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Zvi Griliches

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Technology, Education, and Productivity

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PREFACE

We are pleased to publish *Technology, Education, and Productivity* as the eighteenth in our series of Occasional Papers, which feature reflections on broad policy issues by noted scholars and policy makers.

In this paper, Zvi Griliches presents an overview of his early research on how technological change affects long-term economic growth. The analysis focuses on his belief that such change can and should be analyzed and measured rather than be considered an exogenous variable. Within this framework, he examines the importance of education, investment in research, and economies of scale as sources of long-term productivity growth.

In economic growth measurement, aggregation is extremely useful to substantiate economic models that help us understand the growth process. But we know that aggregated macrovariables are the result, not the origin, of a complex process of economic activity which starts with, and is carried on by, millions of individuals and corporations at the micro level. Furthermore, the policies that influence the level of investment and production only have effect through their impact on the behavior of economic agents interacting in the economic marketplace. The aggregation of those individual productive activities by sectors and regions of an economy into national accounts poses formidable conceptual and measurement problems. The proper accounting of the inputs of production, and the variety of qualitative and quantitative factors that make them up and lead to their accumulation, matters to the understanding of the growth process and to the identification of the policies, institutions, and organizations that influence it. It is the behavior of economic agents through their own initiatives guided by policy and an institutional framework that determine the resulting aggregates of economic activity.

When neoclassical economic growth models began to account for growth on the basis of standard aggregate measurements of capital and labor in the 1950s, a large unexplained "residual" became a theoretical and methodological puzzle with significant practical implications for economic policy. Growth could not be viewed only as accumulation of capital and labor in different sectors of the economy but it must also be related to the "productivity" of those inputs, which is a function of a variety of quality and organizational components added to and hidden in an "unexplained" residual.

Classical economics had taught us that production of goods and services was a result of combining key inputs such as capital, labor, and nonrenewable natural resources. The definition of capital as a *stock* of wealth which can be created through investment and which yields a stream (flow) of goods and services on the production side of the economy, equivalent to the income received by owners of factors of production and used by them in the consumption side of the economy, led us to recognize that "capital" is quite heterogeneous. There is physical and human capital. Furthermore, most so-called "nonrenewable" resources are "renewable" through investment and substitutes produced by technology. Such is "land," when a desert can be made more productive than "naturally fertile" land through the addition of water, fertilizers, and some organic matters. Different quantities of capital in human beings are created through proper health and nutrition as well as through education and knowledge accumulation. There is an infinite variety of physical capital created over the centuries by the ingenuity of human beings (knowledge and technology) to produce an ever increasing diversity of goods and services used to improve human welfare. There is also unappropriated capital in the accumulated knowledge, "the state of the arts," which is available to all in a variety of ways.

The economics of many of those aspects of production is better understood now than it was thirty-five years ago thanks in large measure to Professor Griliches's work. His scientific contribution to this field of knowledge earned him early on the John B. Clark award in economics. He was also a recent president of the American Economic Association, and is currently Paul M. Warburg Professor of Economics at Harvard University and director of the Productivity Program at the National Bureau of Economic Research in Cambridge, Massachusetts.

We believe Professor Griliches's paper will make a valuable contribution to the understanding of long-term economic growth and its primary components. It will be of interest to academics and policy makers everywhere concerned with understanding determinants of long-term growth and the policies necessary to achieve it.

Nicolás Ardito-Barletta
General Director
International Center for Economic Growth

Panama City, Panama
July 1994

ABOUT THE AUTHOR

Professor Griliches was born on September 12, 1930, in Kausnas, Lithuania. He studied at the Hebrew University in 1950–51; at the University of California—Berkeley, receiving a B.S. with highest honors in 1953 and an M.S. in 1954, both in agricultural economics; and at the University of Chicago, where he received a M.A. in 1955 and a Ph.D. in 1957, both in economics. He taught at the University of Chicago as assistant professor from 1956–1959, associate professor from 1959–1964, and professor from 1964–1969. Since 1969 he has been a member of the Department of Economics at Harvard. He served as chairman of the department from 1980 through 1983.

