarming epigraph to their review of the identification problem for production functions, written with Jacques Mairesse (1998c), the authors quote Ragnar Frisch (1934, p. 274) on this point: "We have here one of those cases -- so frequent in economic practice -- where it can be 'proved' by abstract reasoning that a solution is not possible, but where life itself compels us nevertheless to find a way out." I can think of nothing more appropriate to say about Griliches's great work on hedonics.

Although hedonic analysis, for all its practical importance, was not central to Griliches's work, the idea that commodities are bundles of attributes is, and has important implications for the appropriate measurement of inputs and outputs in the analysis of changes in total factor productivity, for if the growth in quality adjusted inputs is misestimated and/or if the growth in quality adjusted output is likewise, total factor productivity growth will be biased. The need to adjust both inputs and outputs to measure them appropriately in this context was recognized very early by Griliches (1958b, esp. p. 599, 1960b, 1963c) and exploited very fully in his subsequent work, especially in his paper with Jorgenson (1967a) discussed in the next section. Indeed, it set his research agenda throughout his professional career.

4. Production functions, total factor productivity measurement, supply and derived demand

The basic framework for growth accounting, equivalently, measurement of total factor productivity, was laid out many years ago by Abramovitz (1950, 1956); Griliches elaborated and extended this basic framework in important ways beginning with his early paper on U. S. agriculture (1960d). He gives concise and clear accounts in his article for *The New Palgrave* (1987c) and the introduction to a collection of his early papers (1988a). In summarizing his approach, I can do no better than to quote two paragraphs from the latter (pp. 6 - 7):

¹⁸ This result is discussed by Greene (1993, pp. 290 - 291), following Goldberger (1984), under the heading of "reverse regression." It may be found much earlier in Schultz (1938, App. C) and is certainly implicit in Frisch (1934).

"It may be useful, at this point, to sketch out a more explicit statement of the productivity measurement problem. It provides a framework and a motivation for much of the research that was to come. A conventional measure of residual technical change (TFP) in an industry can be written as

$$\hat{t} = y - sk - (1-s)n$$

where y , k , and n are percentage rates of growth in output, capital, and labor respectively; s is the share of capital in total factor payments, and the relevant notion of capital corresponds to an aggregate of actual machine hours weighted by their respective base period (equilibrium) rentals. This procedure assumes that all the variables are measured correctly, that all the relevant variables are included, and that factor prices represent adequately the marginal productivity of the respective inputs. The last assumption is equivalent to the assumption of competitive equilibrium and constant returns to scale. To analyze t , the 'unexplained' part of output growth, it is useful first to think in terms of a more general underlying production function:

$$\begin{aligned} y^* - f &= \alpha(k^* - f) + \beta(n^* - f) + \gamma z + t \\ y &= y^* + u \end{aligned}$$

where the 'true' production function is defined in terms of correctly measured outputs and inputs (the starred magnitudes) and at the technologically more relevant plant or firm level. That is, f is the rate of growth of the number of plants (firms) in the industry and implicitly, the production function is defined at the average plant level; α and β are the true elasticities of output with respect to capital and labor, while γ is the elasticity of output with respect to the z 's, the inputs (or, rather, their rate of growth) which affect output but are not included in the standard accounting system. These could be services from the accumulated stock of past private research and development expenditures or services from the cumulated value of public (external) investments in research and extension in agriculture and other industries, or measurable disturbances such as weather or earthquakes. The measurement error in output is u . It differs from t in being more random and transitory while the forces behind t are thought to be more permanent and cumulative. The α , β , and γ coefficients need not be constants. If they are we have the Cobb-Douglas case. The whole framework can be complicated and generalized by adding square terms in rates of growth as approximations to a CES or translog type production function.

Defining two more shorthand terms: $s^* = \alpha/(\alpha + \beta) = \alpha/(1 - h)$ where s^* is the true relative share of capital, and $h = \alpha + \beta - 1$ is a measure of economies of scale with respect to the conventional inputs k and n ; the production function can be rewritten in terms of the 'true' residual measure of technical change t , as

$$t = (y - u - f) - (1 + h)[s^*k^* + (1 - s^*)n^* - f]$$

Subtracting this from the conventional measure of residual technical change \hat{t} , we get an expression for the total 'error' in our usual measures of total factor productivity growth:

$$\hat{t} - t = s(k^* - k) + (1 - s)(n^* - n) + (s^* - s)(k^* - n^*) \\ + h [s^*k^* + (1 - s^*)n^* - f] + g + u$$

