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The importance of both science and technology for modern economic growth has been accepted as almost self-evident since at least the middle of the nineteenth century [283, p. 355; 342]. But it was not until the mid-1950s that economists attempted to measure the contribution of technical change to economic growth [1, 444, 480, 506].

The primary focus of the early studies on technical change and productivity growth was simply to measure the contribution of technical change, relative to conventional resources, to growth in output. Technical change itself was treated as a response to the economic opportunities resulting from autonomous advances in scientific and technical knowledge.[1] By the mid-1960s, however, increasingly serious efforts were being made to explore the influence of economic forces on technical change.

In this paper we attempt to review and assess the literature on the impact of economic forces on the rate and direction of technical change. The paper begins by considering the impact of economic forces on invention and innovation. In Part 2 we examine the impact of factor endowments and prices on the direction of technical change, and in Part 3 we examine the process of the diffusion of technology.

1.0 SUPPLY AND DEMAND EXPLANATIONS OF INVENTION AND INNOVATION

Schumpeter, whose writings have been exceptionally important in formulating 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" [487, Vol. 1, p. 84]. Rosenberg has argued that the effect has been to divert the attention of economists away from those activities that are most relevant to technical innovation and the diffusion or transfer of technology [432, pp. 66-68]. Other students of technical change have argued that the Schumpeterian distinction between invention and innovation is excessively artificial. For analytical purposes it is more useful to use the term _innovation_ to designate any "new thing" in the area of science or technology and to reserve the term _invention_ to refer to that subset of technical innovations that are patentable [263, p. 2; 351, p. 103; 445, p. 605].

1.1 Processes of Invention

At the time economists first became interested in the economics of invention and innovation there were already well-defined traditions of scholarship in the literature on applied technology, sociology, and history. In his classic study, _A History of Mechanical Inventions_, Usher [547, pp. 56-83] identified three general approaches to the emergence of inventions. He termed these the _transcendentalist_ approach, the _mechanistic process_ approach, and the _cumulative synthesis_ approach.

The _transcendentalist approach_ attributes the emergence of invention to the inspiration of the occasional genius who from time to time achieves insight into essential truth through the exercise of personal energy, intuition, and skill. This heroic approach to the process of invention bears striking resemblance to the Schumpeterian view of the entrepreneur. The transcendentalist perspective dominated much of the early historical and biographical scholarship on technical change [234, 501].[2] Usher rejected the transcendentalist view as unhistorical. He argued that the act of insight was not the rare, unusual phenomenon assumed by the transcendentalists and further that the act of insight that results in the perception of new relationships requires a highly specific conditioning of the mind within the framework of the problem to be solved. It was not an accident that Henry Ford, a bicycle mechanic, contributed to the development of the automobile or that Harry Ferguson, a self-taught mechanic, was the first to apply basic physical principles to the integrated design of tractors and tractor equipment.

The <u>mechanistic process</u> theory viewed invention as proceeding under the stress of necessity with the individual inventor being an instrument of historical processes. This view emerged from the detailed investigations of invention sequences by the Chicago sociologists, Ogburn and Gilfillan.[3] By demonstrating that the process of invention typically represented a new combination of a large number of individual elements accumulated over long periods of time, the sociologists erected an effective challenge to the claims of the transcendentalists. But Usher argued that the approach overlooked the significance of discontinuities inherent in the process of invention and insisted that the "acts of insight" required to bridge the discontinuities are possible for only a limited number of individuals operating under conditions that bring both an awareness of the problem and the elements of a solution within their frame of reference. And even under these conditions it is not certain that the specific act of insight required for a solution to the problem will occur.

Usher suggested a cumulative synthesis approach as an alternative to the transcendentalist and mechanistic process theories of invention. With this framework, which drew on Gestalt psychology, major inventions are visualized as emerging from the cumulative synthesis of relatively simple inventions, each of which requires an individual "act of insight." A major or strategic invention, or advances in technology, represents the cumulative synthesis of many individual inventions. Many of the individual inventions do no more than set the stage for a major invention that then requires substantial critical revision to adapt it to a particular use. A schematic presentation of the elements of the individual act of insight and the cumulative synthesis as visualized by Usher are presented in Figures 1.1 and 1.2.

Usher's cumulative synthesis approach provides the element of a critical theory of the social process by which "new things" come into existence and are improved, a process that is broad enough to encompass the whole range of activities characterized by the terms science, invention, and innovation. One is no longer forced to maintain, as Schumpeter did, the increasingly artificial distinction between the processes of invention and innovation or to explain away the association between scientists, inventors, and entrepreneurs as merely a chance coincidence. But the Schumpeterian system has remained an obstacle to the efforts by economists to understand the processes of technical innovation [432, pp. 66-68].

A major contribution of Usher's cumulative synthesis theory was that it clarified the points at which economic forces could be used to speed the

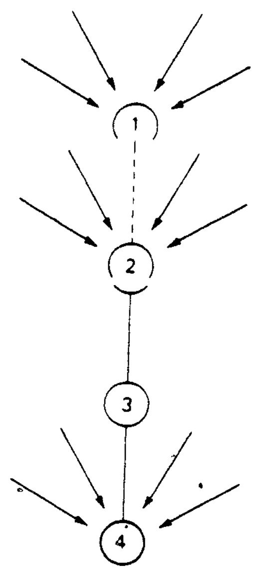

Figure 1.1 The emergence of novelty in the act of insight

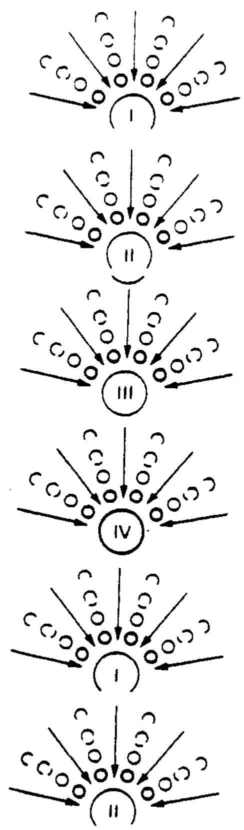

Figure 1.2 The process of cumulative synthesis

rate or alter the direction of technical change. The possibility of allocating research resources to influence the rate or direction of technical change was obscured by the transcendentalist approach, with its dependence on the emergence of the hero inventor, and was denied by the mechanistic process approach, with its dependence on inexorable historical trends or forces. The focus of conscious effort to affect the rate or direction of technical innovation centers around the second and fourth steps in the process as outlined by Usher--in setting the stage and in critical revision. By consciously bringing together the elements of a solution--by creating a favorable environment--the stage can be set to enhance the probability that the critical act of insight will occur. Two of the great institutional innovations of the nineteenth century, the industrial research laboratory and the agricultural experiment station, were consciously designed to set the stage more effectively for technical innovation.[4]

The impulses that gave rise to both the transcendentalist and mechanistic process approaches continue to be reflected in contemporary efforts to understand the forces that influence the rate and direction of technical change. The transcendentalist perspective was essentially a supply-side perspective. Its equivalent is the contemporary view that autonomous advances in scientific and technical knowledge determine the rate and direction of technical change. There are both supply-side and demand-side variants of the mechanistic process perspective. In the supply-side variant, technical change is a near automatic response to advances in material culture or knowledge, and in the demand-side variant it is a near automatic response to growth in product demand or to changes in relative factor prices.

The dialogue about the sources of technical change continues to center around whether technical change has been driven primarily by autonomous advances in science and technology or driven primarily by economic forces--whether technical change is most appropriately viewed as exogenous or endogenous to the economic system. In the next section we review the recent dialogue and evidence on this issue.

1.2 Sources of Technical Change: Demand Pull and Supply Push

Before the beginning of the nineteenth century the linkages between advances in scientific knowledge and advances in technology were relatively weak. "Science was traditionally aristocratic, speculative, intellectual in intent; technology was lower-class, empirical and action oriented" [561, p. 79]. Science had remarkably little to offer to those who were engaged in advancing technology.

The nineteenth century witnessed a remarkable fusion of theoretical and empirical inquiry [287]. By the middle of the twentieth century a new orthodoxy had emerged to the effect that modern technology was simply applied science [27]. Basic science developed theory and understanding; applied science took that knowledge and used it in the design of new technology. In the United States this new orthodoxy was reinforced by the success of World War II science-based military technology. It found its most influential expression in the report by Vannevar Bush on post-war scientific research [77]. The Bush report became the charter for post-war science and technology policy. And the science-based technology development perspective tended to dominate many of the early post-war studies of invention and innovation [302].