Professor Griliches' first major award was given to him in 1957 by the American Farm Economic Association for his dissertation on "Hybrid Corn: An Exploration in the Economics of Technological Change." He was elected a fellow of the Econometric Society in 1964; received the John Bates Clark Medal from the American Economic Association in 1965; and was elected to the American Academy of Arts and Sciences and to fellowship in the American Statistical Association also in 1965. He was elected a fellow of the American Association for the Advance of Science in 1966 and to the National Academy of Sciences in 1975. He was president of the Econometric Society in 1975, and president of the American Economic Association in 1993. He received the W.S. Woytinsky Award from the University of Michigan in 1989; and was awarded an honorary degree from The Hebrew University and elected a distinguished fellow of the American Agricultural Economic Association in 1991.

ZVI GRILICHES

Technology, Education, and Productivity

This essay summarizes the findings of my more important and interesting early papers.* They all reflect my continued interest in technological change as the main source of long-run economic growth and my attempt to understand it, to comprehend what happened and why, through the collection and analysis of relevant economic data. The questions I asked about the determinants of the diffusion of new technology, the measurement of physical capital, the role of education in economic growth, and the contribution of research and development were all to be components in an ultimately richer understanding of the sources and processes of economic growth. The style of this work, however, is less general. It tends to focus on the particular and to take measurement and measurement issues seriously. Detail matters. It reflects my belief that one cannot get much insight from aggregate facts unless one appreciates their components, how they are constructed, and how they interact.

A unifying thread that runs through my work is the view that technological change is itself an economic phenomenon and hence also an appropriate topic for economic analysis. Too many economic studies tend to take it as exogenous, as a manna from heaven which descends on us at a constant (or sometimes changing) rate. Early on I tried to argue

*Adapted from the Introduction to *Technology, Education, and Productivity*, Zvi Griliches (Basil Blackwell, 1988), 1–24, by permission of the author.

that this is not necessarily so, that 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 quantitative work, however, takes much effort, is heavily data-dependent, and is rarely definitive. At its best it opens up new subjects but rarely provides closure. It shows, by example, what can be done and what might be interesting to do more of, and often the question is as interesting as the possible answers.

The essay is divided in two parts: The first summarizes some of the most relevant issues related to productivity, technology, and education as determinants of long-term economic growth, their role in the behavior of economic activity, and their response to market signals. The second elaborates on my approach to research on the diffusion of technology, the measurement of productivity change, the contribution of education, the economics of research and development activities to technological change, and, finally, the contribution of all these elements to the accounting for economic growth.

Productivity change has been the major source of per capita income growth in this century. While productivity is usually measured at the aggregate country or industry level, in fact it happens at the individual enterprise and worker level. It is here where policy can have and has had an impact through its effects on individual decisions on how and where to invest and on how much effort to expend on productive activities as against alternative uses of time, including tax avoidance, governmental persuasion, and outright bribery. The measurement of productivity growth at the aggregate levels is full of problems, both in the way aggregate output may be measured and in the proper accounting for the changing quantities and qualities of the various economic inputs into the production processes. The measurement of the same variables at the micro level is even harder, both because of data difficulties and lacunae, and because the results of individual behavior are mediated by the institutional environments in which they find themselves. Our current quantitative tools do not, however, measure and analyze such environments effectively. Nevertheless, it is at the micro level where most of the changes are occurring and that is where we have to look to gain a better understanding of the determinants of economic growth.

When economists first started to analyze aggregate economic growth and "account" for its various sources in the 1950s, they stumbled onto a very large unexplained "residual." Standard measures of labor and capital growth could account only for a fraction of measured growth, leaving us with a major theoretical and empirical puzzle. The immediate problem was "solved" by relabeling this residual as "technical change" and turning the problem around from the accounting of growth to the measurement of this concept. But measurement is only a first step toward explanation and it was well understood (almost from the beginning) that this residual must be a combination of improvements in the various qualities of the inputs as well as in the methods of combining them in production. Moreover, organizational and institutional forces all play a role both in the development of such qualities and their spread across different enterprises and industries. The view that eventually prevailed sees measured "productivity" as the ultimate product of various unmeasured aspects of physical, human, and social capital, and considers the determinants of investments in such capitals as the most important ultimate sources of economic growth.