The various terms in this formula can be interpreted as follows. The first term is the effect of the rate of growth in the measurement error of conventional capital measures on the estimated 'residual.' The second term reflects errors in the measurement and definition of labor input. The third term reflects errors in assessing the relative contribution of labor and capital to output growth. It would be zero if factor shares were in fact proportional to their respective production function elasticities or if all inputs were growing at the same rate (then the relative weights do not matter). The fourth term is the economies of scale term. It would be zero if there were no underlying economies of scale in production ($h = 0$) or if the rate growth in the number of new firms (plants) just equalled the growth in total (weighted) input. The fifth term (g) reflects the contribution of left-out inputs (private or public), while the sixth term (u) represents the various remaining errors in the measurement of output."

The last formula is revealing in terms of Griliches' research agenda and his progression in this agenda: Griliches' work on hybrid corn led him to consider two other major changes in U. S. agriculture, increasing use of chemical fertilizer (1958b) and mechanization (1960b), and, in turn, to a more general formulation of the total factor productivity problem (1960d). Along the way, he encountered difficulties in the measurement of fertilizer and machinery and other capital inputs. Since these measures are obtained by dividing expenditures by an index of prices, it is possible to interpret the "errors" in terms of mismeasurement of prices, and this, in turn, led straight to hedonics, discussed in section (3). Much of the work on patents and R & D discussed in section (2) is related to the fifth term. Proper measurement of capital input, k^* , requires not only attention to quality changes and prices but, in addition, to the determination of new investment, additions to the stock, and as to how such investments are translated into the relevant input variable (1960b, 1963a, 1966, 1968a, 1984g, and, more recently the computer "revolution," 1993b, 1994b, 1995b). Measurement of the "correct" labor input, n^* , requires attention to the quality of the labor force, or the stock of "human capital" embodied in it; and this, in turn, leads to the attempt to measure the effects of education on the productivity of labor (1969a, 1970, 1972, 1974, 1975a-b, 1976b-c, 1977a-b, 1978, 1979b, 1980d, 1981a-b, 1997c). These studies are all closely related to Griliches' work on the analysis of unobserved or latent variables; consequently I will deal with them in detail in the next section. Griliches dealt relatively little with the mismeasurement of output, u , *per se* in the context of total factor productivity (but see 1989a), and not at all, as far as I can discover, with cyclical effects on productivity, except insofar as these affect capital utilization (1967a).¹⁹ Finally the fourth term, returns to scale, or more generally increasing returns, is related to Griliches' attempts to estimate production functions in a variety of contexts in order to ascertain the significance and extent of such increasing returns (1957b, 1960c, 1963b-c, 1967a,c-d, 1968b, 1969a, 1971, 1990e, 1996f).²⁰ These papers are discussed below.

¹⁹ The adjustments to capital stock utilization Griliches and Jorgenson made in this connection were severely criticized at the time. But as I suggest above the conclusion of this paper, that the "residual" contribution to total factor productivity growth can be entirely explained away by such means, has been widely misinterpreted. Much of Griliches' work on hedonics, however, can be interpreted as an indirect attack on the problem of correct measurement of output, especially his recent work on computers and pharmaceuticals. This, in effect, provides a frame work for further investigation into the sources of growth and a deeper understanding of the process.

²⁰ Much of Griliches' work in which he attempts to adjust inputs for quality changes can, however, be interpreted as looking for the sources of increasing returns. In his remarkable paper, Allyn Young (1928) attributes economic growth to increasing returns quite generally. See Schultz (1993, esp. pp. 7 - 10). The late Frank Knight maintained (1944) that, under conditions of perfect competition, properly interpreted, *all* production technology must be characterized by constant returns (factors paid their marginal products must

