Bulletin Number 96-4 **December 1996**

ECONOMIC DEVELOPMENT CENTER

SOURCES OF TECHNICAL CHANGE: INDUCED INNOVATION, EVOLUTIONARY THEORY AND PATH DEPENDENCE

VERNON W. RUTTAN

ECONOMIC DEVELOPMENT CENTER
Department of Economics, Minneapolis
Department of Applied Economics, St. Paul

UNIVERSITY OF MINNESOTA

SOURCES OF TECHNICAL CHANGE
INDUCED INNOVATION, EVOLUTIONARY THEORY AND PATH DEPENDENCE

VERNON RUTTAN

ABSTRACT

The 1960s through the 1980s were very productive of new theory and empirical insight into the sources of technical change. In this paper I argue that each of the three approaches that have been advanced – induced technical change, evolutionary theory and path dependence – is approaching a dead end. The induced technical change process is driven b change in the economic environment in which the firm (or public research agency) finds itself. But its internal mechanism, the learning and search process, remain inside a black box. The evolutionary model builds on the behavioral theory of the firm in an attempt to provide a more realistic description of the internal workings of the black box. The strength of the path dependence interpretation lies in the importance it places on the sequence of specific micro-level historical events. But it holds only for network technologies characterized by increasing returns to scale – and only until the increasing returns have been exhausted. The three approaches should be regarded as components of a more general theory of the sources of technical change. In the later section of the paper steps that might be taken toward the development of a more general theory of the sources of technical change are suggested.

J.E.L. Classification: O31

The author is Regents Professor in the Department of Applied Economics and the Department of Economics and Adjunct Professor in the Hubert H. Humphrey Institute of Public Affairs, University of Minnesota.

VWR WORKING COPY
EVOLTHEORY MANUSCRIPT
DRAFT: NOVEMBER 18, 1996

SOURCES OF TECHNICAL CHANGE: INDUCED INNOVATION, EVOLUTIONARY THEORY AND PATH DEPENDENCE*

VERNON W. RUTTAN**

This is an appropriate time to take stock, as economists, of our understanding of the determinants of the rate and direction of technical change. The 1960s through the 1980s were very productive of new theory and empirical insight into the process of technical change. In the 1960s and 1970s major attention focused on the implications of changes in demand and in relative factor prices. In the late 1970s and early 1980s attention shifted to evolutionary models inspired by a revival of interest in Schumpeter's insight into the sources of economic development. Since the early 1980s these have been complemented by the development of historically grounded "path dependent" models of technical change.

Each of these models has contributed substantial insight into the generation and choice of new technology. It appears to me, however, that each research agenda is approaching a dead-end. In this paper I argue that the three models--induced, evolutionary and path dependent--represent elements of a more general theory. The purpose of this paper is to review the development of the three models to identify their complementarity and to suggest how they might be incorporated into a more general theory.

***** The author is indebted to Esben Sloth-Anderson, W. Brian Arthur, Erhard Bruderer, Jason E. Christian, Jerry Donato, Giovanni Dosi, Laura McCann, Richard Nelson, Nathan Rosenberg, Tugrul Temel, Michael A. Trueblood, Andrew Van de Ven, and Sidney Winter for comments on an earlier draft of this paper. Earlier versions of this paper have been presented in seminars at the International Institute of Applied Systems Analysis (IIASA), at the University of Minnesota Economic Development Center and at the Hong Kong University of Science and Technology. The research on which the paper is based was supported, in part, by a grant from the Alfred P. Sloan Foundation. Some of the material in this paper has appeared in Ruttan (1996a). An introduction to the issues discussed in the paper will appear in an Economic Journal "controversy" (Ruttan, 1997).

****** Vernon W. Ruttan is Regents Professor in the Department of Applied Economics and in the Department of Economics, and Adjunct Professor in the Hubert H. Humphrey Institute of Public Affairs at the University of Minnesota.

INDUCED TECHNICAL CHANGE

There are at least three major traditions of research that have attempted to confront the impact of change in the economic environment on the rate and direction of technical change. The "demand pull" tradition has emphasized the relative importance of market demand on the supply of knowledge in inducing advances in technology. There has also been a longstanding debate among economic historians about the extent to which differences in English and American technology during the 19th Century were influenced by relative factor endowments and prices. A third tradition stems from attempts by economic theorists to understand the apparent stability in factor shares in the American economy during the 20th Century in spite of the very large substitution of capital for labor. At a more micro level there is a large literature in the fields of agricultural and resource economics on the role of differences and changes in relative factor endowments on the direction of technical change.

Demand Pull and the Rate of Technical Change

Schumpeter, whose writings have been exceptionally important in influencing the way economists think about technical change, made a sharp distinction between invention (and the inventor) and innovation (and the innovator):

> "Innovation is possible without anything we should identify as invention, and invention does not necessarily induce innovation but produces itself . . . no economically relevant effect at all" (Schumpeter, 1934, Vol. I:84).

The Chicago sociologist, Gilfillan, viewed invention as proceeding under the stress of necessity with the individual innovator being an instrument of luck and process (Gilfillan, 1935).

In his now classic study of the invention and diffusion of hybrid maize, Zvi Griliches demonstrated the role of demand in determining the timing and location of invention (Griliches, 1957). Jacob Schmookler in a massive study of patent statistics for inventions in four industries (railroads, agricultural machinery, paper, petroleum), concluded that demand was more important in stimulating inventive activity than advances in the state of knowledge (Schmookler, 1962; 1966). The Griliches-Schmookler demand induced model received further support from papers by Lucas (1967) and Ben-Zion and Ruttan (1975, 1978) that showed technical change to be responsive to aggregate demand. In the mid-1960s, Raymond Vernon (1966, 1979) introduced a demand pull model to interpret the initial invention and diffusion of consumer durable technologies--such as automobiles, television, refrigerators and washing machines--in the United States rather than in other developed countries. His interpretation came just as the United States was about to lose its dominance in several of these technologies to Japan.

Arguments about the priority of the role of demand side forces and supply side forces, such as advances in knowledge, in inducing advances in technology were intensified in the late 1960s. A study conducted by the Office of the Director of Defense Research and Engineering purported to show that the significant "research events" contributing to the development of 20 major weapons systems were predominantly motivated by military need rather than disinterested scientific inquiry. This view was challenged in studies commissioned by the National Science Foundation that, not unexpectedly, found that science events were of much greater importance as a source of technical change (Thirtle & Ruttan, 1987, pp. 6-11).

In a review of the "demand pull-supply push" controversy, Mowery and Rosenberg argued that much of the research purporting to show that technical change has been demand induced is seriously flawed (Mowery and Rosenberg, 1979). They insist that the concept of demand employed in many of the studies has been so broad or imprecise as to embrace virtually all possible determinants. Rosenberg also insists that the demand pull perspective has ignored "the whole thrust of modern science and the manner in which the growth of specialized knowledge has shaped and enlarged man's technological capacities." (Rosenberg, 1974). Research conducted from a demand pull perspective appears to have atrophied since the late 1970s, partly as a result of the Rosenberg criticism.

Careful industry studies such as the study of innovation in the chemical industry by Vivien Walsh suggest that both "supply and demand factors play an important role in innovation and in the life cycles of industries, but the relationship between the two varies with time and the maturity of the industrial sector concerned" (Walsh, 1984, p. 233). A rigorous econometrics study by Scherer (1982) that simultaneously tests both the demand induced and supply push hypotheses across a broad range of industries confirms the earlier Schmookler finding of strong association between capital goods investment and invention. But, Scherer found a weaker association between demand pull and industrial materials inventions. He also found that the introduction of an index of technological opportunity based on the richness of an industry's knowledge base added significantly to the power of his model to explain differences in the level of inventive activity among industries.

It should no longer be necessary to insist that basic research is the cornucopia from which all inventive activity must flow to conclude that investment in the generation of scientific and technical knowledge can open up new possibilities for technical change. Nor should it be necessary to demonstrate that advances in knowledge, inventive activity and technical change flow automatically from changes in demand to conclude that changes in demand represent a powerful inducement for the allocation of research resources.

Factor Endowments and the Direction of Technical Change

Modern interest in the effect of factor endowments on the direction of technical change dates to the early 1960s. Hicks had earlier suggested:

> "The real reason for the predominance of labor saving inventions is surely that which was hinted at in our discussion of substitution. A change in the relative prices of the factors of production is itself a spur to innovation and to inventions of a particular kind--directed at economizing the use of a factor which has become relatively expensive" (Hicks, 1932, pp. 124-25).

Hicks suggestion received implicit assent but little attention until the early 1960s. In his work on the theory of wages, Rothschild repeated the Hicks' argument (Rothschild, 1956, pp. 118, 176). In a book on economic growth, Fellner argued that firms with some degree of monopsony power had an incentive to make "improvements" that economized on the progressively more expensive factors of production and that expectations of future changes in relative factor prices would be sufficient to induce even firms operating in a purely competitive environment to seek improvements that would save the more expensive factors (Fellner, 1956, pp. 220-22; see also Fellner 1961, 1962).

An intense dialogue around the issue of induced innovation by economic theorists in the 1960s and early 1970s was triggered by Salters' explicit criticism of the Hicks' induced technical change hypothesis. Salter insisted "at competitive equilibrium each factor is being paid its marginal value product; therefore all factors are equally expensive to firms" (Salter, 1960, p. 16). He went on to argue that "the entrepreneur is interested in reducing costs in total, not particular costs or capital costs. When labor costs rise any advance that reduces total cost is welcome, and whether this is achieved by saving labor or saving capital is irrelevant" (Salter, 1960, 43-44; See also Blaug, 1963). It is difficult to understand why Salters' criticism attracted so much attention except that students of economic growth were increasingly puzzled about why, in the presence of substantial capital deepening in the U.S. economy, factor shares to labor and capital had appeared to remain relatively stable. The differential growth rates of labor and capital in the U.S. economy were regarded as too large to be explained by simple substitution along a neoclassical production function.

<u>The growth theoretic model</u>. The debates about induced technical change centered on two alternative models--one a growth theoretic approach and the second a micro-economic version. The most formally developed version was the growth theoretic approach introduced by Kennedy (1964). The Kennedy article initiated an extended debate on the theoretical foundations and the implications of incorporating the process of induced technical change into the theory of economic growth (Samuelson, 1965; Kennedy, 1966; Samuelson, 1966; Drandakis and Phelps, 1966, Wan, 1971).

In the Kennedy model the initial conditions included: (a) given factor prices, (b) an exogenously given budget for research and development, and (c) a fundamental trade-off (a transformation function) between the rate of reduction in labor requirements and the reduction of capital requirements. The model assumes a production function with factor augmenting technical change. Kennedy cast his analysis in terms of the effect of changes in relative factor shares rather than changes in relative factor prices on bias in invention because of the growth theory implications.

The following example from Binswanger represents an intuitive interpretation of the Kennedy model. "Suppose it is equally expensive to develop either a new technology that will reduce labor requirements by 10 percent or one that will reduce capital requirements by 10 percent. If the capital share is equal to the labor share, entrepreneurs will be indifferent between the two courses of action. . . . The outcomes of both choices will be neutral technical change. If, however, the labor share is 60 percent, all entrepreneurs will choose the labor reducing version. If the elasticity of substitution is less than one, this will go on until the labor and capital shares again become equal, provided the induced bias in technical change does not alter the (fundamental) trade-off relationship between technical changes that reduce labor requirements on the one hand, or capital requirements on the other" (Binswanger, 1973; 1978, p. 32).