The interaction between advances in science and technology is, however, much more complex than is reflected in the early post-war perspective [168, 287, 400]. Instead of a single path running from scientific discovery through applied science to development, it is more consistent with historical evidence to model science-oriented and technology-oriented research as two parallel but interacting paths. These two paths are connected through a common pool of existing scientific knowledge; both paths lead from and feed back into further advances in both scientific and technical knowledge (Figure 1.3).

Since the early 1960s, an increasingly serious challenge has been mounted against the new orthodoxy. The challenge has proceeded along three fronts. One has been to challenge the historical accuracy of the view that the flow of knowledge has run in a linear sequence from science to technology.[5] A second has been to document that the allocation of resources to inventive activity and to research has been strongly influenced by changes or differences in demand.[6] A third has been an attempt to show that the development and diffusion of commercially successful technical innovations have been primarily a response to changes (or differences) in demand.[7]

Arguments about the priority of the role of market demand and the supply of knowledge in inducing advances in technology were intensified by the late 1960s by a study conducted by the Office of the Director of Defense Research and Engineering (HINDSIGHT) [374, 497] that purported to show that the significant "research events" that had contributed 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 and conducted by the Illinois Institute of Technology (TRACES) [236] and the Battelle Research Institute [30]. The TRACES and Battelle studies adopted a much longer time horizon than the 20-year period employed in the HINDSIGHT study. And, not unexpectedly, they found that science events were of much greater importance, relative to technology events, as a source of technical change than was shown in the HINDSIGHT study.

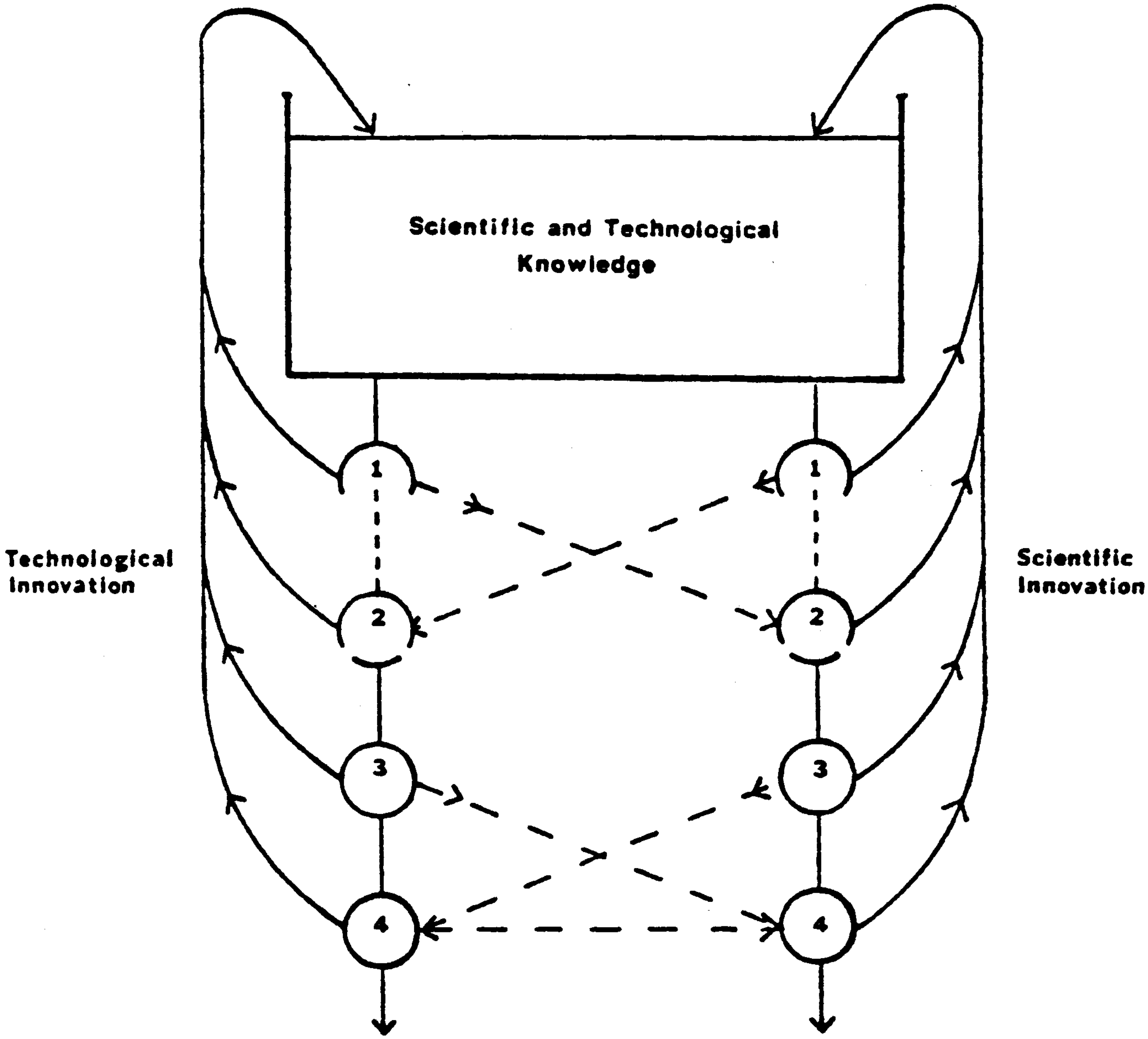

Figure 1.3 The interaction between advances in scientific and technical knowledge

From an analytical perspective the "demand pull" or "demand-induced" theory of technical change can be thought of as a scheme in which the demand for technical change, in the form of product and process innovations, is derived from the demand for commodities; the demand for inventive activity, including research and development, is derived from the demand for technical change; and the demand for advances in scientific knowledge is, in turn, derived from the demand for inventive activity.

In spite of the large literature on the influence of market demand on technology development, the evidence on the relative significance of "demand pull" on the rate and direction of technical change has not been firmly established. Mowery and Rosenberg argue that much of the recent research purporting to show that technical innovation has largely been demand-induced is seriously flawed by lack of rigor in the specification of demand [346, 434, pp. 192-241].[8] The demand pull model of technological change has also been criticized for ignoring both the internal logic of scientific progress and the historical contribution of science to technical progress. Much of the earlier research in the philosophy and history of science and in the sociology of knowledge presumes that advances in science are largely determined by the internal logic of discovery in the several scientific disciplines [280, 400].[9] The demand pull perspective has been criticized as ignoring "the whole thrust of modern science and the manner in which the growth of specialized knowledge has shaped and enlarged man's technological capacities" [431, 432, p. 264].

The supply or technology push view, restated in economic terms, is that autonomous advances in scientific and technical knowledge permit the substitution of calculation or computation for the more expensive process of trial and error. The effect of advances in science is to shift the supply curve for technical change to the right [351, p. 106]. A classical example is the invention of the contact process for sulfuric acid. Mathematical modeling indicated with great precision that there was only one practical way to achieve synthesis of sulfuric acid by the contact process [351, pp. 105-111].

Rosenberg has suggested that "to establish the independent importance of supply-side considerations, it is necessary to demonstrate several things: (1) That science and technology progress, in some measure, along lines determined either by internal logic, degree of complexity or at least in response to forces independent of economic need; (2) that this sequence in turn imposes constraints or presents opportunities which materially shape the direction and the timing of the inventive process; and (3) that, as a result, the costs of invention differ in different industries" [432, pp. 265-266].

Our review of the literature does not lead us to a rejection of the "demand pull" model of technical change in spite of the Mowery-Rosenberg criticisms. The model is supported by rigorous studies at both the sector [190, 481] and macroeconomic levels [36, pp. 261-275; 301]. The model has also provided the theoretical framework for the estimates of the rates of return to research developed initially by Griliches [191].

It is also our view that the dialogue over the relative priority of "demand pull" and "supply push" explanations of the rate and direction of technical change has been misplaced. It is not necessary to demonstrate that basic research is the cornucopia from which all inventive activity must flow to conclude that investment in the generation of new scientific and technical knowledge can open up new possibilities for technical change. Nor is it 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 resources to research [351].

What can be said at this stage about the relative importance of the demand pull or demand-induced theory, and of the supply or technology push theory, in accounting for the rate and direction of technical change? The only study we have been able to identify that attempts to test simultaneously the demand-induced and the supply push hypotheses was conducted by Scherer [478]. The Scherer analysis confirmed the earlier Schmookler findings of strong association between capital goods inventions and investment. But Scherer found that the association between industrial materials inventions and measures of demand pull (materials purchased and value added) was considerably weaker than in the capital goods industries. He also found that 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 invention activity among industries.