The classical view was that production of goods and services results from a combination of capital and labor inputs and possibly from those of nonrenewable natural resources. An important advance was the recognition of human capital as a parallel concept to physical capital. Different qualities of human effort are created by education, training, proper nutrition and health practices, and effective family and community environments. All these, as well as the more explicit contributions of science and other forms of knowledge accumulation, are the result of direct and indirect investment of resources by individuals, families, and various social organizations, and are affected by economic incentives and the prevailing economic climate for them. Together they create both a "qualified" labor force and the associated "state of the arts," the levels of technology used in the production of goods and services in the particular economy.

More recently, we have also started to think about "knowledge capital" as a separate concept, underlying the notion of the "state of the art" or the levels of technology. One can think of knowledge capital as a subset of the more general idea of human capital, but it is useful to distinguish between concepts of labor "quality," produced by education and training, which are largely embodied in individuals and can only be delivered directly by them, and more general "disembodied" aspects of knowledge and information. The latter have the peculiar property of being nonrival. That is, the use by others does not diminish their availability. Since such knowledge is not embodied directly in goods or people but in designs, ideas, and formulae, this creates serious problems of appropriability and difficulties in providing adequate incentives for its production. Moreover, the presence of such "capital" is a major source of increasing returns, which in turn lead to both growth in productivity and difficulties with conventional pricing systems.

The economic aspects of the contribution of knowledge and knowledge capital to production are better understood today than was the case forty years ago when I began my work in this area, but much still remains to be learned. Our measurement tools for both the measurement of "technology" and "knowledge capital" remain rudimentary. The two are not the same, because the first defines the current state of (average) practices, while the second incorporates ideas about the current "potential," the production possibilities frontier. The first is imbedded in current machines, equipment, human beings, and institutions. The second may exist only in blueprint form or in isolated experimental implementations. The shift of the average to the potential has been studied under the label of the "diffusion of technology" and was the first topic that I turned my attention to in my own research career. Ultimately, however, continuous growth comes from the growth in the potential, the stock of economically valuable knowledge. The latter is the result of the interaction of current investments in science, engineering, and other more informal ways of trying to comprehend and improve the world, with the large amount of previously accumulated bits and pieces of heterogeneous knowledge and the unknown state of the physical world around us. We know only very little about how to affect this process and make it more efficient. But it is most important that we learn more about it. The future of our children depends on it.

Most of my professional work has been devoted to trying to understand these issues better. I have pursued issues in the measurement of output and inputs as a precondition for understanding the relationship between them, and I have also studied directly the various determinants of technological change such as research and development (R&D) and the diffusion of new technologies. My early research focused on the latter topic, looking at several examples of the then new agricultural technologies such as hybrid seeds, fertilizers, and tractors and other farm machinery. It showed that the level and rate of adoption of new agricultural technologies responded to economic incentives, that variations in adoption could be explained by variables that represented the profitability of such adoptions. Entrepreneurs were behaving largely in a rational fashion, adopting new techniques faster where their profitability was higher. Similarily, declines in the relative price of new techniques would stimulate their "learning" processes and speed up the rate of adoption.

A major issue, opened up by this work, was the level of social and private benefits arising from such new technologies. I found that the level of social returns to public and private investments in research into agricultural technology was quite high. In the early stages, new adopters were able to increase their returns as the result of lower production costs (higher productivity) from their use of these new inputs. In a competitive industry, such as agriculture, these benefits are eventually transferred to consumers through lower product prices, as a result of the expanded output. Eventually, private returns from such innovations are reduced to "normal" levels and this eliminates the incentives to expand output, unless and until a new technology appears on the scene. The private returns are not really dissipated. They are, rather, transferred to consumers in the form of consumer surplus, and constitute the major component of social returns to such investments. Understanding this issue is a prerequisite for the making of reasonable decisions whether particular R&D projects should be financed publicly or privately, or in some combination of such investments. The criterion for public financing is the social return on such a project, while privately financed R&D will be only pursued to the extent that the developer of the new ideas or hardware can capture (for a time) some non-negligable fraction of the benefits that will arise from the ensuing increases in productivity and cover their development costs.