The Kennedy variant of induced innovation was subsequently incorporated into neoclassical growth theory (Wan, 1971). Nordhaus notes, "Until recently, only Harrod-neutral (or purely labor augmenting) technological change could be introduced into neoclassical growth without leading to bizarre results. Neo-classical growth models were "saved" from such restrictiveness by the introduction of the theory of induced innovation. Under the usual neoclassical assumptions and, in addition, when the innovation possibility curve takes the form assumed by Kennedy and Samuelson the system settles down into a balanced growth path exactly like that of the labor-augmenting case" (p. 209).

By the early 1970s the growth theoretic approach to induce technical change was under severe attack (Wan, 1971; Nordhaus, 1969, pp. 93-115; Nordhaus, 1973; David, 1975, pp. 44-57). Nordhaus notes that in the Kennedy model, no resources are allocated to inventive activity. A valid theory "of induced innovation requires at least two productive activities; production and invention.

If there is no invention then the theory of induced innovation is just a disguised case of growth theory with exogenous technological change." (Nordhaus, 1973, p. 210). He further notes that the Kennedy innovation possibility frontier (IPF) implies that the rate of capital augmenting technological change is independent of the level of labor augmentation. Thus, as technological change accumulates there is no effect on the trade-off between labor and capital augmenting technological change (Nordhaus, 1973, p. 215). He insisted that the model is "too defective to be used in serious economic analysis." (Nordhaus, 1973, p. 208). The growth theoretic version of induced innovation has never recovered from the criticism of its inadequate micro-economic foundation.[1]

<u>The micro-economic model</u>. A second approach to induced innovation, built directly on Hicksian micro-economic foundations, was developed by Syed Ahmad (1966). His criticism of the growth theoretic approach initiated a vigorous exchange (Fellner, 1967; Ahmad, 1967a; Kennedy, 1967; Ahmad, 1967b). In his 1973 critique, Nordhaus mentioned that Ahmad was the only person to attempt to formulate the theory of induced technical change along micro economic lines but he did not comment explicitly on the Ahmad paper or on the subsequent exchange.[2]

In his model, Ahmad employed the concept of a historic <u>innovation possibility curve</u> (IPC). At a given time there exists a set of potential production processes, determined by the basic state of knowledge, available to be developed. Each process in the set is characterized by an isoquant with rather narrow possibilities for substitution. Each process in the set requires that resources be devoted to research and development before the process can actively be employed in production. The IPC is the envelope of all unit isoquants of the subset of those potential processes which the entrepreneur might develop with a given amount of research and development expenditure.

Assume that I_t is the unit isoquant describing a technological process available in time **t** and that IPC_t is the corresponding IPC (Figure 1). Given the relative factor prices described by line P_tP_t, I_t is the cost minimizing technology. Once I_t is developed, the remainder of the IPC becomes irrelevant because, for period t+1, the IPC shifts inward to some IPC_{t+1}. This occurs because it would take the same R & D resources to go from I_t to any other technique on $IPC_{\mathbf{t}}$ as to go from $I_{\mathbf{t}}$ to any technique on $IPC_{\mathbf{t+1}}$. If factor prices remain unchanged and technical change is neutral, the new unit isoquant will be $I_{\mathbf{t+1}}$ on $IPC_{\mathbf{t+1}}$. If, however, factor prices change to $P_{\mathbf{t+1}}P_{\mathbf{t+1}}$, then it is no longer optimal to develop $I_{\mathbf{t+1}}$. Instead, a technological process corresponding to some $I'_{\mathbf{t+1}}$ becomes optimal. In the graph, $P_{\mathbf{t+1}}P_{\mathbf{t+1}}$ corresponds to a rise in the relative price of labor. If the IPC has shifted neutrally, $I'_{\mathbf{t+1}}$ will be relatively labor saving in comparison to $I_{\mathbf{t}}$.

Ahmad's graphical exposition is useful as an illustration of the induced innovation process of a one period micro-economic model in which a firm or a research institute has a fixed exogenous budget constraint. When research budgets are no longer fixed, a mathematical exposition is more convenient (Binswanger, 1978, pp. 26-27). In a multi period model the shift from $I_{\mathbf{t}}$ to $I'_{\mathbf{t+1}}$ would occur in a series of steps in response to incremental shifts from $P_{\mathbf{t}}$ to $P_{\mathbf{t+1}}$. One way of describing this process would be to appeal to "learning by doing" and "learning by using" concepts (Arrow, 1962; Rosenberg, 1982).

Dialogue With Data

The initial dialogues about the logic of the Kennedy-Samuelson-Weizsäcker growth theoretic and the Hicks-Ahmad micro-economic approaches to induced technical change were conducted within the confines of the standard two factor (labor and capital) neoclassical model. Among economic historians there has been a continuing debate about the role of land abundance on the direction of technical change in the industrial sector. Among agricultural economists there has emerged a large literature on the bias of technical change along mechanical (labor saving) and biological (land saving) directions.

Habakkuk (1962) argued that the ratio of land to labor, which was higher in the United States than in Britain, raised real wages in American agriculture and thereby increased the cost of labor to manufacturers. Habakkuk argued, in effect, that in the 19th Century, the higher U.S. wage rates resulted not only in the substitution of capital for labor (more capital) but induced technical changes (better capital) biased in a labor saving direction (James and Skinner, 1985). The issue became controversial among economic historians even before they became fully sensitive to the emerging theoretical debates of the 1960s around the issue of induced technical change or the earlier emperical work by Hayami and Ruttan (1970, 1971).

The criticisms of the Rothbard-Habakkuk labor scarcity theses by Temin (1966) and the debates that his criticism engendered (Fogel, 1967; Ames and Rosenberg 1968; David, 1973, 1975, pp. 24-30) focused primarily on the issue of the impact of land abundance on the substitution of capital for labor--the `more capital' rather than the `better capital' part of the thesis. David argued that economic historians "steered away from serious re-evaluation of the proposition about the rate and bias of innovation, precisely because standard economic analysis was thought to offer less reliable guidance there than on questions of the choice of alternative known techniques of production" (David, 1975, p. 31).

David insisted that the argument could not be resolved without a more intensive mining of the historical evidence. But recourse to measurement could not be expected to get very far without a theoretically grounded definition of an operational concept that distinguishes between choice of technology and technical change and between bias in the direction of technical change and the rate of technical change. David argued that can this can be done by embracing "the concept of a concave, downward sloping `innovation-possibility frontier' . . . along the lines of the neoclassical theory of induced technical progress due to Kennedy, Weizsäcker and Samuelson" (David, 1975, p. 32). He then went on to argue along the same lines as Wan (1971) and Nordhaus (1973) that the particular pattern of changes in macro-production relationships observed in the United States could be rationalized within the framework of a stable innovation-possibility frontier. "While shifts of the innovation-possibility frontier are entirely conceivable, the necessity of accepting their occurrence in this context signifies a practical failure of the underlying theoretical construct. For the latter treats the position of the frontier as established autonomously for each economy, and has no explanation to offer for it" (David, 1975, p. 33).

David also insisted that bias in the direction of technical change could only be understood by building a theory of induced innovation on micro-economic foundations consistent with engineering and agronomic practice. To David this also meant abandoning both neoclassical growth theory and the neo-classical theory of the firm. Furthermore, it would be necessary to incorporate the intimate evolutionary connection "between factor prices, the choice of technique and the rate and direction of global technical change" (David, 1975, p. 61).

In attempting to develop a non-neoclassical "evolutionary and historical" approach to induced innovation, David introduced the concepts of (a) linear fixed-coefficient processes or techniques from activity analyses (which he credits to Chenery), (b) a latent set of potential processes that could be designed with the currently existing state of knowledge (which he attributed to Salter). These two concepts are illustrated with Figure 2. He then added (c) localized learning which directs technical change toward the origin along a specific process-ray (which he attributes to Stiglitz); and (d) a probablistic learning process that is bounded by transition probabilities that depend on the firm's initial technical state (David 1975, pp. 57-86). The model of the search process appears to have been inspired by the Nelson-Winter evolutionary model (see next section). He insisted, however, that his transition probabilities, in which past states--the firms initial myopic selection of a technical process--influences the future course of development, is "clearly non-Markovian" (David, 1975, p. 81).

David differentiated his approach from neoclassical production theory by suggesting that substitution may involve an element of innovation. This is similar to the mechanism that Ahmad (1966) and Hayami and Ruttan (1970) had earlier employed to account for the shift in the IPC (or in David's terms, the FPF). It should be viewed an extension rather than an alternative to the neoclassical model. He also differentiated the mechanism that accounts for the evolutionary nature of technical change from that form employed by Nelson and Winter.

David then turned to the technical relationships among natural resources, labor and capital. He argued, drawing on the work of Ames and Rosenberg (1968) and his own earlier work (David, 1966), that in the mid-19th Century mechanical technology and land were complements--"The relevant fundamental production functions (FPF of Figure 2) for the various branches of industry and in agriculture did not possess the property of being separable in the raw materials and natural resource inputs; instead the relative capital intensive techniques . . . were also relatively resource using" (David, 1975, p. 88). Greater availability of natural resources facilitates the substitution of capital for labor. "Thus, even if the same labor capital price ratios had faced producers in Britain and America, the comparatively greater availability of natural resources would have suggested to some

American producers the design and to others the selection of more capital intensive methods. . . . In America the on-going capital formation spurred by the greater possibilities of jointly substituting natural resources and capital for labor may well have been responsible for driving up the price of labor from the demand side" (David, 1975, pp. 89-90). The formal introduction of the role of relative resource abundance (or scarcity) clearly represents an important extension as compared to the traditional two-factor (labor and capital) neoclassical models. But the primary significance is that David opened the door, and identified most of the elements, of what has since become known as the path dependent model of technical change (David, 1975, pp.65,66).

There are substantial differences in the extent to which the several induced technical change models have been tested against empirical data. The demand induced model was developed in close association with empirical studies and was not subjected to formal modeling or theoretical critique until fairly late (Lucas, 1967; Mowery and Rosenberg, 1979). The growth theoretic version of factor induced technical change has been peculiarly unproductive of empirical research. The only test against empirical data seems to have been by Fellner. Fellner interpreted his results as indicating that, except during periods of very rapid increase in rising capital intensity, and hence rapidly rising demand for labor the induced labor saving bias was sufficient to prevent the labor share from rising (Fellner, 1961).

The micro-economic version of factor induced technical change has in contrast, been highly productive in stimulating a wide body of applied research. The first formal test based directly on micro-economic foundations was the Hayami-Ruttan test against the historical experience of agricultural development in the United States and Japan (Hayami and Ruttan, 1970).[3] It seemed apparent that neither the enormous differences in land-labor ratios between the two countries or the changes in each country over time could be explained by simple factor substitution. Hayami and Ruttan employed a four-factor model in which (a) land and mechanical power were regarded as complements and land and labor as substitutes, and (b) fertilizer and land infrastructure were regarded as complements and fertilizer and land as substitutes.

The process of advance in mechanical technology in the Hayami-Ruttan model are illustrated in the left hand panel of Fig. 3. I_0^* represents the innovation possibility curve (IPC) in time zero; it is the envelope of less elastic unit isoquants that correspond, for example, to different types of harvesting machinery. The relationship between land and power is complementary. Land-cum-power is substituted for labor in response to a change in the wage rate relative to an index of land and power prices. The change in the price ratio from BB to CC induces the invention of labor saving machinery--say a combine for a reaper.

The process of advance in biological technology is illustrated in the right hand panel of Fig. 3. Here i_0^* represents an IPC that is an envelope of relatively inelastic land-fertilizer isoquants such as L_0. When the fertilizer-land price ratio declines from bb to cc a new technology--a more fertilizer responsive crop variety--represented by C_1 is developed along i_0^*. Since the substitution of fertilizer for land is facilitated by investment in land and water development the relationship between new fertilizer responsive varieties and land infrastructure is complementary.