Both private and public sector research managers are faced with questions about the relative priority of the allocation of research resources (a) to advance knowledge in those fields in which scientific and technological opportunities appear most favorable or (b) for applied research and development in those industries characterized by current or anticipated rapid growth in demand. The research we have reviewed in this section gives us little guidance beyond Nelson's conclusions of a quarter century ago: "Though the expected profitability of an invention in a particular field affects the rate of invention activity in that field, the tremendous uncertainties involved in making any major technological breakthrough preclude either the routinization of invention or the precise prediction of invention. Conditions of demand and of scientific knowledge provide us with guides for prediction and analysis, but only with rough guides" [351, p. 115].

The dialogue with respect to the role of "demand pull" and "supply push" has been relatively unproductive in the generation of either a rigorously testable empirical proposition or a useful guide to research policy. A second body of literature that has focused on the impact of changes or differences in resource endowment and factor prices on the direction of technical change has been much more productive. We turn in the next part to a review of the literature on factor bias and induced technical change.

2.0 INDUCED INNOVATION AND FACTOR BIASES

The total factor productivity studies[10] of the 1950s showed that only a small proportion of the long-term growth of output of the American economy could be explained by conventionally measured increases in the quantities of labour and capital. Solow's [506] classic estimation, consistent with his own growth model [505], attributed 87.5 percent of per capita growth to technical change and 12.5 percent to increased capital per head.

The unexpected importance of the residual measure of technical change or productivity growth[11] led to a revival of interest in the classification and explanation of changes in technology.

2.1 Neutrality and Bias in Technical Change

The term technical progress has been used to describe both increases in the stock of knowledge pertaining to the art of production and the effects of such new technology on the level of output [272]. The increase in output obtained from the same quantities of inputs, or equivalently,[12] the decrease in inputs required to produce a given level of output, provides a measure of technical progress.[13] This definition of technical change is appealing because it is straightforward and constant with the neoclassical representation of technical change as the movement of the isoquant towards the origin (Figure 2.1), or an upward shift of the production function[14] (Figure 2.2). The disadvantage is that technical change is unlikely to affect all factor inputs equally. This difficulty, which raises the issue of factor bias in technical change, has led several authors to

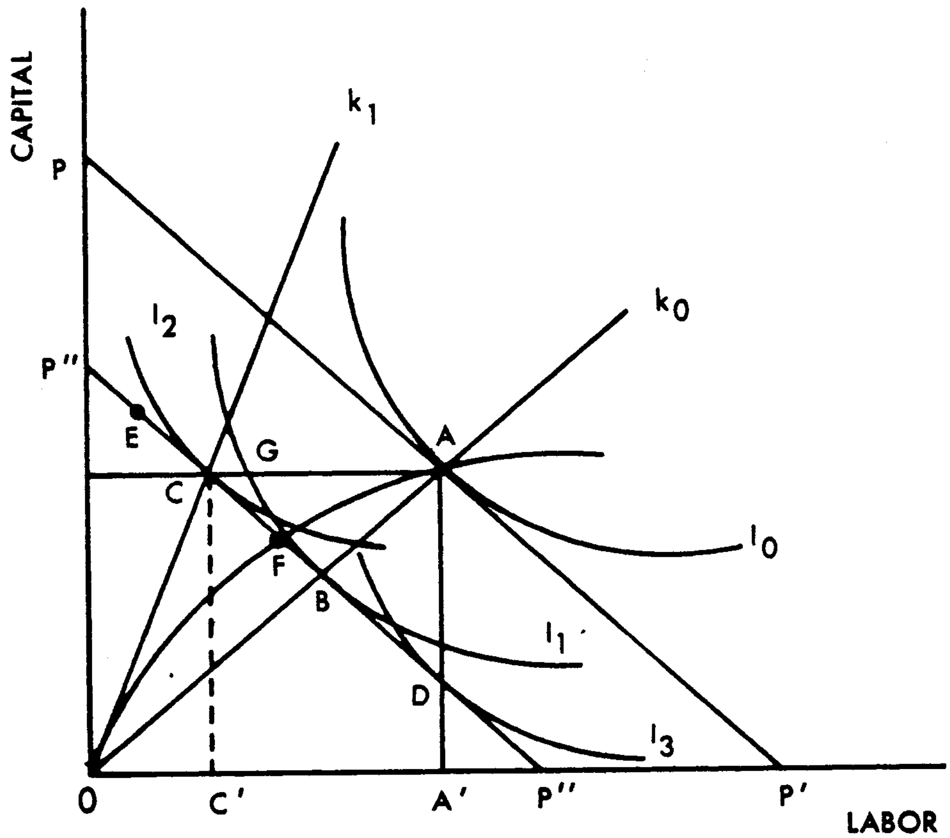

Figure 2.1 Neutrality and bias of technical change at constant factor prices

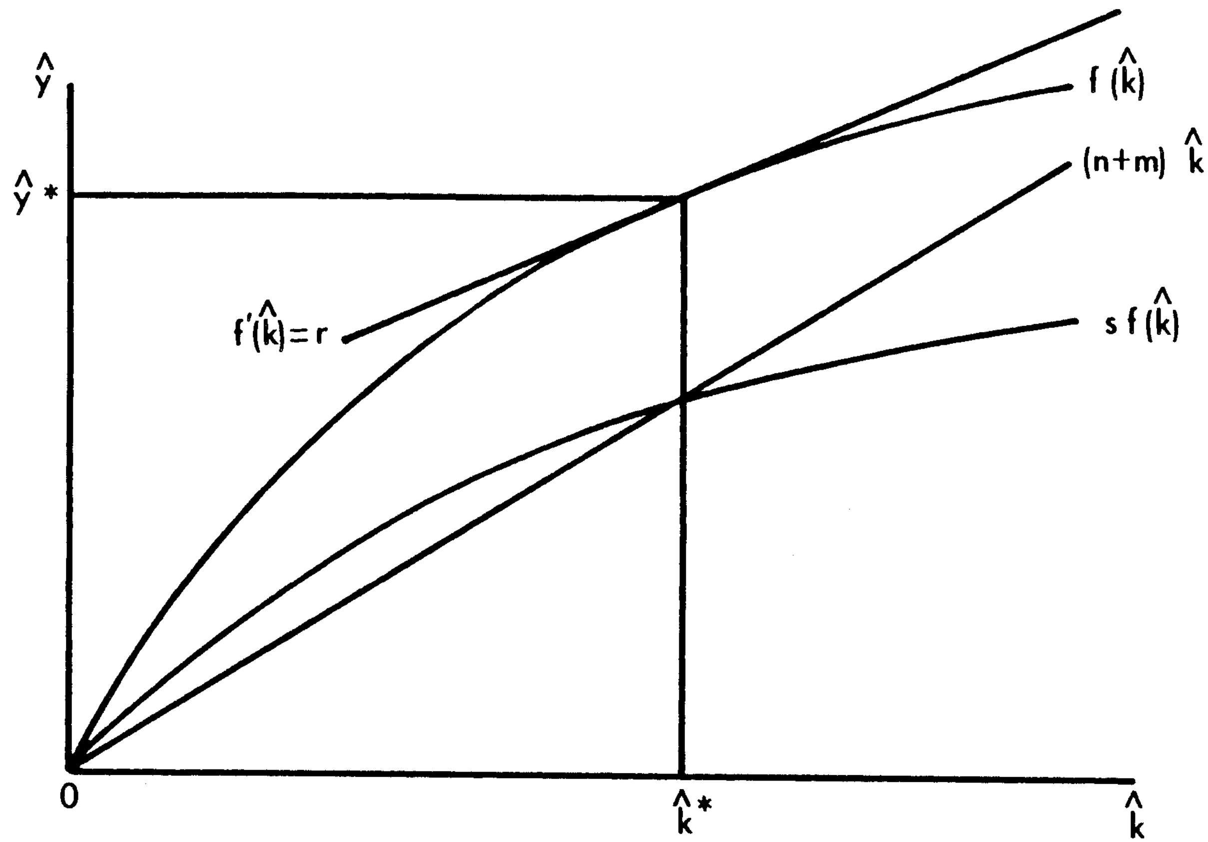

Figure 2.2 Technical change in the neoclassical growth model

define technical change in terms of the proportional decrease in production costs at constant factor prices.[15]

2.11 Hicks Neutrality and the Microeconomic Approach to Technical Change

In Figure 2.1 inputs of labour and capital are measured in homogenous physical units and all four isoquants represent a fixed level of homogenous output. Initial equilibrium is at point A where the isoquant I is tangential to the isocost constraint PP'. Since the slope of the isoquant is determined by the ratio of the marginal products of the two inputs and the slope of PP' represents the ratio of factor prices, the two ratios must be equal at equilibrium points such as A. The isoquants I_1, I_2 and I_3 represent alternative new technologies. For all three, the proportional saving in resources is OP"/OP', but the factor-saving biases differ. If the new technology results in a new equilibrium at point B on isoquant I_1, then technical change saves both factors in the same proportion as they were being used and the original factor ratio k_0 is maintained. This is the notion of neutrality in technical change associated with Hicks [225].