Much of my subsequent work pursued measurement and estimation issues, especially as they relate to the measurement of the changing quality of capital and labor input and the parameters of the production relationships between them. The basic idea was to reduce the unexplained residual in the growth of output by better measurement, the introduction of additional relevant variables, and by expanding the estimation framework to allow also for increasing returns to scale and spillovers from local and general public investments in agricultural R&D. As far as conventional investments in physical capital are concerned, I found that capital inputs tend to be overdeflated and overdepreciated. Furthermore, items with different expected lives were being added up wrongly, in terms of their respective purchase values rather than their implicit service or rental prices, and that little allowance was being made for the changing utilization of such capital equipment. The development and application of better deflators and capital quality measures allowed capital to play a larger role in explaining output growth, thereby reducing the unexplained residual. Similar results followed from a parallel application of these ideas to the measurement of the quality of labor, using data on the changing educational levels of the labor force.

Education is an important direct contributor to the growth in labor quality and productivity. The returns to this investment are themselves affected by the state of the economy and its rate of growth. In times of rapid technological change better-educated enterpreneurs have the advantage of comprehending the ongoing changes faster and adopting the new technology quicker. This leads to an interaction between the rate of technical change and the levels of human capital. A similar interaction with investment in physical capital was analyzed under the label of "capital-skill complementarity," showing that more educated labor has been more of a complement to, rather than a substitute for, various new advanced forms of machinery and equipment. It is reasonably clear that education has been a major contributor to the improvement in that average standard of living, both in the U.S. and elsewhere. But the claim that education will reduce inequality may be exaggerated. Large public investments in education, and especially in its higher branches, may not be as progressively targeted as advertised. Often the primary beneficiaries of such subsidies are the children of the middle- and upper-classes. Nevertheless, education does increase social mobility, and additional schooling can be used to remove social class handicaps and to compensate for other systematic sources of inequality.

While rapid technological change increases the value of education that makes one more competent in coping with such processes, investments in education and knowledge creation also carry their own seed of destruction. Some of the previously acquired skills and knowledge become obsolete as new ideas arise to supplant them. Moreover, technological developments in communication and the ease of reproduction have reduced the cost of transmission of knowledge and made its appropriation even harder, thereby reducing its scarcity value.

In spite of all the pitfalls and the many remaining unanswered questions about productivity growth and its measurement, the results of the research efforts pursued by myself and others during the last forty years have left me with the clear conviction that education, public and private investment in science and research, and economies of scale (both at the level of the firm and the level of the market), are the most important sources of productivity growth in the long run.

One should take these findings into account when development policy choices are to be made. One has to bear in mind the importance of physical and human capital accumulation for growth and human welfare and the role of education, science, and technology in improving the productivity of such investments. Where social returns are high due to spillovers, lack of appropriability, and other externalities, a variety of public support mechanisms may be necessary. To encourage private activity in these areas requires flexible price mechanisms, effective information systems, and most importantly, a stable legal and political structure and a clear system of property rights, including intellectual property rights. Entrepreneurs and workers must be able to enter into longer-term explicit and implicit contracts, contracts that will allow them to make the necessary investments and give, thereby, hostage to fortune.

Lessons from Research on Technology, Education, and Productivity

My work in this area started with a paper on the diffusion of hybrid corn, based on my Ph.D. thesis, and continued with a series of papers on the measurement of productivity and its various components, which outlined, essentially, my research program for the years to come. While trying to understand and improve the measurement of productivity I ran into a number of issues, each with its own significant research agenda: the treatment of product quality change in the construction of price indexes, for which I revived the "hedonic regression" solution; the problem of measuring capital and its accumulation and depreciation correctly; and the problem of measuring the contribution of education, which led me perilously close to the nature–nurture debate. I also investigated the impact of public and private investments in research on the rate of technological advance, a topic which has been at the center of my research activities during the past decade.

The discussion of the research that follows is incomplete in two important aspects. First, it excludes my somewhat more technical econometric methodology papers—papers dealing with specification bias, aggregation, distributed lags, errors-in-variables, panel data, and related topics. Second, it does not cover any of my more recent work. The latest paper discussed explicitly was written in 1971. This is due, in part, to space limitations, to the yet incomplete nature of some of my current work, and to my desire to use some of this material in a more focused specific volume on patents and R&D, which I plan to write in the not too distant future. Nevertheless, I do believe that the essays discussed here provide a good introduction to the range of my interests and the style of my work. In this paper I hope to compensate for the lack of immediacy by discussing where I think the subject has moved to since, pointing out the relevant newer literature and describing some of my later work on these topics.