In Figure 3 the impact of advances in mechanical and biological technology on factor ratios are treated as if they are completely separable. This is clearly an oversimplification. It is not essential to the Hayami-Ruttan induced technical change model that changes in the land-labor ratio be a direct response to the price of land relative to the wage-rate (Thirtle and Ruttan, 1987, pp. 30,31).

The econometric tests conducted by Hayami and Ruttan suggested that the enormous changes in factor proportions that occurred during the process of agricultural development in the two countries "represents a process of dynamic factor substitutions accompanying changes in the production function induced by changes in relative factor prices (Hayami and Ruttan, 1970, p. 1135).

The initial Hayami-Ruttan article and the further exposition in their book on Agricultural Development (1971, 1985) became the inspiration for a large number of empirical tests of the micro-economic version of the induced technical change hypothesis in the agricultural and natural resource sector. Binswanger advanced the methodology for measuring technical change bias with many factors of production (1974a; 1974b). In a 1987 literature review, Thirtle and Ruttan (1987) listed 29 empirical studies of induced technical change in agriculture. Most of the studies draw their inspiration from the initial study by Hayami and Ruttan (1970). Thirtle and Ruttan also list 38 empirical studies in the industrial sector. The initial studies of biased technical progress change in industry typically did not involve direct tests of the induced technical change hypotheses. By the late 1970s and early 1980s, however, a substantial number of studies, some stimulated by the rise in energy prices in the 1970s, involved direct tests of the induced technical change hypotheses. Within the industrial sector the evidence is strongest in the natural resource and raw material using industries (Jorgenson and Fraumeni, 1981; Wright, 1990). As of the mid-1980s the evidence of tests of the induced technical change hypotheses in agriculture, both in the United States and abroad, was sufficient to support the view that changes (and sometimes differences) in relative factor endowments and prices exert a substantial impact on the direction of technical change.[4]

EVOLUTIONARY THEORY

The modern revival of interest by economists in an evolutionary theory of technical change derives largely from a series of articles by Richard R. Nelson and Sidney G. Winter in the mid-1970s (Nelson and Winter, 1973; 1974; 1975; Nelson, Winter and Schuette, 1976; Nelson and Winter, 1977).[5] These articles in turn served as a basis for the highly acclaimed book, Evolutionary Theory of Economic Change (Nelson and Winter, 1982). The theory advanced by Nelson and Winter has been identified by the authors as "Schumpeterian" in its interpretation of the process of economic change. In much of the literature that has drawn its inspiration from Nelson and Winter, evolutionary and Schumpeterian have been used as interchangeable.[6] The second cornerstone of the Nelson-Winter model is the behavioral theory of the firm in which profit maximizing behavior is replaced by decision rules that are applied routinely over an extended period of time (Simon, 1955; 1959; Cyert and March, 1963).

The Nelson-Winter evolutionary model, particularly Chapters 9-11, jettisons much of what they consider to be the excess baggage of the neo-classical micro-economic model--"the global objective function, the well defined choice set, and the maximizing choice rationalization of firm's actions. And we see `decision rules' as very close conceptual relatives of production `techniques' whereas orthodoxy sees these things as very different." (Nelson and Winter, 1982, p. 14). The production function and all other regular and predictable behavior patterns of the firm is replaced by the concept of "routine"--"a term that includes characteristics that range from well-specified technical routines for producing things, procedures for hiring and firing, ordering new inventory, or stepping up production of items in high demand to policies regarding investment, research and development (R&D), or advertising, and business strategies about product diversification and overseas investment"

(Nelson and Winter, 1982, p. 14). The distinction between factor substitution and shifts in the production function is also abandoned. The two fundamental mechanisms in the Nelson-Winter models are the search for better techniques and the selection of firms by the market (Elster, p. 14). In their models the microeconomics of innovation is represented as "a stochastic process dependent on the search routines of individual firms" (Dosi, Giannetti and Toninelli, 1992:10). The activities leading to technical changes are characterized by (a) local search for technical innovations, (b) imitation of the practices of other firms, and (c) satisfying economic behavior.

In their initial models, search by the firm for new technology, whether generated internally by R & D or transferred from suppliers or competitors, is set in motion when profits fall below a certain threshold. The models assume that in this search the firms draw samples from a distribution of input-output coefficients (Figure 4). If A is the present input combination then potential input coefficients are distributed around it such that there is a much greater probability of finding a point close to A then if finding one far away. Search is local. Once the firm finds a point B it makes a profitability check. If costs are lower at B than at A, the firm adopts the point B and stops searching. Otherwise, search continues. Thus, the technology described by the point $\overset{o}{B}$ input-output and factor ratios will be accepted if labor is relatively inexpensive, that is, if relative prices are described by line CD. But if labor is relatively expensive, as described by C′D′, the firm will reject the $\overset{o}{B}$ technology and continue to search for another technology until it finds another point, say $\overset{o}{B}'$. The technologyat point $\overset{o}{B}'$ will be labor saving relative to that at $\overset{o}{B}$.

The stochastic technology search process is built into a model with many competing firms. All profits above a "normal" dividend--investors are satisficers rather than optimizers--are reinvested so that successful firms grow faster than the unsuccessful ones. The capital stock of the economy is determined by the total investment by all firms. Labor supply is elastic to the firm.

Simulation runs rather than formal analysis or tests against historical experience are employed to demonstrate the plausibility of the models. The simulations start from an initial point where all firms are equal. The model determines endogenously the output of the economy, the wage-rental rate, and the capital accumulation rates. Nelson and Winter have used a series of variations in their basic model to explain how changes in market structure influences the rate of technical change, the direction of technical change, and the importance of imitation and innovation.

When firms check the profitability of alternative techniques that their search processes uncover, a higher wage rate will cause certain techniques to fail the more profitable tests that would have passed at a lower wage rate, and enable others to pass the test that would have failed at a lower wage rate. The latter will be capital intensive relative to the former. Thus a higher wage rate nudges firms to move in a capital-intensive direction compared with that in which they would have gone. Also, the effect of a higher wage rate is to make all technologies less profitable (assuming, as in their model, a constant cost of capital) but the cost increase is proportionately greatest for those that involve a low capital-labor ratio. Since firms with high capital labor ratios are less adversely affected by high wage rates then those with low capital-labor ratios, capital intensive firms will tend to expand relatively to labor-intensive ones. For both of these reasons a higher wage rate will tend to increase capital-intensity relative to what would have been obtained" (Nelson and Winter, 1974, p. 900). The responsiveness of the capital labor ratio to changes in relative factor prices is rather striking because, except for the profitability check, search (or research) outcomes are random (Nelson and Winter, 1982, pp. 175-84), and the inducement mechanism comes about through competition, survival and growth rather than through efforts to maximize profits.

The early Nelson-Winter models were criticized for the "dumb manager" assumption in which the search (or research) process is triggered only when profits fall below a threshold level. For example, "here we assume that firms with positive capacity do not search if they are making positive or zero profits; they satisfice on their prevailing routines." (Nelson and Winter, 1982, p. 149). An implication is that an increase in demand for the product of an industry, can lead to a reduction in research effort. This was hardly consistent with either historical evidence (Schmookler, 1966) or with a Schumpeterian perspective. The restriction was relaxed in the second round of Nelson and Winter models by the explicit introduction of directed research. As the wage/rental ratio rises research effort is allocated to sampling the spectrum of capital intensive techniques (Nelson and Winter, 1975; 1977).

Winter has devoted considerable attention to extensions of the initial Nelson-Winter models. In a 1984 article, for example, he abandons the assumption of the level playing field in which the initial conditions were the same for all firms. The basic model is augmented by a model that includes entirely new firms. Winter uses this expanded model to explore the growth path of two industrial regimes. One is an "entrepreneurial regime" which he identifies with the early Schumpeter of <u>The Theory of Economic Development</u> (1934; originally published in German, 1911). The second is a "routinized regime" which he identifies with the Schumpeter of <u>Capitalism, Socialism and Democracy</u> (1950). The entrepreneurial regime model is designed so that innovations are primarily associated with the entry of new firms. In the routinized regime innovations are primarily the result of internal R & D by established firms. Several suggestions for further extension of the Nelson and Winter models, to include the creation of new industries, interaction among industries, and product innovation and imitation, for example, have been summarized and extended by Andersen (1994, pp. 118-31).

It is important to clarify the role of historical process in the Nelson-Winter evolutionary models. The condition of the industry in each time period shapes its condition in the following period. "Some economic processes are conceived as working very fast, driving some of the model variables to (temporary) equilibrium values within a single period (or in a continuous time model, instantaneously). In both the entrepreneurial and routinized Schumpeterian models, for example a short-run equilibrium price of output is established in every time period. Slower working processes of investment and of technological and organizational change, operate to modify the data of the short-run equilibrium system from period to period (or from instant to instant). The directions taken by these slower processes of change are directly influenced by the values taken by the subset of variables that are equilibrated in the individual period or instant" (Winter, 1984, p. 290)

Two questions that I find difficult to resolve is why there have been so few efforts by other scholars to (a) advance the Nelson-Winter methodology[7] or, (b) to test the correspondence between the plausible results of the Nelson-Winter simulations against the historical experience of particular firms or industries.[8] Simulation is capable of generating a wide range of plausible behavior. But the hypothesis generated by the simulations have seldom been subjected to rigorous empirical tests. The closest they or others come to empirical testing is the demonstration that it is possible to generate plausible economy wide growth paths or changes in marketshare.

PATH DEPENDENCE

The argument that technical change is "path dependent" was vigorously advanced, by W. Bryan Arthur and several colleagues in the late 1970s and early 1980s (Arthur, Ermoliev and Kaniovski, 1983; Arthur, 1983; see also Arthur 1989 and 1994. [9] In the mid and late 1980s Paul David, drawing on the earlier work of Arthur for inspiration, presented the results of a series of historical studies--of the typewriter keyboard, the electric light and power supply industries and others--that served to buttress the plausibility of the path dependence perspective (David, 1985, 1986, 1993; David and Bunn, 1988). The emphasis on path dependence in David's more recent work represents, as noted earlier, an extension of his earlier research on the relationship between labor scarcity and modernization in nineteenth century America (David, 1975). This earlier work was strongly influenced by Kenneth Arrow's article on learning by doing (Arrow, 1962) and by Habakkuk's historical research on British and American technology in the 19th Century (Habakkuk, 1962).

The effect of the work by Arthur and his colleagues has been to emphasize the importance of increasing returns to scale as a source of technological "lock-in". In some nonlinear dynamic systems positive feedbacks (Polya processes) may cause certain patterns or structures that emerge to be self-reinforcing: Such systems tend to be sensitive to early dynamical fluctuations (Figure 5). Often there is a multiplicity of patterns that are candidates for long term self-reinforcement; the accumulation of small events early on `pushes' the dynamics of technical choice into the orbit of one of these and thus `selects' the structure that the system eventually locks into" (Arthur, Ermoliev and Kaniovski, 1987, p. 294).