If the production function can be written in the factor-augmenting form,

$$(1) \qquad Y = F[A(t)K,\ B(t)L],$$

Hicks neutrality requires that

$$(2) \qquad \frac{A(t)}{A(t)} = \frac{B(t)}{B(t)} = m,$$

so that technical change augments[16] both factors equally, and if constant returns to scale are assumed, the production function can be written as

(3) $\quad Y = A(t)\ F(K,L).$

Bias is defined relative to neutrality, so that if the new eqilibrium is at any point to the northwest of B, along P"P", technical change is said to be labour-saving. Since the proportional reduction in labour is greater than that for capital, the result is an increase in the capital-labour ratio. For example, if the new equilibrium were at C on isoquant I_2, the proportional reduction in labour input is C'A'/OA', while the input of capital remains unchanged and the capital-labour ratio is increased to k_1. In terms of the factor-augmenting production function of equation (1), this requires that

(4) $$\frac{A(t)}{A(t)} = 0 \quad \frac{B(t)}{B(t)} = m \ .$$

Technical change is *purely* labour-saving or augmenting, but this is not a limiting case. A point such as E could also represent the new equilibrium, in which case the change is labour-saving and capital-using in the sense that absolutely more capital is required. Unfortunately the term *capital-using* has been applied to all changes that save a larger proportion of labour (relative to initial usage) than of capital (all points to the northwest of B). Similarly, point D represents a purely capital-saving technical change, which in terms of factor augmentation requires that

(5) $$\frac{A(t)}{A(t)} = m, \quad \frac{B(t)}{B(t)} = 0 \ .$$

To summarise, Hicks neutrality and bias can be defined [53, 462] in terms of the proportional change in the capital-labour ratio at *constant factor prices*:

$$(6) \qquad \frac{(K/L)}{t}\,\frac{1}{(K/L)} \left| \begin{array}{l} > 0 \text{ labour-saving} \\ = 0 \text{ neutral} \\ < \text{ capital-saving} \\ \text{factor prices } (\frac{W}{R}) \end{array} \right.$$

Salter [462] argues convincingly in favour of the above definitions at the micro level of the firm or single industry, but the distribution of income at the economy-wide level was the main object of interest in the earlier studies of Hicks [225] and Robinson [417]. Hicks [225, p. 121] originally argued that "we can classify inventions accordingly as their initial effects are to increase, leave unchanged or diminish the ratio of the marginal product of capital to that of labour. We may call these inventions 'labour-saving,' 'neutral' and 'capital-saving.'"

But to compare situations before and after a change in technique, something must be held constant. For aggregate analysis, factor endowments, rather than factor prices, may be regarded as fixed. This has led to widespread acceptance [204, 206, p. 213] of definitions similar to that of Kennedy and Thirlwall [272, p. 20], who assert that "Hicks defined a 'neutral' invention as one which with given factor proportions raised the marginal product of labour in the same proportion as the marginal product of capital."

Economic interpretation is again simple and appealing. A labour-saving innovation makes labour in some sense more plentiful relative to capital than it was previously, with the result that the marginal product of labour must fall relative to that of capital. Since the equilibria shown in Figure 2.1 require that the ratio of marginal products be equal to the ratio of factor prices, this is equivalent to a rise in the price of capital relative to that of labour.

Bias and neutrality can again be formally defined in terms of the proportional change in the ratio of marginal products as a constant factor ratio.

$$(7) \qquad \frac{\left(\frac{F_k}{F_l}\right)}{t} \frac{1}{\left(\frac{F_k}{F_l}\right)} \Bigg| \begin{array}{l} > \text{ labour-saving} \\ = 0 \text{ neutral} \\ < \text{ capital-saving} \\ \text{factor ratio } \left(\frac{K}{L}\right) \end{array}$$

Salter [462, pp. 32-33] argues that this definition reverses the reasoning of the first approach but results in the same division of innovations into labour- and capital-saving categories. Binswanger notes that equation (1) is actually equal to equation (7) multiplied by the elasticity of substitution. So, although the two definitions have varying economic implications, formally they differ only by a scalar multiple. Both of these statements of the relationship require careful qualification, for they are true only for a restricted class of production functions. Early critics of the "Hicks-Robinson" classification (equation (7) above) argued that it is only for linear homogenous production functions that marginal productivities depend only on factor ratios and are independent of the level of output [61]. Alternative definitions of Hicks neutrality and the relationship between them implied by different restictions on the production function are investigated by Blackorby, Lovell and Thursby [60].[17]

A third definition of neutrality follows from those above. If, at constant factor prices, the ratio of capital to labour increases, the ratio of capital's share relative to that of labour, $(\frac{rK}{wL})$, must also increase. Alternatively, if at a constant factor ratio the price of capital increases relative to the price of labour, capital's relative share must increase. Thus by equation (6) or (7), technical change must be labour-saving if capital's share increases, neutral if shares remain constant, and capital-saving if capital's relative share falls.[18]

The attraction of the factor shares definition is that it generalises easily to handle many factors of production. A single measure of bias for each factor[19] is given by

$$(8) \qquad \frac{dS_i}{dt}\,\frac{1}{S_i}\;\left|\;\begin{array}{l} > 0 \text{ factor } i \text{ saving} \\ = 0 \text{ neutral} \\ < 0 \text{ factor } i \text{ using} \\ \text{relative factor prices constant} \end{array}\right.$$

where S_i is the share of factor i (in total costs) [53, p. 21]. Empirical applications of this measure are becoming increasingly common in multiple input studies and will be discussed in Section 2.3.

2.12 Harrod Neutrality and the Theory of Economic Growth

In the long run, neither factor prices nor factor input ratios can realistically be held constant. In growth models, the equivalent of the static equilibrium of the last section is the steady state, in which all variables grow at constant rates. Harrod's definition of neutrality is compatible with the existence of steady state growth,[20] allowing technical change to be incorporated in standard growth models without disturbing the balance between labour and capital. This is achieved by exploiting the fact that purely labour-saving (augmenting) technical change[21] is analogous to population growth. On the balanced growth path of the neoclassical model, all variables grow at the same rate as the exogenously determined growth rate of population. If this rate is $\frac{\dot{L}(t)}{L(t)} = n$, then exogenous labour-augmenting technical change at rate $\frac{\dot{B}(t)}{B(t)} = m$ can be incorporated by redefining labour in "efficiency units," $L = B(t)L$, that grow at rate n+m.

This proposition is shown in Figure 2.2, where the labour-augmenting specification of the production function

(9) $Y = F[K, B(t)L]$

is assumed to exhibit returns to scale so that it may be written in the labour-intensive form, $y = f(k)$, where $y = {}^{Y}/_{B(t)L}$ and $k = {}^{K}/_{B(t)L}$.

The standard neoclassical growth model diagram can then be defined in terms of efficiency units of labour, with a steady state equilibrium at k^* where saving per effective worker, $(s\ f(k))$, is equal to the growth of effective labour, $(n+m)$.

Modern adaptations of Harrod's definition of neutrality [247, p. 164] require that technical change should leave the marginal product of capital unchanged at a constant capital-output ratio.[22] The diagram shows this to be the case, since Y and K both grow at the same rate of (n+m), and $\dot{Y}/\dot{K} = f'(k)$ is constant at the steady state equilibrium of k^*. The terms y and k are also constant, but are defined in efficiency units. Hence, Y/L and K/L, in natural units, both grow at the rate of technical change, which is m. Thus, including a simple representation of technical progress in the model does not damage the harmonious results and gives conclusions that are closer to Kaldor's [258] "stylised facts" of economic growth.

Again, bias can be defined relative to neutrality for the Harrod classification of neutrality, but this is of little interest since there have been no growth-theoretic empirical investigations of biased technical change. Instead, Section 2.25 takes up the theoretical problem of explaining the systematic Harrod neutrality of technical change, since if this requirement cannot be justified the conventional steady state approach to growth is hard to defend.