Although both (1963b) and (1967a) explicitly recognize that measurement of total factor productivity and estimation of a production function are equivalent, most of Griliches's work on productivity measurement does not explicitly introduce such a function.²¹ This is also the case with his paper with Jorgenson (1967a, p.249), hereinafter G & J: "The purpose of this paper is to examine a hypothesis concerning the explanation of changes in total factor productivity. This hypothesis may be stated in two alternative and equivalent ways. In the terminology of the theory of production, if quantities of output and input are measured accurately, the growth in total output is largely explained by growth in total input. Associated with the theory of production is a system of social accounts for the real product of real factor input. The rate of growth of total factor productivity is the difference between the rate of growth of real product and the rate of growth of real factor input. Within the framework of social accounting the hypothesis is that if real product and real factor input are accurately accounted for, the observed growth in total factor productivity is negligible." G & J assume that the underlying production technology is constant returns to scale, that factors are paid their marginal products, and that the economy is in competitive equilibrium. They proceed by a series of adjustments to eliminate what they consider to be "errors" in the measurement of real output and real factor input, in order to compute average total factor productivity growth (TFP) for the period 1945 - 1965: (1) Output = U. S. private domestic product in constant prices; input = sum of labor and capital services in constant prices, labor and capital services assumed proportional to stocks; TFP = 1.60%. (2) Correction for aggregation errors by weighting labor and capital services in various categories by shares in total factor payments and output by weighting by shares of consumption and investment goods in total expenditures; TFP = 1.49%. (3) Correction of investment goods prices using output prices on both the output and input sides, correcting the implicit deflator for producers' durables to be the same as for consumers' durables, and correcting the implicit deflator for changes in business inventories; TFP = 1.41%. (4) Adjustment of labor and capital for relative utilization separately, assuming the relative utilization of capital in manufacturing and nonmanufacturing is the same and adjusting by relative utilization of electric motors,²² correction of data on manhours for variations in labor intensity, TFP = 0.96%. (5) Correct aggregation of capital services by the before tax prices of various categories of investment goods (land, residential and nonresidential structures, equipment and inventories), TFP% = 0.58%. (6) Correct aggregation of labor services, males only by relative earnings for categories broken down by years of schooling, TFP = 0.10%. There is thus remarkably little left over for the "residual," that is the unexplained growth in output per unit of total input -- too little. One suspects "overkill." Perhaps for this reason, much of the subsequent work of both Griliches and Jorgenson was devoted to refining these adjustments.

Beginning with his early paper (1957b), applying Theil's analysis of the effects of left-out variable in OLS regression to the problem of differential managerial ability in production function estimation, Griliches published a number of papers dealing explicitly with the estimation of agricultural, manufacturing or aggregate production functions, or the associated systems of derived demand and supply functions. In a somewhat neglected book (1971), Griliches and Ringstad estimate a number of production functions from data on a large number of individual manufacturing establishments from the 1963 Norwegian Census of Manufactures.²³ Their particular concern is to separate economies of plant size from market size. Since their pioneering study, more such studies using individual establishment data have been attempted by others. The fundamental identification problems of production function estimation from cross-section data discussed at great length by Marschak and Andrews (1944) is addressed in section 8.1, Chapter 4, pp. 93-97. Subsequent papers (1984b, 1990e, 1996f) raise the issue implicitly. The main contribution of (1971) was to demonstrate the feasibility of using census of manufactures data on individual establishments, an

exhaust total output). *Properly interpreted* is the key phrase here. Aghion and Howitt (1998, p. 36) regard modern endogenous growth theory as an attempt to formalize Young's ideas.

²¹ Although such an approach is possibly inefficient from an econometric point of view as compared with parametric specification of a production function, it is less open to specification error.

²² This particular finesse came in for exceptionally heavy criticism.

²³ Vidar Ringstad has described the origin in late 1965 of this collaboration in a personal communication. Ringstad was then working with Haavelmo, who when asked whether working with Griliches would be a good idea, replied, "It does not matter what you are doing as long as you do it properly!" This surely motivated Griliches throughout his work too.

approach Griliches was later to put to good use in his work on R & D using the Census-NSF matched sample (1982). However, in a paper written near the end of his life (1998c), Griliches returned to the problem of identification of production function parameters and confronted the simultaneity problems raised by Marschak and Andrews (1944) head on. In this paper, Griliches and Mairesse go through all of the proposed solutions to the problem of production function identification and conclude that although there is no one solution -- everything depends on context -- the best approach is via the analysis of micro firm data, an area in which Griliches pioneered, but with a careful attention to model specification and data quality. But, "Besides better and more data, we need also a richer theoretical framework to help us understand why firms are different, not only in their capital-labor ratios, but also in the product mix they produce, the quality of their workforce, the technologies they use, their organizational structures, the markets that they serve."