The authors provide an intuitive example: Think of an urn of an infinite capacity. "Starting with one red and one white ball in the urn, add a ball each time, indefinitely, according to the following rule. Choose a ball in the urn at random and replace it; if it is red, add a red; if it is white, add a white. Obviously this process has increments that are path dependent--at any time the probabilities that the next ball added is red exactly equals the proportion red. . . . Polya proved in 1931 that in a scheme like this the proportion of red balls does tend to a limit X_1 and with probability one. But X is a random variable uniformly distributed between 0 and 1" (Arthur, et al., p. 259). Thus in an industry characterized by increasing returns small historical or chance events that give one of several technologies an initial advantage can (but need not) "drive the adoption process into developing a technology that has inferior long run potential" (Arthur, 1989, p. 117).[10]

The historical small events that result in path dependence are "outside the ex ante knowledge of the observer--beyond the resolving power of his model or abstraction of the situation" (Arthur, 1989, p. 118). Arthur employs a series of progressively complex models to simulate situations in which several technologies compete for adoption by a large number of economic agents. Agents have full knowledge of the technology and returns functions but not of the events that determines entry and choice of technology by other agents. His analyses is carried out for three technological regimes (constant, increasing, and diminishing returns) with respect to four properties of the paths of technical change (predictable, flexible, ergodic, path efficient).[11] The only unknown is the set of historical events that determine the sequence in which the agents make their choices. The question he attempts to answer is whether the fluctuations in the order of choice will make a difference in final adoption shares.

Arthur's simulations re-enforce the importance of increasing returns as a necessary condition for technological lock in. "Under constant and diminishing returns the evolution of the market reflects only a-priori endowments, preferences, and transformation possibilities; small events cannot sway the outcome. . . . Under increasing returns, by contrast, many outcomes are possible. Insignificant circumstances become magnified by positive feedbacks to `tip' the system into the actual outcome `selected.' The small events in history become important. . . ." (Arthur, 1989, p. 127). The network externalities are important not only because of their impact on the direction or path of technology development, but because they represent a source of market failure--welfare losses that cannot be resolved by normal market process--and hence call for public intervention (Arthur, 1994, pp. 9-10).

In Technical Choice, David characterizes his work as an evolutionary alternative to neoclassical theory. As noted earlier he explicitly rejected the Fellner and Kennedy versions of the induced technical change approach to the analysis of factor bias. He also rejected the early work of Nelson and Winter as being "fundamentally neo-classical-inspired" (David, 1975, p. 76).[12] But he shares the Nelson and Winter view that the neoclassical model is excessively restrictive since factor substitution typically involves not simply a movement along a given production function but an element of innovation leading to a shift in the function itself. He does assume that the firm has knowledge of available (or potentially available) alternative technologies and chooses rationally among them.

David's early analysis of factor bias, particularly his graphical expansion (Figure 2) was remarkably similar to the Hicks-Ahmad-Hayami-Ruttan interpretation of the process of induced technical change. And, in spite of his emphasis in Technical Choice that the future development of the system depends not only on the present state but also on the way the present state evolved, I find his research on path dependence in the 1980s a distinct departure from his research on factor bias in the 1970s.

In his research in the mid and late 1980s, David employs historical analysis of a series of technical changes--the typewriter keyboard, the electric light, and power supply industries--to buttress the plausibility of the path dependence perspective. His already classic paper on the economics of QWERTY (the first six letters on the left of the topmost row of letters on the typewriter and now the computer keyboard) explored why an inefficient (from today's perspective) typewriter keyboard was introduced and why it has persisted.[13] David's answer is that an innovation in typing method, touch typing, gave rise to three features "which were crucially important in causing QWERTY to become "locked in" as the dominant keyboard arrangement. These features were technical inter-relatedness, economics of scale, and quasi-irreversibility of investment" (David, 1985, p. 334). Technical interrelatedness refers to the need for system compatibility--in this case the linkage between the design of the typewriter keyboard and typists' memory of a particular keyboard arrangement. Scale economics referred to the decline in user cost of the QWERTY system (or any other system) as it gained in acceptance relative to other systems. The quasi-irreversibility of investments is the result of the acquisition of specific touch typing skills (the "software"). These characteristics are sometimes bundled under the rubric of positive "network externalities."

As David has drawn increasinly on Arthurs path dependence model it has biased his research even further in the direction of interpreting the QWERTY-like phenomenon in dynamic systems characterized by network externalities and path dependent technical change as a dominant paradigm for the history of technology (David, 1993, pp. 208-31). This paradigm would seem particularly apt at a time when the impact of scale economics on productivity growth has been rediscovered and embodied in a "new growth economics" literature (Romer, 1986; Lucas, 1988; Barro and Sala-i Martin, 1995).[14] But Arthur's results suggest some caution. "Increasing returns, if they are bounded, are in general not sufficient to guarantee eventual monopoly by a single technology" (Arthur, 1989, p. 126). And there is substantial empirical evidence that scale economies, which often depend on prior technical change, are typically bounded by the state of technology (Levin, 1977, pp. 208-21).

Both induced innovation and evolutionary theory suggest that as scale economies are exhausted (and profits decline) the pressure of growth in demand will focus scientific and technical effort on breaking the new technological barriers. Superior technologies that have lost out as a result of chance events in the first round of technical competition have frequently turned out to be successful as the industry developed.[15] And induced technical change theory suggest that research effort will be directed to removing the constants on growth resulting from technological constraints or inelastic (or scarce) factor supplies.[16]

The transition from coal to petroleum based feedstocks in the heavy organic chemical industry is a particularly dramatic example. From the 1870s through the 1930s, German leadership in the organic chemical industry was based on coal-based technology. Beginning in the 1920s with the rapid growth in demand for gasoline for automobiles and trucks in the United States, a large and inexpensive supply of olefins became available as a by-product of petroleum refining. By the end of World War II, the U.S. chemical industry had shifted rapidly to petroleum-based feedstocks. In Germany this transition--impeded by skills, education and attitudes that had been developed under a coal-based industrial regime--was delayed by more than a decade. By the 1960s, however, Germany was making a rapid transition to the petroleum based feedstock path of technical change in heavy organic chemicals (Grant, Patterson and Whitston, 1988; Stokes, 1994).

TOWARD A MORE GENERAL THEORY?

In this section I first summarize my assessment of the strengths and limitations of each of the three models of technical innovation. I then outline the elements of a more general theory. I would like to make clear to the reader my particular historical and epistemological bias: Departures from neo-classical microeconomic theory, when successful, are eventually seen as extensions and become incorporated into neo-classical theory. Thus, for example, the micro-economic version of induced technical change can now be viewed as an extension of, rather than a departure from, the neo-classical theory of the firm.[17]

Assessment

One common theme pervading the three approaches to understanding sources of technological change is the disagreement with the assumption in neoclassical growth models that a common production function is available to all countries regardless of human capital, resource or institutional endowments. It should now be obvious that differences in productivity levels and rates of growth cannot be overcome by the simple transfer of capital and technology. The asymmetries between firms and between countries in resource endowments and in scientific and technological capabilities are not easily overcome. The technologies that are capable of becoming the most productive sources of growth are often location specific.

A second common theme is an emphasis on micro foundations. This emphasis on micro foundations is common to the approaches that have abandoned neoclassical micro-economics as well as to those that have attempted to extend neoclassical theory (Dosi letter, 1995). This stands in sharp contrast to the limited attention to micro foundations in both the old and the new growth economics.

The major limitation of the growth theoretic version of the induced innovation model is the implausibility of the innovation possibility function (IPF). The shape of the IPF is independent of the bias in the path of technical change. As technical change progresses there is no effect on the `fundamental' trade-off between labor and capital augmenting technical change. Thus as Nordhaus notes, the growth theoretic approach to induced innovation fails to rescue growth theory from treating technical change as exogenous. It has been unproductive of empirical research and is no longer viewed as an important contribution to growth theory.

The major limitation of the micro-economic version is that its internal mechanism--the learning, search and formal R & D processes--remain inside a black box. The model is driven by exogenous changes in the economic environment in which the firm (or public research agency) finds itself. The micro-economic model has, nevertheless, been productive of a substantial body of empirical research and has helped to clarify the historical process of technical change, particularly at the industry and sector level both within and across countries.

The strength of the evolutionary model is precisely in the area where the micro-economic induced innovation model is weakest. It builds on the behavioral theory of the firm in an attempt to provide a more realistic description of the internal workings of the black box. It allows the researcher to construct artificial worlds in which to explore the implications of complex but plausible assumptions about firm behavior on interactions between the firm and its environment. In the early models fixed behavioral patterns or routines--for production activities, personnel action, determination of product mix, plant expansion, research and development--dominate normal decision making. In later models, Nelson and Winter develop a "search and selection" process that incorporates, at least in a limited way, elements of rational choice. In one such model they explore the effects of relative price changes or changes in the distribution of the firms search effort. The model generates a path of technical change that is not unlike the path implied by the neo-classical micro-economic induced innovation model from a similar shift in relative prices (Nelson and Winter, 1975, pp. 466-86).

The Nelson and Winter evolutionary approach has not, however, become a productive source of empirical research. The results of the various simulations are defended as plausible in terms of the stylized facts of industrial organization and of firm, sector and macro-economic growth. It is possible that the reason for the lack of empirical testing is that the simulation methodology lends itself to the easy proliferation of plausible results. At present the evolutionary approach must be regarded as a "point of view" rather than as a theory (Arrow, 1995).

The strengths of the path dependence model lies in the insistence of its practitioners on the importance of the sequence of specific micro-level historical events. In this view current choices of techniques became the link through which prevailing economic conditions may influence the future dimensions of technology and knowledge. However, the concept of technological lock in, at least in the hands of its more rigorous practitioners, applies only to network technologies characterized by increasing returns to scale. In industries with constant or decreasing returns to scale historical lock in does not apply.

There can be no question that technical change is path dependent in the sense that it evolves from earlier technological development. In spite of somewhat similar motivation the path dependent literature has not consciously drawn on the Nelson-Winter work for inspiration (Arthur, 1996). It is necessary to go beyond the present path dependent models, however, to examine the forces responsible for changes in the rate and direction of technical change. But there is little discussion of how firms or industries escape from lock in. What happens when the scale economies resulting from an earlier change in technology have been exhausted and the industry enters a constant or decreasing returns stage? At this point in time it seems apparent that changes in relative factor prices would, with some lag, have the effect of bending or biasing the path of technical change along the lines suggested by the theory of induced technical change. Similarly a new radical innovation may, at this stage, both increase the rate and modify the direction of technical change.

The study of technical change in the semiconductor industry by Giovanni Dosi (1984) represents a useful illustration of the potential value of a more general model. The Dosi study is particularly rich in its depth of technical insight. At a rhetorical level, Dosi identifies his methodology with the Nelson-Winter evolutionary approach. In practice, however, he utilizes an eclectic combination of induced innovation, evolutionary and path dependence interpretations of the process of semi-conductor technology development. A more rigorous approach to the development of a general theory of the sources of technical change will be required to bridge the three "island empires."

Integration of Factor and Demand Induced Technical Change Models

A first step toward developing a more general theory of technical change is to integrate the "factor induced" model and the "demand induced" models (Ruttan and Hayami, 1994; p. 180). Binswanger, drawing on Nordhaus (1969, pp. 105-09) and Kamien and Schwartz (1969), has sketched the outlines of how a more general model that make both the rate and direction of technical change endogenous (Binswanger, 1978, pp. 104-10). If one assumes decreasing marginal productivity of research resources in applied research and technology development and, in addition, incorporates the effects of changes in product demand, then growth (decline) in product demand would increase (decrease) the optimum level of search and research expenditure. The larger research budget, induced by growth in product demand, increases the rate at which the meta-production function shifts inward toward the origin. Even when the initial path of technological development is generated by "technology push", factor market forces often act to modify the path of technical change. Differential elasticities of factor supply result in changes in relative factor prices and direct research effort to save increasingly scarce factor supplies. The result is a non-neutral shift in both the neo-classical and the meta-production functions.

More recently Christian has elaborated the Binswanger model and analized more formally the innovators decision to conduct research and development directed toward process innovation (Christian, 1993). As yet, however, there has been no attempt to implement empirically an integrated factor and demand induced innovation model.