2.13 Extensions: Two-Sector Growth Models and Other Definitions of Neutrality

Though the discussion above includes the case of several factors of production, further complications arise if more than one good or sector is considered. Then neutrality in aggregate depends not only on the direction of technical change in each sector, but also on the relative rates of change and the relative sizes of the sectors. As a result, technical change is affected by demand [149] and further complicated by changing relative prices.[23] Jones' [248] diagrammatic treatment is accessible to non-specialists and includes a summary of possibilities in the two-sector case plus references to earlier studies. Whereas Jones concluded that Hicks neutrality is "unlikely," Steedman's [513] model allows for inter-industry linkages and reaches the conclusion that under several plausible conditions, Hicks neutrality is in fact impossible. Chang [83] offers a detailed discussion of the relationships between Hicks, Harrod, and Solow neutrality[24] in the case of the two-sector model.

2.14 Critique: Technical Change, Factor Substitution, and Returns to Scale

Hicks' definition of technical change was intended to distinguish it from factor substitution, another concept introduced in the same book [225] in which he also suggested that innovations may be "induced" by "a change in relative factor prices." The following section will show that much confusion over the induced innovation hypothesis is attributable to the more basic conceptual difficulty of separating technical change from factor substitution.

The neoclassical conventional wisdom defines the production function to be the boundary of the production set. It is thus the locus of technically efficient input combinations for differing levels of output, embodying all known techniques. The economically efficient point on the production function itself, or on the isoquant derived from it, depends on relative price ratios. Thus, factor substitution is a (costless and instantaneous) movement along an existing production function or isoquant, in response to a change in prices. By contrast, new technology, which shifts the isoquant or production function, is the product of research that requires time and consumes real resources.

This clear theoretical distinction may be a poor description of a more complex reality in which "substitution of real capital for labour in response to innovations which made the increased use of machinery and equipment technically feasible and economically profitable is even today the main instrument for actualizing productivity gains" [479]. But the basic problem is the isoquant itself. Why would a society with a high capital-labour ratio even have available detailed knowledge of labour-intensive techniques of production, given that knowledge of production is costly? Rosenberg [432, p. 63] suggests that "the notion of a wide range of alternatives readily available, as implied by the drawing of smooth, continuous isoquants, is largely a fiction." If a firm has to commit resources to research and development to allow factor substitution, new knowledge is being created and the activity should be called technical change rather than factor substitution. Even if alternative techniques do exist, Rosenberg [432, p. 64] argues that "today's factor substitution possibilities, in other words, are the product of yesterday's technological exploration." David's [100, Ch. 1] "linear programming" approach similarly questions the validity of the distinction between factor substitution and technical change and stresses the importance of learning by doing and the localised nature of technical knowledge.[25] Atkinson and Stiglitz [18] argue that technical change would shift only that portion of the production function in the immediate vicinity of the factor ratio actually being used (above k^* in Figure 2.2). For example, would the firm "really want to raise productivity on handcarts as well as forklift trucks?" (p. 577).

To summarize, Nelson [353, pp. 64-66] notes that "if one drops the assumption that learning and doing are different activities, then the clean distinction between moving along a production surface and shifting the production function is smudged.... Rather than facing a sharply defined set of well-understood techniques with closely predictable inputs and outputs (and an abyss beyond), it would seem more plausible to characterise a firm as having a number of techniques that it can use with considerable confidence, others which might require a certain amount of research and development and learning-by-doing, and still other techniques about which the firm is even more uncertain and which likely would require even more resources and time before the firm could get them under effective control."

Apart from the conceptual problems considered above, serious difficulties arise in the empirical estimation of technical change. Indeed, a literature has developed on the impossibility of the simultaneous estimation of the elasticity of substitution and the biases of technical change [113, 114, p. 444; 468]. These papers also consider the problems of distinguishing technical change from returns to scale, an issue that has attracted attention since the exchange between Solow and Stigler [517]. Most contributions are considered in three survey articles [272, 349, 392], while recent developments are discussed by Dogramaci [121], Sato [468], and Sato and Suzawa [471].

Though recent contributions to the empirical literature covered in Section 2.3 show the progress that has been made since the early production function studies of technical change that imposed constant returns to scale, the problem persists, since a new technology may allow economies of scale to be realized that were not previously attainable [392, p. 505]. Even the assumption of constant technology in cross section studies is invalid if diffusion is not instantaneous. Part 3 of this survey suggests that large units adopt new technology more quickly than smaller competitors. In such cases, cross section estimates of "increasing returns to scale" may actually be a measure of technical superiority.

The quality and meaning of estimates of biased technical change will also depend on the approach taken to the interdependent problems of aggregation, quality adjustment, and index numbers. These issues are covered in the surveys of technical change [272, 349, 392] but recent progress has been rapid [268]. Particularly, the realisation that index number formulae can be derived explicitly from particular production functions has provided a powerful new basis for selecting index procedures [81]. A production function with suitable properties can be selected and the corresponding "exact" index derived. Diewert [117] argues in favour of flexible functional forms (that can provide a second order approximation of an arbitrary production function), calling index numbers that are exact for such functions "superlative."

These empirical issues are deferred while we move from the classification and measurement of exogenous technical change to the induced innovation hypothesis, which attempts to increase the explanatory power of economics by endogenising technical change. Binswanger [53, p. 13] provides a definition: "Models of induced innovation and empirical tests of such models are an attempt to discover the roles played by factor prices, goods prices, and other economic variables in determining the rate and direction of technical change."

2.2 Endogenous Technical Change: The Induced Innovation Hypothesis

Economic explanations of the rate and bias of technical progress have been prominent in the study of economic history, at least since Mantoux's [320] classic study of the industrial revolution in Britain, which stressed "economic needs and the spontaneous efforts they call forth." A good sample of historical examples is used in Rosenberg [429] to explain how imbalances, bottlenecks, and expensive or troublesome labour stimulated particular mechanical inventions. Recent work on the industrial revolution in England [341] is more critical, pointing out that bottlenecks were frequently overcome by reallocation of factors, rather than invention.

2.21 Induced Innovation in Economic History

The historians' main contribution to induced innovation is to be found in the lengthy debate on British and American technology in the nineteenth century. Rothbarth's [439] original statement of "the labor scarcity hypothesis" attributes high labor productivity in the United States relative to Britain to the greater use of labor-saving equipment, caused by the relatively higher industrial wage rate in the United States. The high industrial wage rate in the United States is explained by the need to compete with high returns to labor in the agricultural sector, which result from the abundance of a third factor, land. Rothbarth's work and the more extensive study by Habakkuk [203] highlight many of the difficulties involved in the study of biased technical change.

Temin [538] points out that neither author offers a clear distinction between factor substitution and innovation; yet there is a considerable difference between more machinery per unit of labor and better machinery. In addition, Saul [474, p. 18] argues that "a careful distinction must be drawn between invention, innovations and diffusion." Best practice techniques could have been the same in the two countries but the United States has a better capital stock in aggregate due to a more rapid diffusion of innovations. Indeed, if the U.S growth rate were greater and/or the durability of machinery lower, then embodied technical change would lead to a superior capital stock (but not automatically to a labor-saving bias) in the United States, regardless of the inducement mechanism driven by relative factor prices (see Williamson [567] for a discussion of this view). Ames and Rosenberg [11] include land, in the form of natural resources, in the manufacturing production function[26] and suggest that the "technological superiority" of U.S. industry was in fact dependent on "natural resource" intensive techniques. Christensen [90] follows this lead, arguing that labor-saving, capital-intensive American technologies were resource-using, especially in the sense of exploiting the plentiful cheap horsepower that was available.

Though too brief to do justice to the literature on British and American technology, this summary serves to show that a rigorous theoretical framework is required to distinguish between factor substitution and the rate and bias of technical change. Empirical tests of the propositions raised in the debate are covered in the empirical section (2.3) of this survey. For a comprehensive review of the debate see David [100, Ch. 1].

2.22 Microeconomic Approaches

Confusion over the meaning of induced innovation can be traced directly back to Hicks' original, widely quoted statement: "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 economising the use of a factor which has become relatively expensive" [225, pp. 124-125].

In later contributions, Hicks [228, Chs. 1 and 2] explains the mechanism whereby autonomous inventions provide the initial impulse, which would peter out due to labor scarcity raising wages but for the "children" of the original innovation, the labour-saving secondary innovations induced by the original improvement. "But whether such 'induced inventions' were to be regarded as shifts in the Production Function, or as substitutions within an unchanged Production Function, was left rather obscure" [228, Ch. 1, p. 2].