Diffusion of Technology Amenable to Economic Analysis

The goal of my first paper on this range of topics, "Hybrid Corn: An Exploration in the Economics of Technological Change," was to show that the process of diffusion of an important technological innovation was amenable to economic analysis. It was rather common, in formal economic analysis of the time, to put such events outside the scope of normal "equilibrium" theory. Technological change was, and often still is, treated as an exogenous event, something to be taken as given from outside the economic system which needs to be explained by it. This paper indicates that such a dichotomy was not necessary.

The paper interprets the innovation process, that is, the supply of new technology in the form of specific hybrids adaptable to particular areas, and also the diffusion of technology, the speed with which it was being adopted, as both being under the influence of economic variables. It shows how observed differences in the timing of such processes across states and regions can be rationalized by measurable differences in economic incentives. Using the logistic growth curve to summarize the spread of hybrid corn in the various regions of the United States, it focused on the estimates of its three main parameters (origin, slope, and ceiling) in these regions as different aspects of the diffusion process to be explained by other economic variables.

A number of issues raised or implied in this paper have reverberated through the subsequent literature: Is the logistic the ''right'' functional form for the study of diffusion processes? Do most new technologies diffuse in a similar pattern? What is the appropriate model to use in describing and observing diffusion processes? How important are considerations of information diffusion and uncertainty about the qualities of the technology as compared to considerations of size, access to funds, and personal characteristics of the actors in these events?

When I chose the logistic form to analyze diffusion behavior I did it both because the data in front of me looked as if the logistic would fit quite well and because one could give a reasonable theoretic interpretation to it, either as an information-spread phenomenon based on mathematical epidemic models, or as a learning under uncertainty process based on sequential sampling or Bayesian considerations. But I did not claim then, and in fact I do not believe it to be the case now, that the logistic function represents some underlying invariant ''law'' of diffusion behavior. That is why I have been somewhat nonplussed by the various efforts to derive ''the'' model of diffusion or to argue at length about particular modifications of the functional form, adding more parameters or changing to another growth curve family, such as the Gompertz. If I were to return to this topic today I would take a more ''dynamic'' point of view and respecify the model so that the ceiling is itself a function of economic variables that change over time. I tried something like that in Appendix B of my thesis, but the state of econometric technology at that time prevented me from pursuing it very far.

Diffusion research emphasizes the role of time (and information) in the transition from one technology of production or consumption to another. If all variables describing individuals and affecting them were observable, one might do without the notion of diffusion and discuss everything within an equilibrium framework. Since much of the interesting data are unobservable, time is brought in to proxy for a number of distinct forces: (1) the decline over time in the real cost of the new technology due to decreasing costs as the result of learning by doing and to cumulative improvements in the technology itself; (2) the fall in price charged for the new technology due to rising competitive pressures faced by its original developers and the growth in the overall market for it; (3) the dying-off of old durable equipment, slowly making room for the new; and, (4) the spread of information about the actual operating characteristics of the technology and the growth in the available evidence as to its workability and profitability. In the work on hybrid corn I focused on the fourth "disequilibrium" interpretation, and emphasized the importance of differences in profitability both as a stimulus toward closing the disequilibrium gap and as the determinant of the time it takes to become aware of its existence. ("Disequilibrium" here means that additional change, diffusion, will happen even if prices and incomes do not change further, driven by changes in the information available to individual decision makers.) Alternatively (see, e.g., David 1969),* one can focus on reasons (1) or (3), in which case the existing size distribution of firms or the existing age distribution of the equipment to be replaced becomes one of the major determinants of the rate of "diffusion" and explanation of how and why "ceilings" shift over time. The relative importance of these forces varies from technology to technology, and the optimal mode of analysis is likely to be quite sensitive to that and to the kinds of data available to the analyst. In any case, all such approaches lay stress on the economic determinants of diffusion although they differ in the emphasis that they put on them.

In my original paper I emphasized differences in "profitability" as the major determinant of the rate of diffusion, and claimed in a final footnote that all other possible determinants such as various personal

*References to the subsequent literature mentioned in this essay are to be found at the end of this paper in the "References" section.