Integration of Path Dependence and Induced Technical Change Models

A second step would be the integration of the induced technical change and the path dependent models. As noted earlier David has pointed to the persistent failure to replace the inefficient QWERTY layout of the typewriter and computer keyboards with the more efficient DSK keyboard. Gavin Wright (1990) has suggested that the historical resource intensity of American industry, based on domestic resource abundance, has been an important factor in weakening the capacity of American industry to adapt to a world in which lower transportation costs and more open trading systems have reduced the traditional advantage of United States based firms. If this perspective is correct Japan's industrial success may be attributed to its historical resource scarcity.

The difference in perspective seems to hinge on how the elasticity of substitution changes over time in response to changes in resource endowments or relative factor prices. From a historical perspective the issue seems to be how dependent the path of technical change is on the initial conditions under which a "gateway technology" emerges. While it is always true that today's technical changes draw on the advances in knowledge and technology from the past it is hard to believe that in a competitive environment technological competition would not result in a "bending" of the path of technical change in the direction implied by changing factor endowments. In my perspective the path dependence and the induced innovation models should be considered as complementary rather than as alternative interpretations of the forces that influence the direction of technical change.

The path dependent model will remain incomplete until it is fully integrated with the micro-economic version of the induced technical change model and with the Nelson-Winter evolutionary model. Development of an industry seldom proceeds indefinitely along an initially selected process ray (Landes, 1944). As technical progress slows down or scale economies erode a shift in relative factor prices can be expected to induce an intensified search for technologies along a ray that is more consistent with contemporary factor prices.[18]

Integration of Induced Innovation, Path Dependence and Trade Theory

A third step would be the integration of induced technical change, path dependence and international trade theory. Relative factor endowments play an important role in both the Hecksher-Ohlin approach to trade theory and the theory of induced technical change. Under the Hecksher-

Ohlin assumptions each country exports its abundant factor-intensive commodity. Induced technical change acts to make the scare factor (or its substitutes) more abundant. Except for an early article by Chipman (1970) and a more recent articles by Hamilton and Soderstrom (1981), and Davidson (1979) the relationship between the theory of induced technical change and international trade theory has remained almost completely unexplored. To the extent that trade can release the constraints of factor endowments on growth the theory of induced technical change loses part of its power to explain the direction of bias in productivity growth. Conversely, to the extend that technical change can release the constraints on growth resulted from inelastic factor supplies, the power of the differential factor endowments explanation for trade is weakened.

The revival of interest in growth theory combined with recent developments in the theory of international trade are opening up opportunities to explore the sources, rate and direction of technical change more fruitfully (Grossman and Helpman, 1991; Srinivasan, 1995).

Induced Technical Change and Endogenous Growth Models

Since the late 1980s, students of economic growth have been engaged in a re-evaluation of neoclassical growth models. The re-examination has been stimulated by concern that the neoclassical growth models are inconsistent with the evidence of lack of convergence of growth rates between rich and poor countries (Baumol, 1986; DeLong, 1988; Baumol and Wolf, 1988; Dollar and Wolf, 1993). One result of this re-examination has been the emergence of a new generation of endogenous growth models.

The major focus of the new "macro-endogenous" growth models is to attribute differences in growth performance among countries to endogenous factors such as investment in human capital, learning by doing, scale economies and technical change (Romer, 1986 and 1990; Lucas, 1988). In the initial Romer-Lucas framework the accumulation of human capital adds to the productivity of the person in whom it is embodied.[19] But the general level of productivity rises by more than can be accounted for or captured by the person or firm that makes each particular investment. Gains in scale economies are enhanced by the integration into multinational trading systems of economies that are human capital intensive (Grossman and Helpman, 1991).

The new growth literature has yet to incorporate the richness and depth of understanding of the sources of technical change that the three traditions reviewed in this paper have achieved (Bardhan, 1995; Ruttan, 1996). Like the older neoclassical growth literature its focus is on the proximate sources of growth rather than the sources of technical change. A major challenge for the future is to integrate the insights about endogenous growth gained from the theoretical and empirical research conducted within the induced technical change the evolutionary and path dependence theories, with new insights into the relationship between human capital, scale and trade opened up by the macro-endogenous growth models.

FIGURE 1. AHMAD'S INDUCED INNOVATION MODEL. [ADAPTED FROM SYED AHMAD, "ON THE THEORY OF INDUCED INVENTION," ECONOMIC JOURNAL 76 (1966), FIGURE 1 AMENDED.]

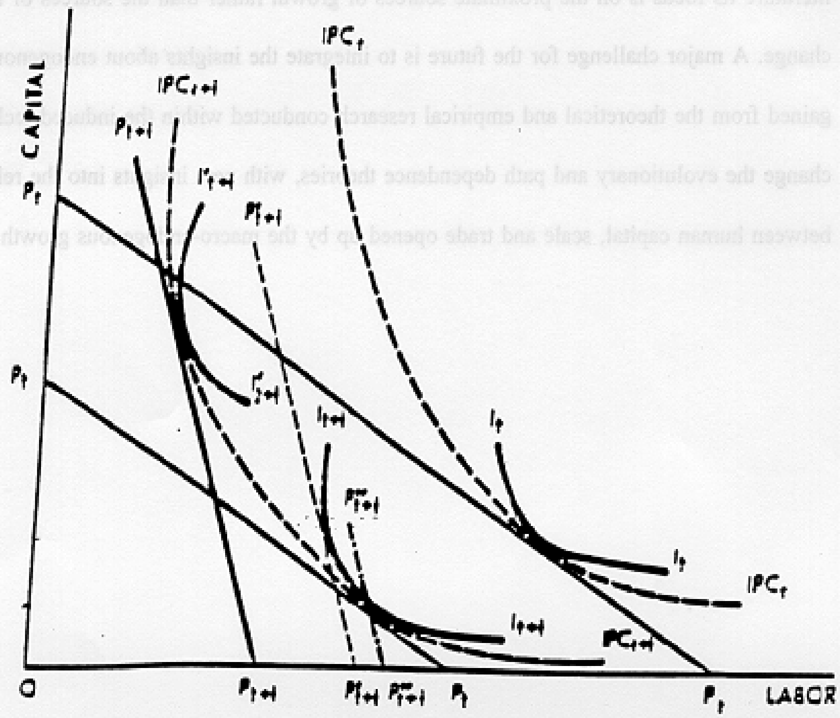


FIGURE 2. TECHNICAL INNOVATION VIEWED AS SUBSTITUTION [FROM PAUL A. DAVID, TECHNICAL CHOICE, INNOVATION AND ECONOMIC GROWTH (CAMBRIDGE: CAMBRIDGE UNIVERSITY PRESS, 1975):63]

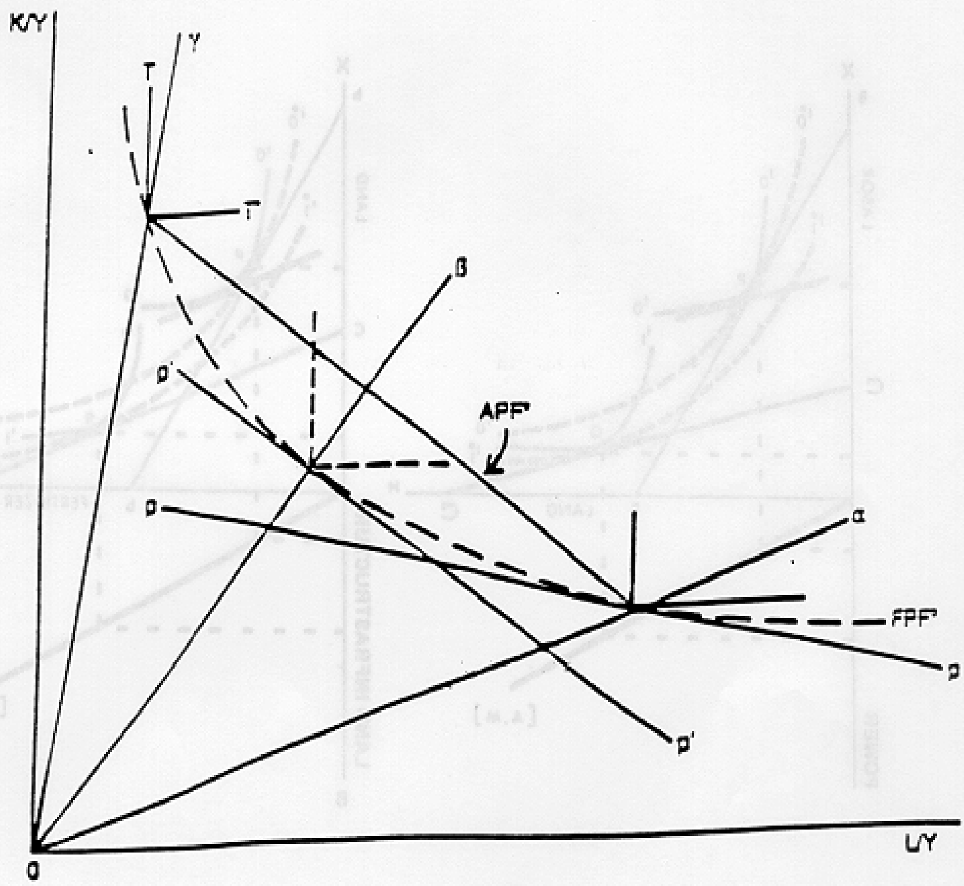


FIGURE 3. INDUCED TECHNICAL CHANGE IN AGRICULTURE (YUJIRO HAYAMI AND VERNON W. RUTTAN, AGRICULTURAL DEVELOPMENT: AN INTERNATIONAL PERSPECTIVE (BALTIMORE: JOHNS HOPKINS UNIVERSITY PRESS, 1985, P. 91).

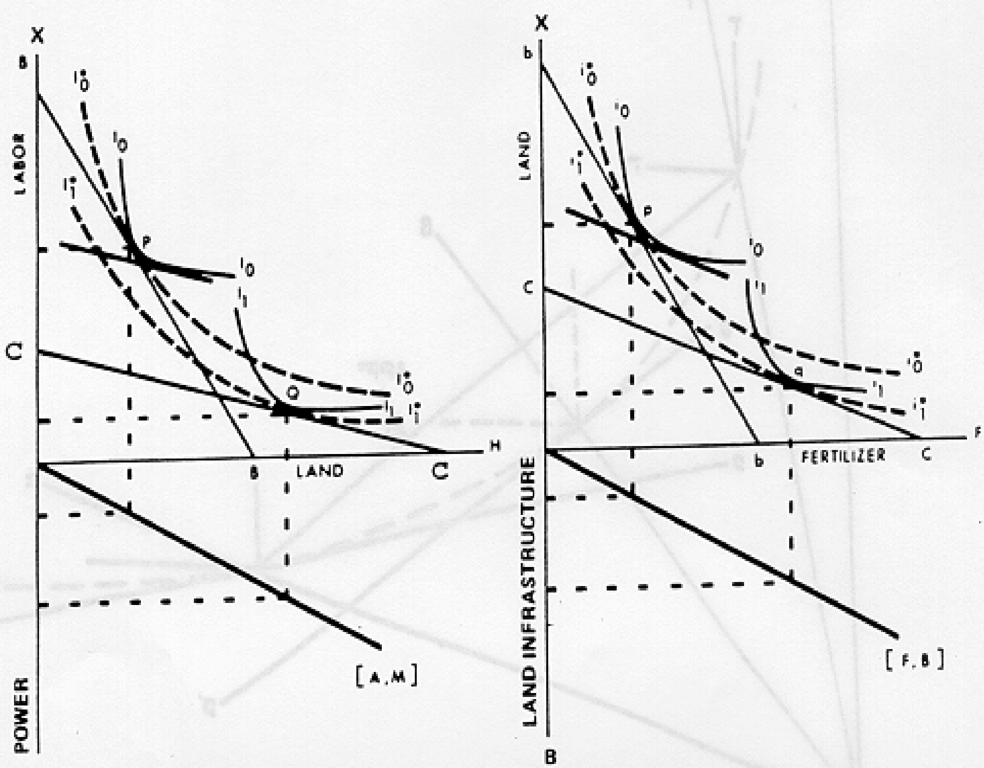


FIGURE 4. SAMPLING AND SELECTION OF NEW INPUT-OUTPUT COEFFICIENTS. [ADAPTED FROM RICHARD R. NELSON AND SIDNEY G. WINTER, "FACTOR PRICE CHANGE AND FACTOR SUBSTITUTION IN AN EVOLUTIONARY MODEL," BELL JOURNAL OF ECONOMICS 6 (1975):472]