As a result, the induced innovation hypothesis was not readily accepted by economists. In his survey of process innovations, Blaug [61] refers to "the troublesome notion of innovations induced by changes in factor prices--this would seem to involve factor substitution, not technical change." Indeed, Salter's [461] refutation of inducement was favourably received by economists [156, p. 337; 429]. He argued that, "at competitive equilibrium, each factor is being paid its marginal value product; therefore all factors are equally expensive to firms" [461, p. 16]. Factor substitution ensures that this efficiency condition will be re-established so that no factor is ever "relatively expensive." Thus, "the entrepreneur is interested in reducing costs in total, not particular costs such as labour costs or capital costs. When labour costs rise, any advance that reduces total cost is welcome, and whether this is achieved by saving labour or capital is irrelevant" [461, pp. 43-44].

Clearly, Salter does not reject factor substitution and it is the problem of differentiating this from induced innovation that underlies his objection to the concept. Intending to keep logically separate the technological possibilities and the economic forces that determine the techniques actually in use [462, p. 15], "Salter defined the production function to embrace all possible designs conceivable by existing scientific knowledge and called the choice among these designs 'factor substitution' instead of 'technical change'" [222, p. 86]. As Rosenberg [433, p. 65] points out, factor substitution then swallows up much of technical change since the production function is no longer a set of blueprints on the shelf, but is also the "much wider range of techniques which could be designed with the current stock of knowledge" [461].

Salter's rejection of induced innovation is semantic, showing that isoquants can be defined so as to leave no room for technical change or none for factor substitution. The second extreme is exemplified by Brozen [74, p. 88], who considered the distinction between known but previously unused techniques and new technology to be so problematic operationally that he defined technological change as "any change in production methods in an enterprise or industry." Fellner, in a series of studies [148, 149, 150, 151, and 152], both expressed a view similar to that of Salter and rehabilitated the induced innovation hypothesis. He argued firstly, that when change occurs, even a perfectly competitive firm will find itself in a quasi-monopsonistic situation, facing a less than perfectly elastic supply curve for a factor that is in relatively short supply at the economy-wide level and will learn to direct innovative activity toward saving that factor. Secondly, even a perfect competitor will adapt to a persistent and discernible relative factor shortage. The expectation of future factor shortage is sufficient to generate a bias in inventive activity.

Ahmad's [2] rehabilitation of the inducement hypothesis does not require imperfect markets or expectation. The novelty of Ahmad's model is the introduction of the innovation possibility curve (IPC), which he defines to be the "envelope of all the alternative isoquants (representing a given output on various production functions) which the businessman expects to develop with the use of the available amount of innovating skill and time (assumed constant throughout this analysis)" [2, p. 347].

If relative factor prices change, factor substitution will occur in the short run, but over a longer time period there will be substitution along the IPC so that a new isoquant is created and selected.[27] However, Ahmad assumes that over this same longer period, research and development expenditures will have neutrally[28] shifted the IPC closer to the origin, so that the new equilibrium will be on an isoquant associated with a new IPC(t+1).[29] If the IPCs have the properties of input homothetic isoquants (see footnote 17), then changing actual relative prices will induce a factor-saving bias. This need not be the case, Ahmad cautions; the IPCs could be drawn to show an innate factor-saving bias in innovation possibilities.

Ahmad's model has been extended to encompass several inputs and applied to the problem of agricultural development by Hayami and Ruttan [222], who propose that "technology can be so developed as to facilitate the substitution of relatively abundant (hence cheap) factors for relatively scarce (hence expensive) factors in the economy" (p. 73). Their model is developed by utilizing the identity

(10) $Q/L = (A/L)(Q/A)$

where Q is output, L is labour, and A is land.

Land area per worker (A/L) can be increased by technical improvements in machinery and equipment, which allow power to be substituted for labour. This process may be called mechanical technical change. Similarly, biological advances, such as high-yielding, fertilizer-responsive seed varieties, raise the average product of land (Q/A) and may be referred to as biological technical change.[30]

In Figure 2.3a the initial price ratio P_0 is tangential to the IPC, IPC_0 at point A, and has led to the development of a particular technology (the reaper, for example) described by the isoquant I_0. (At another price ratio, some other isoquant, along IPC_0, would have been developed.) When the factor price ratio changes to P_1, factor substitution allows land to replace labor until a new tangency is reached at point B. However, over a period of time sufficient to allow for the development of new techniques, inventions suited to the new factor price ratio will appear (the combine harvester, perhaps), represented here by the isoquant I_1. The new production point, C, on I_1 lies on a new IPC, labeled IPC_1, which is closer to the origin than the original IPC, the extent of the shift being a function of the level of the research and development budget.[31]

The new technology, I_1, allows a higher land-labor ratio but does require a greater input of power per worker, as is shown by the line (A,M), which implies complementarity between land and power.[32]

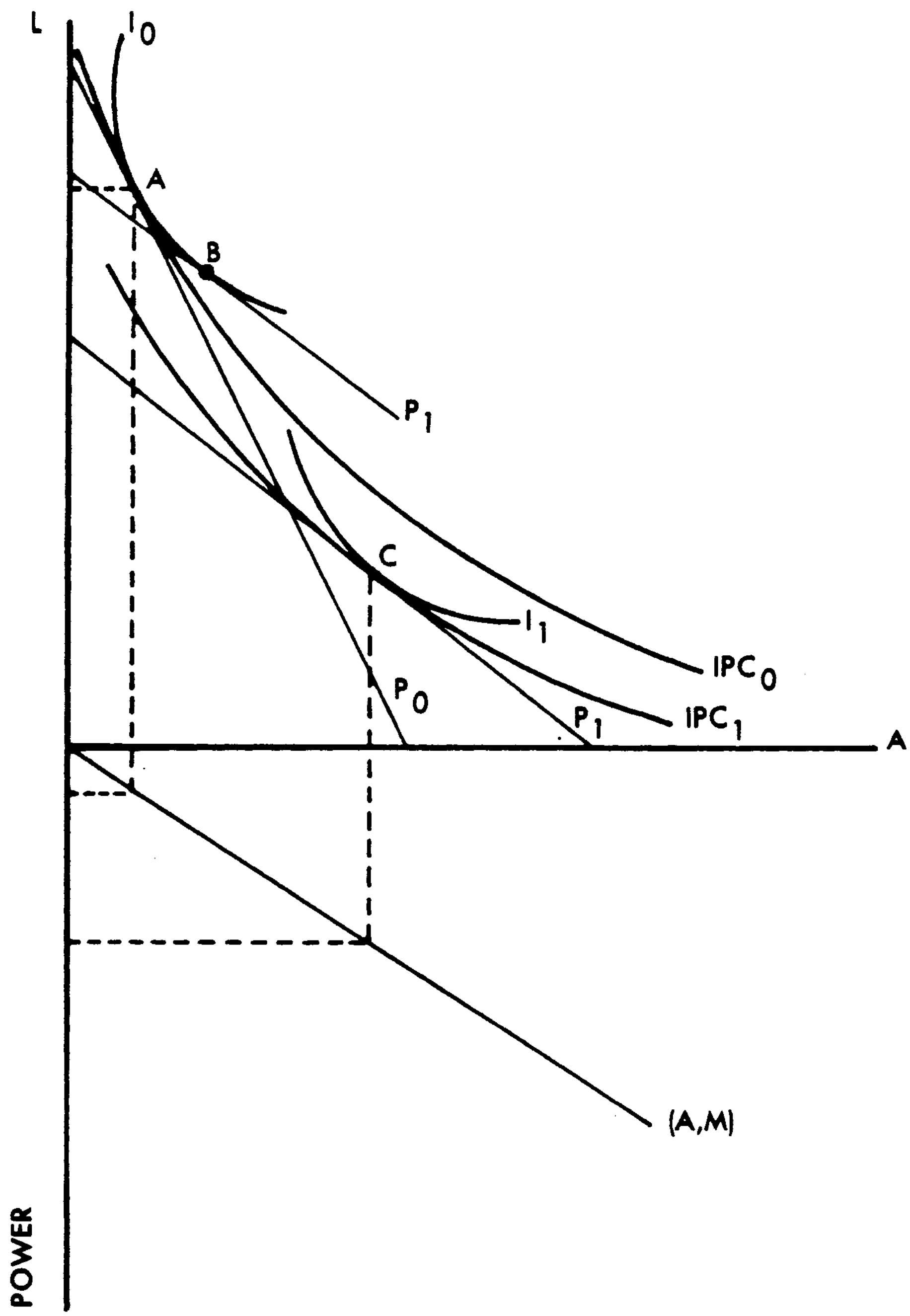

Figure 2.3a Factor prices and induced mechanical technical change

Similarly, biological technical change is shown in Figure 2.3b with the initial equilibrium at point A, where the isoquant I_0 and the IPC, IPC_0 are tangential to the price ratio P_0. The invention of fertilizer-responsive high-yielding varieties, in response to a fall in the relative price of fertilizer, to P_1^1, is represented by the isoquant I_1. This isoquant is one of a family of such curves, for which IPC_1 is the envelope curve. At the new equilibrium point C, fertilizer input per acre is increased but high-yielding varieties require better water control and land management. This complementary relationship between land infrastructure and fertilizer is implied by the line [F,B].[33]

To simplfy the presentation, Figure 2.3a treats the impact of advances in mechanical and biological technology on factor ratios as if they are independent, but biological technical change in Figure 2.3b reduces the land input per unit of output and will thus change the land-labour ratio in Figure 2.3a. Thirtle [540] shows that the assumption that the production function is separable is sufficient to allow a theoretically correct diagrammatic representation that takes account of these interactions and thus avoids specification errors in the empirical tests discussed later. Kaneda [264] has argued in favour of separability (denoted by :) between labour (L) and machinery (M) and land (A) and fertilizer (F) as in equation 11.