5. Unobserved or latent variables. The relation among earnings, education or schooling, and ability

As indicated in the previous section, Griliches's interest in the proper measurement of labor input led him to a series of studies relating earnings to schooling and, perforce, the unobservable variable, ability (1969a, 1970, 1972, 1974, 1975a-b, 1976b-c, 1977a-b, 1978, 1979b, 1980d, 1981a-b, 1997c). Of these, (1974, 1975b, 1977b) plus (1986d) contain the most methodologically important of Griliches's contributions. Although from the standpoint of Griliches's core contribution, this work may have been incidental, in that it was largely related to a desire to adjust the quality of the labor input over time, I regard it as fundamental to the development of panel data econometrics.²⁴ Disturbances in the structural equations are the best-known example of latent or unobserved or latent variables in econometrics: "An unobservable variable is one that is measured with error. Sometimes, the error is due to inaccurate measurement in the narrow sense. More broadly, it arises whenever measurable quantities differ from their theoretical counterparts." (Goldberger, 1974, p. 193.) Here is a typical example from Griliches and Mason (1972): Let y_{kij} be the k th indicator of success (earnings, occupational status, etc.) of an individual j belonging to a family i ; X_{kij} are some exogenous observed factors affecting the individual or the family into which he was born; S_{ij} is schooling received; A_{ij} is an unobserved variable reflecting "ability"; u_{kij} is the usual econometric disturbance reflecting ... (see Haavelmo, 1944), and is assumed to be independent of the disturbance for any other indicator of success and of X_{kij} , S_{ij} , and A_{ij} . A and X are also assumed to be independent. The relations we want to estimate are

$$y_{kij} = X_{kij} \mathbf{a}_k + S_{ij} \mathbf{b}_k + A_{ij} \mathbf{g}_k + u_{kij}$$

one for each k . The parameter of interest is β , the effect of schooling on earnings in particular, for the adjustment of labor input in the measurement of total factor productivity. The problem is, of course, that we don't observe A_{ij} . We can assume that it is highly correlated with schooling so that just leaving it out would bias the measured effects of schooling upwards. Assume

$$S_{ij} = Z_{ij} \mathbf{d} + A_{ij} \mathbf{q} + w_{ij},$$

where Z_{ij} are some exogenous variables, possibly among those included in X , and w_{ij} is a disturbance independent of u_{kij} . Although we cannot observe A_{ij} , we have what Goldberger refers to as multiple indicators of it, namely schooling *and* all the success measures, which however also depend on schooling. We might have other indicators of ability not depending also on the amount of schooling received, such as IQ test scores (1986e) or scores on the Armed Services Qualification test (1972). Such "multiple indicators" as Goldberger (1974) refers to them, help to identify the coefficients in the earnings schooling relationship despite the unobservability of the latent ability variable.²⁵

²⁴ I have dealt with the history of panel data econometrics and the important role Griliches and his students, such as Chamberlain and Mazodier, and collaborators, such as Mairesse, played in it at length elsewhere (Nerlove, 2000).

²⁵ Alternatively, multiple causes are also distinguished by Goldberger, 1974, pp. 200 - 204; e.g., the same unobservable, permanent income, affects various categories of expenditures. This too aids identification.

In subsequent papers published in the decade, Griliches (1974, 1977b) and Chamberlain and Griliches (1975b) further refined these methods relating them to the notion of individual-specific unobserved effects due to left-out variables. The contribution of Chamberlain and Griliches (1975b) is specifically to take into account the information afforded by more than one relationship involving the *same latent variable*, that is, to confront the problem of simultaneous-equations bias head on. They write (pp. 422-423): "The usual response to the availability of data with a group structure, e. g., families and family members, firms and time, is to estimate the relationships of interest from the within-group data. In the context of estimating income and schooling relationships such calculations would 'take care' of parental background differences, even though inefficiently (they ignore the between families information in the sample), but would not correct for possible bias from the individual (within family) genetic differences which may be correlated with achieved schooling levels later on. To take this explicitly into account would require the availability of direct measures of such ability, which were not available in the particular data set we were interested in analyzing. But even in their absence, if the missing variable (such as ability) affects more than one *dependent* variable, a bootstrap operation [not in the sense used today] may be possible. The basic idea for the new approach comes from the realization that such a left out variable must cause similar biases (proportional to each other) in different equations and that taking advantage of that fact may allow one to achieve identification of most of the coefficients of interest."