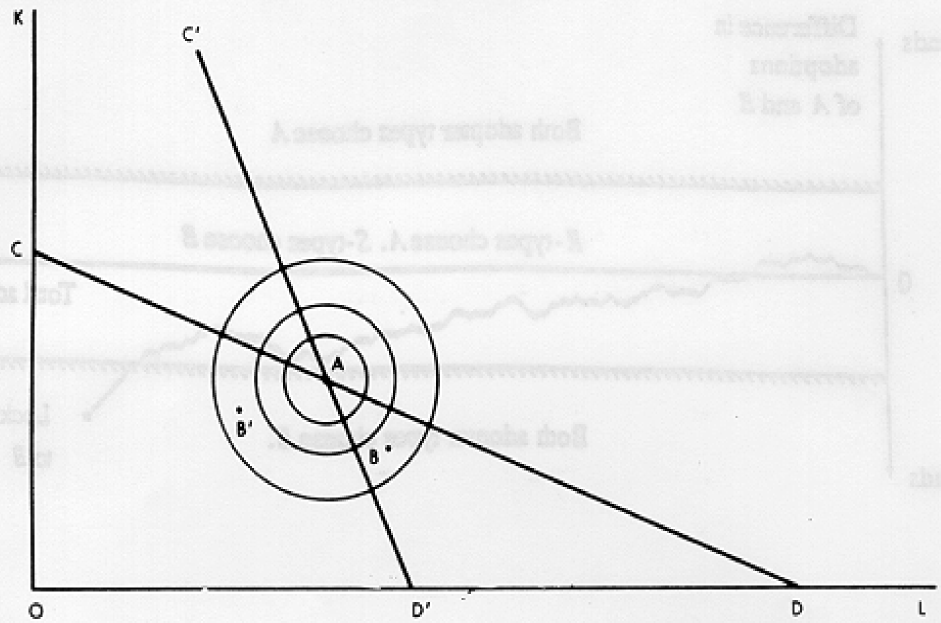
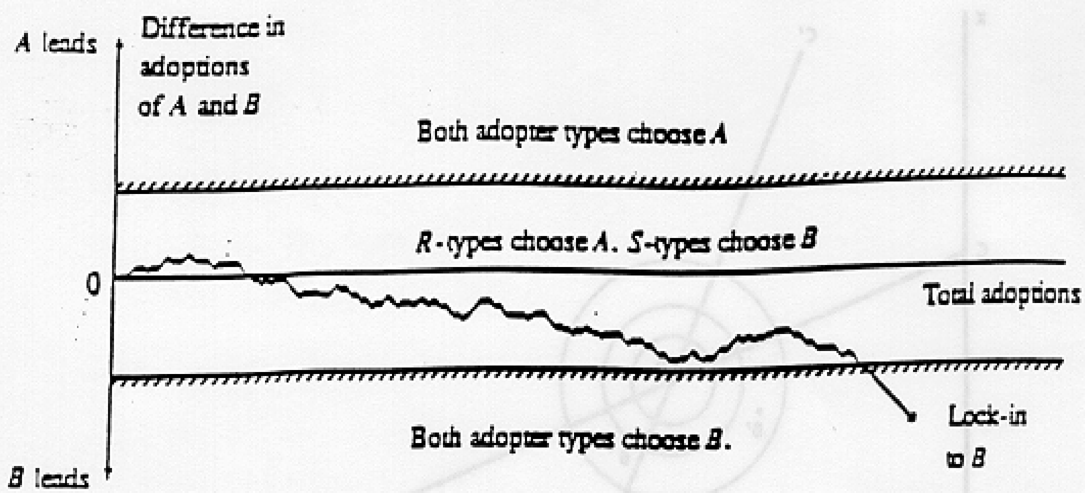


FIGURE 5. INCREASING RETURNS ADOPTION: A RANDOM WALK WITH ABSORBING BARRIERS. [W. BRYAN ARTHUR, "COMPETING TECHNOLOGIES, INCREASING RETURNS, AND LOCK-IN BY HISTORICAL EVENTS," ECONOMIC JOURNAL 99 (MARCH 1989):120]



<u>ENDNOTES</u>

1. Zvi Griliches has recently pointed out to me (in conversation) that another reason for the decline in interest among economic theorists was the difficulty, pointed out by Diamond, McFadden and Rodriquez (1978, pp. 125-147) in simultaneously measuring the bias of technical change and the elasticity of substitution between factors. This problem had, however, already been solved (Binswanger, 1974b; Binswanger and Ruttan, 1978, pp.73-80, 215-242). For a more recent discussion see Haltmaier (1986).

2. It is interesting to speculate on what the future course of induced innovation theory might have been if the Ahmad article had, as it might have, appeared first. The initial drafts of the articles were written while Kennedy was teaching at the University of the West Indies (Kingston) and Ahmad was teaching at the University of Khartoum (Sudan). Ahmad submitted his article to the *Economic Journal* in 1963. Kennedy served as a reviewer of the Ahmad article. His article, which was published in 1964, was originally written as a comment on the Ahmad article. Ahmads article was rewritten, resubmitted and published in 1966 (Ruttan and Hayami, 1994, p. 24).

3. At the time the article was written Hayami and Ruttan were familiar with the growth theoretic literature by Fellner, Kennedy and Samuelson but not with the Ahmad article and his subsequent exchange with Fellner and Kennedy. The inspiration for the 1970 Hayami-Ruttan paper was the historical observations about the development of British and American technology by Habakkuk (1967). See Ruttan and Hayami, 1994.

4. Olmstead and Rhode (1993) have criticized the Hayami and Ruttan work on both conceptual and empirical grounds. At the conceptual level they find confusion between the relative factor "change variant," that is used in explaining productivity growth over time within a given country,

and the "level variant" of the model that is used in analysis of international productivity differences. They also argue, on the basis of regional tests in the U.S., that the induced technical change model holds only for the central grain growing regions. In a later paper (1995) using state level data they found somewhat stronger support for the induced technical change hypothesis. For further criticism and a defense see Koppel (1994).

5. Nelson and Winter identify Alchian (1950) and Penrose (1952) as representing direct intellectual antecedents of their work. For the theoretical foundations of the Nelson-Winter collaboration, see Winter (1971). For the historical and philosophical foundations see Elster (1983, pp. 131-58) and Langolis and Everett (1994, pp. 11-47). Ulrich Witt has assembled many of the most important articles in the field of evolutionary economics in a collection of readings, Evolutionary Economics (1993). For a review of recent evolutionary thought about economic change see Nelson (1995, pp. 48-90).

6. The Nelson-Winter model departs in its treatment of the linkage between invention and innovation. For Schumpeter there was no necessary link between invention and innovation (Ruttan, 1959). Nelson and Winter employ the term evolutionary metaphorically - "We emphatically disavow any intention to pursue biological analogies for their own sake (1982, p. 11). Nelson and Winter regard their approach as closer to Lamankianism than Mendelianism. Yet their description of the evolutionary process of firm behavior and technical change as a Markov process, and their use of the Markov mechanism in their simulation, is analogous to the Mendelian model.

7. For a useful interpretation and extension see Anderson (1944). Anderson's work is particularly helpful in clarifying the "poorly documented" computational steps of the Nelson-

Winter models. Anderson supplements the mathematical notation employed by Nelson and Winter by an algorithmically oriented programming notation. An appendix, "Algorithmic Nelson and Winter Models" (p. 198-219) is particularly useful.

8. Since the mid-1970s there has emerged a large body of empirical research on technical change that can be categorized as broadly Schumpeterian or evolutionary in inspiration (see the review by Freeman, 1994). The point I am making, however, is quite different. There has been very little effort to use the simulation models to generate hypothesis about the process of technology development and then to either identify historical counterparts or to test the outcomes against historical experience in a rigorous manner.

9. Arthur encountered unusual delay before his work was accepted in leading economics journal. His 1986 Economic Journal paper was initialy submitted to the American Economic Reveiw in 1983. It was rejected by the American Economic Review twice and by the Quarterly Journal of Economics twice and accepted by the Economic Journal only after an appeal. By the time the paper was finaly accepted in the Economic Journal referees were noting that the path dependence idea was already recognized in the literature (Goss and Sheperd, 1994, p. 173.

10. Liebowitz and Margolis propose a topology of path dependence that implies much less pervasive efficiency losses: (a) first degree path dependence leads to lock into one of several equally efficient paths; (b) second degree path dependence involves lock into a technology that appeared efficient given the knowledge available at the time of decision but that subsequent events reveal as inferior; (c) third degree path dependence involves failure at the time a decision is made to utilize the available information that could have lead to a more favorable path. The three types of path dependence make progressively stronger claims. First degree path

dependence is a simple assertion of an intertemporal relationship, with no implied claim of inefficiency. Second degree path dependence stipulates that intertemporal effects propagate error. Third degree path dependence requires not only that the inter-temporal effects propagate error, but that the error was avoidable (1995, p. 3). Only third degree path dependence conflicts with the efficiency implications of the neo-classical model.

11. "A process <u>predictable</u> if the small degree of uncertainty built in `averages away' so that the observer has enough knowledge to pre-determine market shares accurately in the long run; <u>flexible</u> if a subsidy or tax adjustment to one of the technologies' returns can always influence future market choice; <u>ergodic</u> (not path dependent) if different sequences of historical events lead to the same market outcome with probability one; . . . and <u>path efficient</u> if at all times equal development (equal adoption) of the technology that is behind in adoption would not have paid off better." (Arthur, 1989, pp. 118, 199.)

12. For a further comparison of the David and Nelson-Winter evolutionary approaches, see Elster (1983, pp. 150-57). Elster notes that David regards the Nelson-Winter model as evolutionary, but ahistorical. In his view it differs from the neo-classical model only in its conception of micro-economic behavior. It is ahistorical since, in David's view, the Markovian-like transition probabilities depend only on the current state and not on earlier state of the system. Elster rejects David's criticism of Nelson and Winter on the bases that for the past to have a causal influence on the present it must be "mediated by a chain of locally causal links." Thus, since all the history that is relevant to the prediction of the future is contained in the state description, if the present state is known prediction cannot be improved by considering the past history of the system (Elster, p. 157).

13. The QWERTY story has acquired the status of a "founding myth" in the path dependence

literature. Liebowitz and Margolis (1990, 1994) argue that David's version of the history of the market's rejection of the supposedly more efficient Dvorak keyboard represents bad history. Given the available knowledge and experience at the time QWERTY became dominant it represented a rational choice of technology. The Liebowitz and Margolis criticism has largely been ignored by the proponents of path dependence.