(11) $$Y = f[(L, M, Tm) : (A, F, Tb)],$$

where Y is output, Tm represents mechanical technical change, and Tb represents biological technical change.[34]

Equation (11) leads directly to a simplification[35] of the Hayami and Ruttan model that can be represented by a single diagram. Figure 2.4 exploits

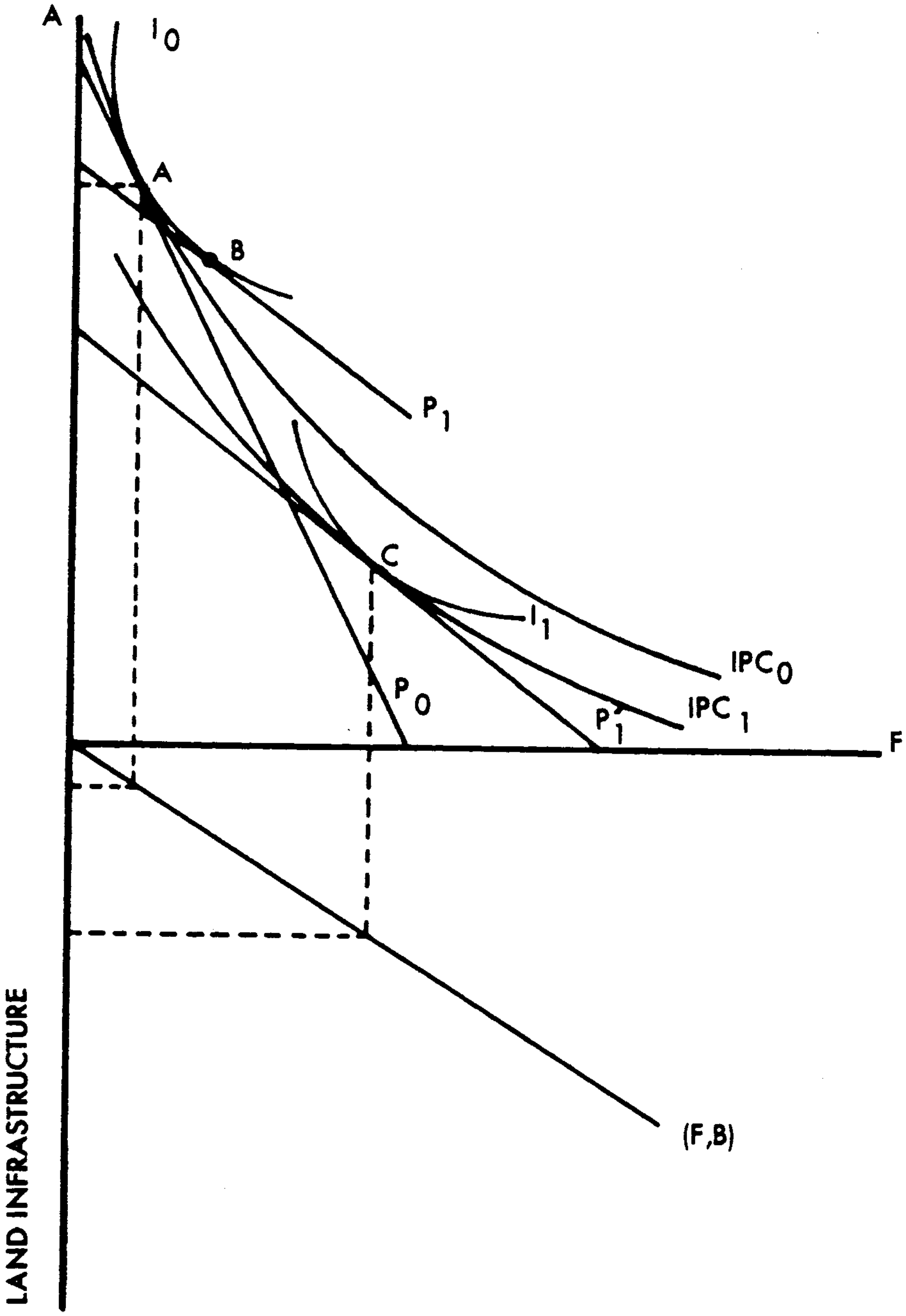

Figure 2.3b Factor prices and induced biological technical change

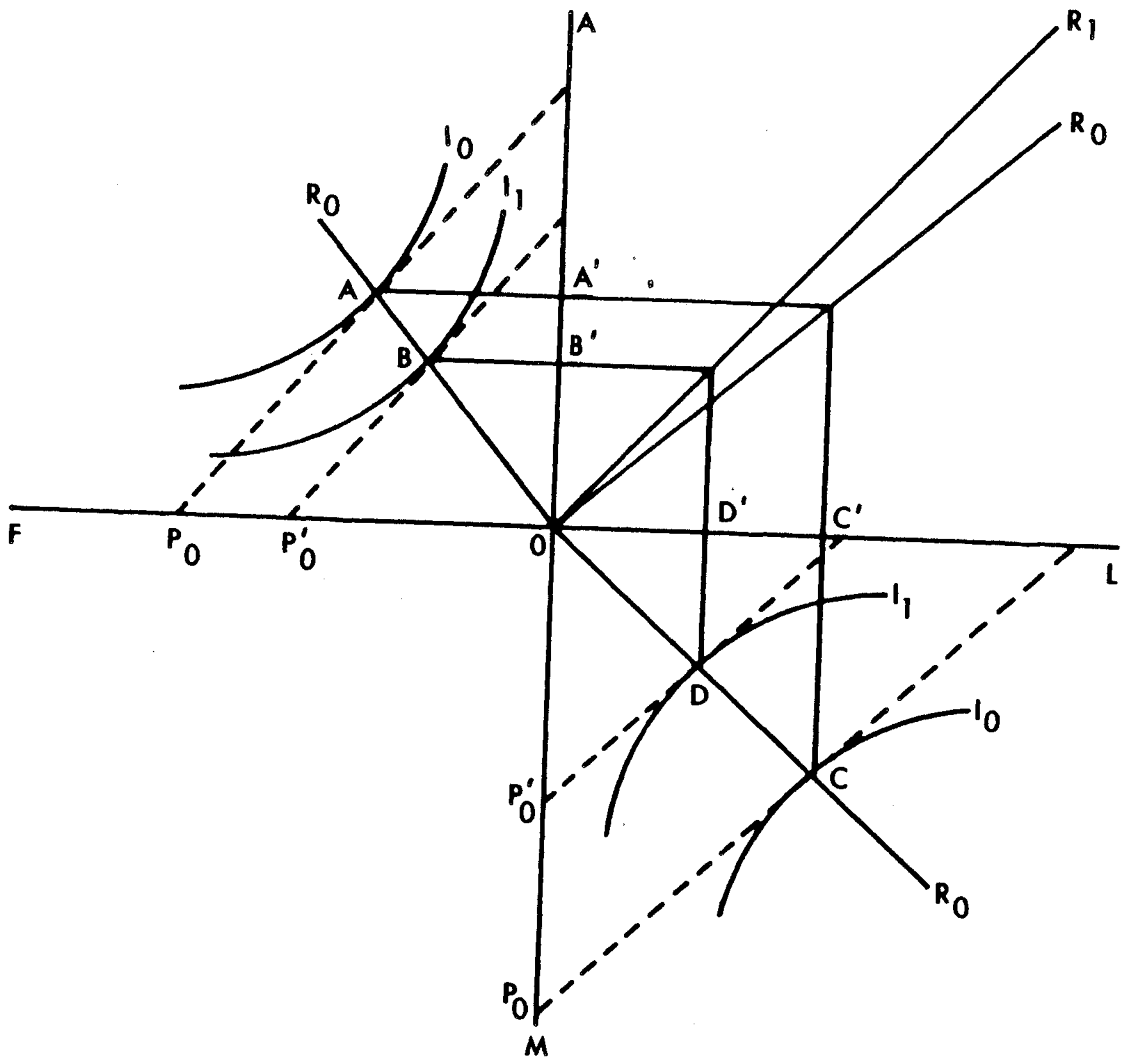

Figure 2.4 A neoclassical reformulation of the Hayami and Ruttan model

the separability assumption, showing labour, machinery, and mechanical TC in the southeast quadrant, while land, fertiliser, and biological/chemical TC are represented in the northwest quadrant. The relationship between land and fertiliser shows the initial equilibrium at point A, where the unit isoquant I_0 is tangential to the relative price ratio P_0. Biological/chemical TC is represented by a neutral shift of the isoquant to I_1, which at constant factor prices results in a new equilibrium at point B. The proportional reduction in the input of land is measured by A'B'/OA'.