Because their model and analysis are so relevant to current discussions of panel data econometrics, I will summarize here the gist of the problem and model posed in Chamberlain and Griliches (1975b), hereinafter CG: Let X_1 and X_2 be a matrices of k_1 and k_2 indicators which may be all or in part the same, and which are taken to be exogenous, such as age. Any discrepancies among the simultaneous equations in the exogenous variables can be handled by zero restrictions, so we can formulate the problem in terms of a common X matrix. In general, truly exogenous variables are hard to come by and difficult to exclude from any particular equation, and this problem is no exception. Let y_1 be the dependent endogenous variable in which we are interested, such as earnings, occupation, test scores, etc. There may be several of interest simultaneously but for this discussion I will restrict the formulation to one plus one more, y_2 , such as schooling. Let a be an unobserved (latent) variable reflecting innate ability. Suppose that we have observations on $i = 1, \dots, I$ families and $j = 1, \dots, J_i$ individuals within each family, and suppose a_{ij} consists of two components: a family effect and all the rest. Thus

$$a_{ij} = f_i + g_{ij}, \quad i = 1, \dots, I, j = 1, \dots, J_i.$$

CG assume the following structure, where the subscripts i and j have been suppressed:

$$\begin{aligned} y_1 &= X\mathbf{a}_1 + \mathbf{b}y_2 + \mathbf{g}_1a + u_1 \\ y_2 &= X\mathbf{a}_2 + \mathbf{g}_2a + u_2 \end{aligned} .$$

Solving for y_1 and y_2 yields

$$\begin{aligned} y_1 &= X(\mathbf{a}_1 + \mathbf{b}\mathbf{a}_2) + w_1 \\ y_2 &= X\mathbf{a}_2 + w_2 \end{aligned} ,$$

where

$$\begin{aligned} w_1 &= (\mathbf{g}_1 + \mathbf{b}\mathbf{g}_2)(f + g) + u_1 + \mathbf{b}u_2 \quad \text{and} \\ w_2 &= \mathbf{g}_2(f + g) + u_2 \end{aligned} .$$

Stacking first with respect to equation, then with respect to family, and finally with respect to family member, the variance-covariance matrix of the w 's can be obtained. It has a more complicated structure than the usual error-components model. The assumption that u_1 and u_2 are uncorrelated is one which it might be difficult to justify, but under it and the assumption of no correlation between f and g and between

each and the u 's, CG are able to show that the parameters α_1 , α_2 , and β are identified (exactly so if there is only one exogenous variable), and that γ_1 and γ_2 are identified up to a multiplicative scale factor (reasonable since the units of a are arbitrary). In principle, then, one can form the likelihood for a set of observations on X , y_1 , and y_2 . Dynamics, such as we might expect in a model of firm behavior, will still further complicate the likelihood formulation, but the principles are clear. Griliches amplified these ideas in his Henry Schultz Memorial Lecture and in his Presidential Address to the Econometric Society (Griliches, 1974, 1977b). Structural models involving latent variables were common in the psychometric literature earlier; indeed CG (1975b) represents a return to the 1920's tradition of Sewell Wright in genetics and a major departure in the econometric literature (Goldberger, 1971, 1972, 1974; Goldberger and Duncan, 1973, especially the introductory chapter by Goldberger; Wright, 1921, is the seminal paper).

Griliches (1986d) contains many wise observations about the nature of economic data. While his substantive work on education or schooling and labor productivity (1969a, 1970, 1972, 1975a, 1976b, 1976c, 1977a, 1978, 1979b, 1980d, 1981a, 1981c, 1997c) is exceedingly important, particularly in respect to his contributions to our understanding of the source of economic growth, it was in this connection that he made his most important contribution to econometric methodology.

6. Miscellaneous econometric issues, particularly distributed lags

I will conclude this "guide to Griliches" by reviewing very briefly four papers on econometric methods proper dealing with aggregation and distributed lag estimation in the presence of serially correlated disturbances (1960e, 1961c, 1967e, 1969b). With the exception of (1967e), which is a broad survey, these papers build on the Theil apparatus for the analysis of omitted variables and aggregation errors (1954), which Griliches so successfully exploited in (1957b).

In (1960e), Griliches and Grunfeld give a rather neat demonstration that, for some purposes, e.g. forecasting, aggregation of microrelations may actually reduce forecast errors. Aggregate relationships may fit better than the underlying micro relationships on which they are based. This finding is similar to Friedman's (1962) subsequent demonstration that mechanical linear interpolation of time series may, under certain circumstances, lead to better results than more sophisticated interpolation by means of a related series -- it's obvious when you think about it, but not beforehand. (1961c) and (1969b) are rather straightforward demonstrations of the effects of serially correlated disturbances on the estimation of geometric lag distributions using the omitted variable apparatus. (1967e) surveys work on formulation and estimation of distributed lag models through the mid-1960s, with particular attention to generalizations of the geometric distributed lag model and to the problems of distinguishing between different lag schemes on the basis of typical economic data and the estimation problems associated with the estimation of autoregressive models with serial correlated disturbances (what we now refer to as regression with ARMA disturbances). Although this work was quite influential and widely cited at the time, it was already being superseded by the work of Hannan and Whittle.