14. Scale economies have become the "black box" of contemporary growth theory. It is hard to believe that much of the productivity growth that is presumably accounted for by scale economies is not the disequilibrium effect of prior technical change (Landau and Rosenberg, 1992, p. 93; Liebowitz and Margolis, 1994, p. 139).

15. See, for example, the exceedingly careful study of technological substitution in the case of Cochlear implants by Van de Ven and Garud (1993). The Cochlear implant is a biomedical invention that enables hearing by profoundly deaf people. The industry is characterized by the conditions that David and Arthur identify with technological lock-in. Yet in spite of initial commercial dominance the "single channel" technology was completely replaced by the "multiple channel" technology. For other cases see Foray and Grubler, 1990; Cheng and Van de Ven (1994) and Liebowitz and Margolis (1992, 1995).

16. The development of semiconductor technology as a replacement for vacuum tubes for amplifying, rectifying and modulating electrical signals is an example of a shift in technological trajectories induced by technological constraints See Dosi (1984, pp. 26-45). The development of fertilizer responsive crop varieties represents an example of a shift in technological trajectories induced by changes in resource endowments. See Hayami and Ruttan (1985, pp. 163-98).

17. Nelson and Winter attempt to confront this problem by arguing that there are two alternative

views of neo-classical theory. One is the more rigorous "literal" view. The other is termed "the "tendency" view. Applied economists with a primary interest in interpreting economic history or behavior tend to employ the "tendency" view while theorists who are more concerned with the formal properties employ a more literal interpretation. They identify evolutionary theory with the "tendency" view (Nelson and Winter, 1975:467).

18. See, for example, the patterns of factor substitution in the transition in primary energy sources and transportation infrastructure (Grubler and Nakicenovic, 1988, pp. 13-44; Nakicenovic, 1991).

19. The initial models are frequently referred to as AK models after the assumed production function (Y = AK). In expanded versions of the model K can be thought of as "a proxy for a composite of capital goods that includes physical and human components" (Barro and Sala-i Martin, 1995, p. 146). In a retrospective assessment Romer notes: "My interpretation... was that investments in physical capital tended to be accompanied by investments in new ideas. Looking back...it has pushed the discussion away from knowledge and ideas and toward a more narrow focus on the marginal productivity of capital (Romer, 1993, p. 558).

References

Ahmad, Syed. On the Theory of Induced Innovation. *Economic Journal*, 1966, 76:344-57.

Ahmad, Syed. Reply to Professor Fellner. *Economic Journal*, 1967a, 77:662-64.

Ahmad, Syed. A Rejoinder to Professor Kennedy. *Economic Journal*, 1967b, 77:960-63.

Alchian, Armen A. Uncertainty, Evolution and Economic Theory. *Journal of Political Economy*, 1950, 58:211-22.

Ames, Edward and Nathan Rosenberg. The Enfield Arsenal in Theory and History. *Economic Journal*, 1968, 78:730-33.

Anderson, Esben S. Evolutionary Economics: Post-Schumpeterian Contributions. London: Pinter Publishers, 1994.

Arrow, Kenneth. The Economic Implications of Learning By Doing. *Review of Economic Studies*, 1962, 29:155-73.

Arrow, Kenneth, Viewpoint *Science* March 17, 1995, 267: p. 1617.

Arthur, W. Brian. Competing Technologies, Increasing Returns, and Lock-In by Historical Events. *The Economic Journal*, March 1989, 99:116-31.

Arthur, W. Brian, *Positive Feedbacks in the Economy Scientific American*, February 1990, 262: 92-99.

Arthur, W. Brian. *Increasing returns and path dependence in the economy*. Ann Arbor: The University of Michigan Press, 1994.

Arthur, W. Brian. Letter, October 17, 1996.

Arthur, W. Brian, Ermoliev, Yuri M. and Kaniovski, Yuri M. Path dependence processes and the emergence of macro-structure. *European Journal of Operational Research*, June 1987, 30:294-303.

Bardhan, Pranab. The Contribution of Endogenous Growth Theory to the Analysis of Development Problems: An Assessment. In J. Behrman and T. N. Srinivason (eds.), *Handbook of Development Economics*, Vol. III. New York, 1995, 2984-2998.

Barro, Robert J. and Xavier Sala-i-Martin. *Economic Growth*. New York: McGraw Hill, 1995.

BenZion, Uri and Ruttan, Vernon W. Money in the Production Function: An Interpretation of Empirical Results. *Review of Economics and Statistics*, 1975, 57:246-7.

BenZion, Uri and Ruttan, Vernon W. Aggregate Demand and the Rate of Technical Change. In Binswanger, Hans P. and Ruttan, Vernon W. *Induced innovation: Technology institutions and development*. Baltimore: Johns Hopkins University Press, 1978, 261-75.

Binswanger, Hans. P. The Measurement of Biased Efficiency Gains in U.S. and Japanese Agriculture to Test the Induced Innovation Hypothesis. Raleigh, North Carolina State University: Ph.D. Dissertation, 1973.

Binswanger, Hans P. A Cost Function Approach to the Measurement of Elasticities of Factor Demand and Elasticities of Substitution. *American Journal of Agricultural Economics*, 1974a, 56:377-86.

Binswanger, Hans P. The Measurement of Technical Change Biases With Many Factors of Production. *American Economic Review*, 1974b, 64:964-76.

Binswanger, Hans P. Induced Technical Change: Evolution of Thought, in Binswanger, Hans P. and Ruttan, Vernon W. (eds), *Induced innovation: Technology, institutions and development.* Baltimore: The Johns Hopkins University Press, 1978.

Binswanger, Hans. P. The Micro Economics of Induced Technical Change, in Binswanger, Hans P. and Ruttan, Vernon W. (eds) *Induced innovation: Technology, institutions and development.* Baltimore: The Johns Hopkins University Press, 1978.

Binswanger, Hans P. and Ruttan, Vernon W. *Induced innovation: Technology, institutions and development*. Baltimore: The Johns Hopkins University Press, 1978.

Blaug, Mark. A Survey of the Theory of Process-Innovation. *Economica*, 1963, 63:13-32.

Cheng, Yu-Ting and Andrew H. Van de Ven. Learning the Innovation Journey: Order Out of Chaos? Minneapolis, MN: University of Minnesota Strategic Management Center, Discussion Paper 208, October 1994.

Chipman, John S. Induced Technical Change and Patterns of International Trade, in Vernon, Raymond (ed) *The technology factor in international trade*. New York: Columbia University Press, 1970, pp. 95-127.

Christian, Jason E. The Simple Microeconomics of Induced Innovation. Department of Agricultural Economics, University of California, Davis, CA, December 23, 1993 (mimeo).

Cyert, R.M. and James G. March. *A behavioral theory of the firm*. Englewood Cliffs, NJ: Prentice Hall, 1963.

David, Paul A. Mechanization of Reaping in the Ante-Bellum Midwest, in Rosovsky, Henry (ed) *Industrialization in two systems: Essays in honor of Alexander Gerscherkron*, 1966, New York: John Wiley, pp. 3-39.

David, Paul A. Labor Scarcity and the Problem of Technological Practice and Progress in the Nineteenth Century. Cambridge, MA: Harvard Institute of Economic Research, May 1973, Research Paper 297.

David, Paul A. *Technical choice, innovation and economic growth*. Cambridge: Cambridge University Press, 1975.

David, Paul A. Clio and the Economics of QWERTY. *American Economic Review*, 1985, 76:332-37.

David, Paul A. Understanding the Economics of QWERTY: The Necessity of History, in Parker, William N. (ed) *Economic history and the modern economist*. New York: Basil Blackwell, 1986.

David, Paul A. Path Dependence and Predictability in Dynamic Systems With Local Network Externalities: A Paradigm for Historical Economics. In Foray, Dominique and Freeman, Christopher (eds) *Technology and the wealth of nations: The dynamics of contracted advantage*. London: Pinter Publishers, 1993, pp. 208-31.

David, Paul A. and Bunn, Julie Ann. The Economics of Gateway Technologies and Network Evolution: Lessons From Electricity Supply History. *Information Economics and Policy*, 1988, 3:165-202.

Davidson, William H. Factor Endowment, Innovation and International Trade Theory. *Kyklos*, 1979, 32:764-73.

Diamond, Peter, Danial McFadden and Miguel Rodriguez. Measurement of Factor Substitution and Bias of Technological Change. In Melvyn Fuss and Daniel McFadden, *Production Economics: A Dual Approach to Theory and Applications*, Vol 2. Amsterdam: North Holland, 1978:125-147.

Dosi, Giovanni. *Technical change and industrial transformation*. New York: St. Martins Press, 1984:26-45.

Dosi, Giovanni. Sources, Procedures, and Microeconomic Effects of Innovation. *Journal of Economic Literature*, 1988, 26:1120-71.

Dosi, Giovanni, "Letter," February 15, 1995.

Dosi, Giovanni, Keith Pavitt, and Luc Soete. *The Economics of Technological Change and International Trade*. New York: New York University Press, 1990.

Dosi, Giovanni, Renato Giannetti and Pier Angelo Toninelli. (Eds.) *Technology and Enterprise in a Historical Perspective*. Oxford: Oxford University Press, 1992.

Drandakis, E.M. and Phelps, E.S. A Model of Induced Invention, Growth and Distribution. *The Economic Journal*, 1966, 76:823-40.

Elster, Jon. *Explaining technical change*. Cambridge: Cambridge University Press, 1983.

Fellner, William. *Trends and cycles in economic activity*. New York: Henry Holt, 1956.

Fellner, William. Two Propositions in the Theory of Induced Innovations. *Economic Journal*, 1961, 71:305-08.

Fellner, William. Does the Market Direct the Relative Factor Saving Effects of Technological Progress?, in Nelson, Richard R. (ed.) *The rate and direction of inventive activity: Economic and social factors*. Princeton: Princeton University Press for the National Bureau of Economic Research, 1962.

Fellner, William. Comment on the Induced Bias. *Economic Journal*, 1967, 77:664-65.

Fogel, Robert W. The Specification Problem in Economic History. *Journal of Economic History*, 1967, 27:283-308.

Freeman, Christopher. The Economics of Industrial Innovation. Cambridge, MA: MIT Press, 2nd. Ed., 1982.

Freeman, Christopher. The Economics of Technical Change. *Cambridge Journal of Economics*, 1994, 18:463-514.

Foray, Dominique and Arnulf Grubler, Morphological Analysis, Diffusion and Lock-out of Technologies: Ferrous Casting in France and the FRG, *Research Policy* 1990, 19: 535-550.

Gans, Joshua S. and George B. Shepherd, How Are the Mighty Fallen: Rejected Classic Articles by Leading Economics, *Journal of Economic Perspectives* 1994, 8:165-179.

Grant, Wyn, William Patterson and Colin Whitston. *Government and the Chemical Industry: A Comparative Study of Britain and West Germany*. Oxford: Oxford University Press, 1988.

Griliches, Zvi. Hybrid Corn: An Exploration in the Economics of Technological Change. *Econometrica*, 1957, 25:501-22.

Gilfillan, S. Colin. *The sociology of invention*. Chicago: Folliett, 1935.

Grubler, Arnulf and Nakicenovic, Nebojsa. The Dynamic Evolution of Methane Technologies. In Lee, T.H., Linden, H.R., Dryfus, D.A. and Vasco, T. (eds) *The methane age*. Dordrecht: Kluwer Academic Publishers, 1988, pp. 13-44.

Habakkuk, H.J. *American and British technology in the nineteenth century*. Cambridge: Cambridge University Press, 1962.

Haltmaier, Jane. Induced Inovation and Productivity Growth: An Empirical Analysis. Washington, D.C.: Federal Reserve Board Special Studies Paper 220, February 1986.

Hamilton, C. and Soderstrom, H.T. Technology and International Trade: A Heckscher-Ohlin Approach, in Grassman, S. and Londberg, E. (eds) *The world economic order: Past and prospects*. London: Macmillan, 1981, pp. 198-229.

Hayami, Yujiro and Ruttan, Vernon W. Factor prices and technical change in agricultural development: The United States and Japan, 1880-1960. *Journal of Political Economy*, 78 (September-October, 1970), pp. 1115-41.

Hayami, Yujiro and Ruttan, Vernon W. *Agricultural development: An international perspective.* Baltimore: The Johns Hopkins University Press, 1971 and 1985.

Hicks, John. *The theory of wages*. London: Macmillan, 1st ed, 1932/2nd ed, 1963.

James, John A. and Skinner, Jonathan S. Resolution of the Labor-Scarcity Paradox, *Journal of Economic History*, 45 (September, 1985), pp. 513-39.

Jorgenson, Dale W. and Fraumeni, Barbara M. Relative Prices and Technical Change. In Bendt, Ernst R. and Fields, Barry (eds.) *Modeling and Measuring National Resource Substitution*. Cambridge, MA: MIT Press, 1981, pp. 17-47.

Kamien, Morton I. and Nancy L. Schwartz. Optimal Induced Technical Change, *Econometrica*. 36 (1969), pp. 1-17.

Kennedy, Charles. Induced Bias in Innovation and the Theory of Distribution. *The Economic Journal*, 1964, 74:541-7.

Kennedy, Charles. Samuelson on Induced Innovation. *Review of Economics and Statistics*, 1966, 48:442-44.

Kennedy, Charles. On the Theory of Induced Innovation--A Reply. *Economic Journal*, 1967, 77:958-60.

Koppel Bruce M. (ed.) *Induced Innovation Theory and Internaitonal Agricultural Development.* Baltimore: The Johns Hopkins University Press, 1995.

Landau, Ralph and Rosenberg, Nathan. Successful Commercialization in the Chemical Process Industries. In Rosenberg, Nathan, Landau, Ralph and Mowery, David C. (eds.) Technology and the Wealth of Nations. Stanford, CA: Stanford University Press, 1992, pp. 73-119.

Landes, David S. What-Room for Accident in History?: Explaining Big Changes by Small Events. *Economic History Review*, 1994, 47:637-656.

Langolis, Richard N. And Michael J. Everett. What is Evolutionary Economics? In Lars Magnusson (ed). Evolutionary and Neo-Schumpeterian Approaches to Economics. Dordrect: Kluwer, 1994, pp. 11-47.

Levin, Richard C. Technical Change and Optimal Scale: Some Evidence and Implications. *Southern Economic Journal*, Oct.1977, 44:208-21.

Liebowitz, S.J. and Margolis, Stephen E. The Fable of the Keys. *Journal of Law and Economics*, April 1990, 33:1-25.

Liebowitz, S.J. and Stephen E. Margolis. Market Processes and the Selection of Standards. University of Texas at Dallas School of Management Working Paper, March 1992.

Liebowitz, S.J. and Margolis, Stephen E. Network Externality: An Uncommon Tragedy. *Journal of Economic Perspectives*, 1994, 8:2:133-50.

Liebowitz, S.J. and Margolis, Stephen E. Path Dependence, Lock In, and History. *Journal of Law, Organization and Organization*, (forthcoming, 1995).

Lucas, Robert E. Jr. Tests of a Capital-Theoretic Model of Technological Change. *Review of Economic Studies*, 1967, 34:175-80.

Lucas, Robert E. Jr. On the Mechanics of Economic Development. *Journal of Monetary Economics*, 1988, 22:3-42.

Mowery, David C. and Rosenberg, Nathan. The Influence of Market Demand Upon Innovation: A Critical Review of Some Recent Empirical Studies. *Research Policy*, 1979, 8:103-53.

Nakicenovic, Nebojsa. Diffusion of Pervasive Systems: A Case of Transport Infrastructures. *Technological Forecasting and Social Change*. March/April 1991, 39:181-219.

Nelson, Richard R. Recent Evolutionary Theorizing About Economic Change. *Journal of Economic Literature*. March 1995, 33: 48-90.

Nelson, Richard R. and Winter, Sidney G. Toward an Evolutionary Theory of Economic Capabilities. *American Economic Review*, 1973, 63:440-49.

Nelson, Richard R. and Winter, Sidney G. Neoclassical vs. Evolutionary Theories of Economic Growth: Critique and Prospects. *Economic Journal*, 1974, 84:886-905.

Nelson, Richard R. and Winter, Sidney G. Factor Price Changes and Factor Substitution in an Evolutionary Model. *Bell Journal of Economics*, 1975, 6:466-86.

Nelson, Richard R., Winter, Sidney G. and Schuette, Herbert L. Technical Change in an Evolutionary Model. *Quarterly Journal of Economics,* 1976, 40:90-118.

Nelson, Richard R. and Winter, Sidney G. Simulation of Schumpeterian Competition. *American Economic Review*, 1977, 67:271-76.

Nelson, Richard R. and Winter, Sidney G. *An evolutionary theory of economic change*. Cambridge, MA: Harvard University Press, 1982.

Nordhaus, William D. *Invention, growth and welfare: A theoretical treatment of technical change.* Cambridge, MA: The M.I.T. Press, 1969.

Nordhaus, William D. Some Skeptical Thoughts on the Theory of Induced Innovation. *Quarterly Journal of Economics*, 1973, 87:208-19.

Olmstead, Alan L. and Paul Rhode. Induced Innovation in American Agricultures: A Reconsideration. *Journal of Political Economy*, 1993, 101: 100-118.

Olmstead, Alan L. and Paul Rhode. Induced Innovation in American Agriculture: An Econometric Analysis. (Institute of Government Affairs, University of California, Davis, CA, mimeo, 1995).

Penrose, Elizabeth T. Biological Analogies to the Theory of the Firm. *American Economic Review*, 1952, 42:804-19.

Romer, Paul M. Increasing Returns and Long-run Growth. *Journal of Political Economy*. 1986, 94:1002-37..

Romer, Paul M., "Idea Gaps and Object Gaps in Economic Development" *Journal of Monetary Economics* 1994, 8: 3-22.

Romer. Paul M., "Idea Gaps and Object Gaps in Economic Development" *Journal of Monetary Economics* 1994, 8: 543-573.

Rosenberg, Nathan. Science, Invention and Economic Growth. *Economic Journal*, 1974, pp. 225-29.

Rosenberg, Nathan. Learning by Using. In Rosenberg, Nathan. *Inside the Black Box: Technology and Economics*. Cambridge, MA: Cambridge University Press, 1982, pp. 120-40.

Rothschild, Kurt. *The theory of wages*. Oxford: Blackwell Publishers, 1956.

Ruttan, Vernon W., Usher and Schumpeter on Invention, Innovation, and Technological Change. *Quarterly Journal of Economics* 1959, 73: 596-606.

Ruttan, Vernon W. Induced Innovation and Path Dependence: A Reassessment with Respect to Agricultural Development and the Environment, *Technological Forecasting and Social Change*. 1996a, 53:41-60.

Ruttan, Vernon W. Growth Economics and Development Economics: What Should Development Economist Learn (if Anything) from the New Growth Theory" St. Paul: University of Minnesota Department of Applied Economics, 1996b (mimeo).

Ruttan, Vernon W. Induced Innovation, Evolutionary Theory and Path Dependence: Sources of Technical Change, *Economic Journal* (forthcoming, 1997).

Ruttan, Vernon W. and Hayami, Yujiro. Induced Innovation Theory and Agricultural Development: A Personal Account. In Koppel, Bruce (ed) *Induced innovation theory and international agricultural development: A reassessment*. Baltimore: The Johns Hopkins University Press, 1994:22-36.

Salter, W.E.G. *Productivity and technical change*. Cambridge: Cambridge University Press, 1st ed, 1960/2nd ed 1960.

Samuelson, Paul A. A Theory of Induced Innovation Along Kennedy-Weizsacker Lines. *Review of Economics and Statistics*, 1965, 47:343-56.

Samuelson, Paul A. 1966. Rejoinder: Agreements, Disagreements, Doubts and the Case of Induced Harrod-Neutral Technical Change. *Review of Economics and Statistics*, 1966, 48:444-48.

Scherer, Fredrick M. Demand Pull and Technological Inventions: Schmookler Revisited. *Journal of Industrial Economics*, 1982, 30:225-37.

Schmookler, Jacob. Determinants of Industrial Invention, in Nelson, Richard R. (ed) *The rate of direction of inventive activity: Economic and social factors*. Princeton: Princeton University Press, 1962.

Schmookler, Jacob. *Invention and economic growth*. Cambridge: Harvard University Press, 1966.

Schumpeter, Joseph A. *The theory of economic development*. Cambridge, MA: Harvard University Press, 1934.

Schumpeter, Joseph A. *Business cycles*. Vol. I and II. New York: McGraw Hill, 1939.

Schumpeter, Joseph A. *Capitalism, socialism and democracy*. New York: Harper, 1950.

Simon, Herbert A. A Behavioral Model of Rational Choice. *Quarterly Journal of Economics*, 1955, 69:99-118.

Simon, Herbert A. Theories of Decision Making in Economics. *American Economic Review*, 1959, 49:253-83.

Stokes, Raymond G. Opting for Oil: The Political Economy of Technical Change in the West German Chemical Industry, 1945-61. Cambridge: Cambridge University Press, 1994.

Srinivasan, T.N. Long Run Growth Theories and Empirics: Anything New? In Takatoshi Ito and Anne O. Krueger (eds.) Growth Theories in Light of the East Asian Experience. Chicago: University of Chicago Press, 1985, pp. 37-70.

Temel, Tugrul. Endogenous Technological Change via Industry Lobbying in a Two Sector Overlapping Generations Model. Minneapolis, MN: University of Minnesota Graduate School, 1995.

Temin, Peter. Labor Scarcity and the Problems of American Industrial Efficiency. *Journal of Economic History*, 1966, 26:277-98.

Thirtle, Colin G. and Ruttan, Vernon W. *The role of demand and supply in the generation and diffusion of technical change*. London: Harwood Academic Publishers, 1987.

Van de Ven, Andrew and Garud, Raguhi. Innovation and Industry Development: The Case of Cochlear Implants. In Burgelman, R. and Rosenbloom, R. (eds) *Research on technological innovation, management and policy*, Vol. 5. Greenwich, CT: JAI Press, 1993:1-46.

Vernon, Raymond. International Investment and International Trade in the Product Cycle. *Quarterly Journal of Economics*. 1966, 80:190-207.

Vernon, Raymond. The Product Cycle Hypothesis in a New International Environment. *Oxford Bulletin of Economics and Statistics*, 1979, 40:255-67.

Wan, Henry Y., Jr. *Economic growth*. New York: Harcourt Brace Javonovich, 1971, pp. 215-26.

Walsh, Vivien. Invention and Innovation in the Chemical Industry: Demand-Pull or Discovery-Push? *Research Policy*, 1984, 13:211-34.

Winter, Sidney G. Satisficing, Selection and the Innovating Remnant. *Quarterly Journal of Economics*, May 1971, 85:237-61.

Winter, Sidney G. Schumpeterian Competition in Alternative Technological Regimes. *Journal of Economic Behavior and Organization*. 1984, 5:287-320.

Witt, Ulrich. *Evolutionary economics*. Aldersbat, England: Edward Elgar Publishing, 1993.

Wright, Gavin. The Origins of American Industrial Success, 1889-1940. *The American Economic Review*. September 1990, 80: 651-667.