7. The central core

The central core of Griliches's contribution to economic science consists of his contributions to our understanding of productivity growth in the context of general economic growth. His central insight was to see that "technical change," which Abramovitz (1956) and Solow (1957) pinpointed as the principal engine of growth, is not a purely exogenous phenomenon but rather largely the result of economic activity, the main purpose of which is to generate such change. T. W. Schultz (1953), who was Griliches's teacher at the University of Chicago, held that most of technical change in U. S. agriculture had been due to public investments in agricultural research, perhaps too extreme a view. That the rate and direction of technical change ought to be subject to the same rules as other purposeful economic activity was not particularly new or novel at the time Griliches began his pioneering work on the spread of hybrid corn in the United States, but there was little or no quantitative evidence. Beginning with his 1957 paper, Griliches systematically provided such evidence and measured its impact on growth.

Because technical change is typically measured by changes in total factor productivity, be it at the firm, industry, or economy-wide level, measurement of these factor inputs becomes crucial. But more significantly, changes in the quality of factors of production are much more than mere errors of measurement; they "embody" the sources of growth: new knowledge spreads through training and investment in new capital which "embodies" this knowledge. Changes in education and health and other forms of human capital affect the quality of the labor input and thus its productivity. Investment in R & D is "embodied" in new equipment or in new products or in new organizational forms. Again, Griliches systematically measured these effects, and by so doing identified the sources of economic growth. I regard Griliches as the founder of modern growth accounting.

We all await Griliches's definitive statement on growth and its sources with the posthumous publication of his Kuznets Lectures. I suspect that, as he usually did, Griliches will raise a great many unanswered questions. It is sad that those of us who remain to find the answers will no longer have his wise counsel and the benefit of his extraordinary intuition and insight.

8. Selective Bibliography²⁶

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10. Appendix: What Do Hedonic Price Regressions Mean?

Suppose a commodity consists of a bundle of n attributes Z_1, Z_2, \dots, Z_n represented by the vector Z the value of which *defines* a variety, the unit price of which is represented by $P(Z)$. Quantities of the variety with attributes Z exchanged in the market are $Q(Z)$.

Consumer Preferences:

$$(1) \quad P(Z) = \phi_Z[Q(Z), Z, Y], \text{ Y is a vector of consumer characteristics.}$$

Producer Supply:

$$(2) \quad P(Z) = v_Z[Q(Z), Z, W], \text{ W is a vector of producer characteristics.}$$

In general, both prices and quantities of each variety are determined in market equilibrium in a way which reflects both consumer preferences and the difficulties of producing commodities containing particular combinations of attributes.²⁷ The reduced form of (1) and (2) is

$$(3) \quad \begin{aligned} P(Z) &= F[Z, Y, W] \\ Q(Z) &= G[Z, Y, W]. \end{aligned}$$

The relation between prices and quality attributes, ignoring the quantities exchanged at those prices, is the result of a "confluent" relation reflecting both supply and demand considerations. (This is essentially the point made by Rosen, 1974.) It does not reflect either consumer preferences or producer costs alone.

When prices are exogenously given, (3) is irrelevant; consumer preferences are reflected in (1). If we assume a common relation between product characteristics, prices, and consumer characteristics, the subscript Z on ϕ in (1) may be suppressed. Solving for $Q(Z)$:

$$(4) \quad Q(Z) = R[P(Z), Z, Y].$$

Whence the implicit "prices" reflecting marginal rates of substitution among quality characteristics in consumer preferences may be obtained from an estimate of (3) by the implicit function theorem:

$$(5) \quad \partial P / \partial Z_i = - (\partial R / \partial Z_i) / (\partial R / \partial P).$$

When quantities are exogenously given, (3) is again irrelevant; the total derivatives of ϕ_Z with respect to Z represent the "hedonic" weights in the sense of the relative marginal utilities of consuming varieties with additional quantities of a particular characteristic. When there is only *one* unit of each variety, defined by a particular bundle of characteristics, the usual hedonic regression of unit price on the quality attributes of the variety is justified.

²⁷ References for this Appendix are to Other References Cited above. It is interesting to note that in a very early paper on the "bundles of attributes" theory of consumer demand, Gorman (1956) stressed the importance of quantity information.