Similarly, the initial equilibrium in the labour/machinery quadrant is at point C, where the unit isoquant I_0 is tangential to the factor-price ratio P_0. Mechanical TC is represented by the neutral shift of the isoquant to I_1, resulting in a new equilibrium at point D. The proportional reduction in the input of labour is measured by C'D'/OC'.

Figure 2.4 represents a situation in which mechanical TC reduces the input of labour more than biological TC reduces the input of land, (C'D'/OC' > A'B'/OA'), with the result that the land/labour ratio rises from R_0 to R_1 (in the northeast quadrant). Even though the mechanical and biological technical changes are constrained to be Hicks-neutral (in order that they may be measured by single parameters), their effect on the land/labour ratio will be non-neutral unless the two changes are equal. Thus, allowing for the interaction of the two types of technical change permits changes in the land/labour ratio even at constant factor prices. This possibility does not exist in the Hayami-Ruttan model and is not allowed for in their tests, discussed in Section 2.3.

Though the effects of research enter the Ahmad and Hayami-Ruttan models by way of the shifting of the IPC toward the origin, neither approach makes an explicit attempt to model the research process. For the case of one output and two inputs, in the context of the Cobb-Douglas and CES production functions, Kamien and Schwartz [260] include a "research production function," $I(a_1', a_2') = M$, where a_1' and a_2' are the time derivative of the function parameters and M is the size of the research budget (assumed constant). Their model, which maximizes the present value of the future stream of net profits, shows that the optimal direction of disembodied technical change depends on the initial technology, relative factor prices, and the relative costs of acquiring different types of technical change. In a later paper, Kamien and Schwartz [262] allow for a variable research budget and decreasing or constant returns to research expenditure. Subject to the assumptions of the study, the rates of neutral and non-neutral technical change vary inversely with the costs of these changes, directly with the responsiveness of the cost function to that type of change, and directly with firm size. They also find a long-run tendency toward Hicks neutrality and failure of a myopic policy of instantaneous maximisation (as opposed to a dynamic solution) to achieve either the optimal rate or bias of technical change.

The contributions of Binswanger [50, 54, 55] adapt Evenson and Kislev's [132, 133] stochastic model of applied technological research to the problem of induced innovation. Using seed technology as an example, research is viewed as a sampling process from a distribution of potential yield increases that depend upon nature, the state of basic science, and plant breeding techniques. Ex ante, the expected payoff is $E(\Delta\gamma lm) = h\ (m,\mu,\sigma)$ where γlm is the largest yield increase, m is the sample size, and μ and σ are respectively the mean and variance of the distribution.[36] Binswanger

[50] follows Kamien and Schwartz [261] in using a factor-augmenting form of the production function, with the change in the augmentation parameters a function of research effort. Then, for the case of two inputs (hence two augmentation coefficients A and B) and two research processes m and n, innovation possibilities may be specified as

$$(12) \qquad A^* = M(m)\alpha^m + M(n)\alpha^n$$

and

$$(13) \qquad B^* = M(m)\beta^m + M(n)\beta^n,$$

where A^* and B^* are proportional changes in A and B, $M(i)$ are scale functions, and α^i and β^i are the productivity coefficients of research to reduce A and B respectively.[37] The functions are used to maximise the discounted present value of the profit function, subject to a variable research budget. Though Binswanger considers many cases, the main results derived from a maximisation model of discounted expected costs and benefits may be summarized as follows:

1. Any rise in the expected present value of the total cost of a factor will lead to an increased allocation of resources to the research activity that most saves that factor.

2. A rise in the cost of research that saves a particular factor or a decline in the productivity of that research will reduce the allocation to that line of research, and hence bias technical change in the direction of the other factor.

3. With no budget constraint on research activities, a rise in the value of output (due to greater output or higher price) will increase the research budget and hence the rate of productivity growth.

Ex post, none of these results are particularly surprising, but they do clarify several controversial issues in the earlier literature. The first result shows that it is neither factor prices alone, as in the Ahmad and Hayami-Ruttan models, nor the expectation of rising wage rates, as in Fellner's study, nor factor shares, as in the Kennedy-Weizsacker-Samuelson models (see Section 2.25), but the present value of the (expected) factor costs that determines the bias of the research mix and hence of technical change. Moreover, Binswanger shows that the IPC should not be viewed as the "scientific frontier," as no firm will intentionally drive the returns to research to zero. Profit maximisation requires that the effort cease when the marginal cost of research is equal to the marginal product. The third result listed above implies that for both society and the firm, more research resources should be concentrated on commodities with higher prices and larger markets. Thus with respect to their rate of technical change, the model provides theoretical support for the importance of demand in inducing technical change (see Part 1 on the rate of technical change).[38]

In his criticism of the Kennedy and Ahmad approaches to induced innovation, Nordhaus [368] employs a family of "isotechs." The neoclassical isoquant is the zero isotech, and the set of all techniques attainable at a given cost C is the C isotech, which is analogous to Ahmad's IPC except that the rate of technical change is endogenised. There is a set of isotechs that shift closer to the origin as research costs, C_i, increase. Thus both factors can be saved with a larger research budget. The model is not ahistorical, since the actual technique employed on the isotech in the first period will determine the shape of the isotech in the next period. McCain [326] extends this approach to investigate the scale and durability of "new designs" in addition to the capital and labour intensities. Wyatt [576] also extends the isotech approach, showing that when new technology is embodied in capital equipment, the rate of technical change will itself affect the factor-saving bias.

2.23 Criticisms of the Microeconomic Approach to Induced Innovation

Some theoretical limitations of earlier models of induced innovation are discussed or resolved in the previous section by later contributors, particularly Binswanger, but other deficiencies remain unanswered. Hacche [204] argues that the treatment of uncertainty and expectations is inadequate, but his most serious objection is to the Hicks-neutral shifting of the IPCs specified by Ahmad. A similar weakness underlies the growth-theoretic models of technical change, discussed below.

Elster [127, pp. 102-103] attributes the appeal of the Hicksian argument to "an easily committed logical fallacy." If wages are rising relative to capital costs, then for entrepreneurs collectively, labor-saving innovation seems to be appropriate. But labor-saving innovation will reduce wage rates (due to factor substitution), and since entrepreneurs act individually, not collectively, "the proposed explanation fails." This point may amuse logicians but has little to do with economic behaviour in a world where wage-rental ratios have continued to rise over time. Binswanger [54, p. 91] argues specifically that for both society and the individual firm it makes sense to take factor prices into account in determining the amount and direction of research effort.

Most criticism of induced innovation has centered on the practical validity of the market-price-based Hayami-Ruttan model as a foundation on which to build a theory of agricultural development. Rosenberg [429] suggests instead a theory of induced innovation based on the "obvious and compelling need" to overcome the constraints on growth of production or of factor supplies. However, Hayami and Ruttan [221] argue that technical imbalances or bottlenecks should be reflected in an operationally meaningful fashion in terms of relative factor scarcities signaled by market prices. Indeed, Timmer (see footnote 18 in Hayami and Ruttan [220]) suggests that the constraints that give rise to the "obvious and compelling need" are, in a linear programming context, the dual of the factor prices in the Hayami-Ruttan model (provided market failure is ruled out).

Unfortunately, there is a low probability that the conditions required for efficient competitive equilibrium will be fulfilled in developing countries, as was pointed out by Beckford [31]. Especially when risk is taken into account, low-income agricultural producers may not be profit maximizers and any divergence between private and social cost may distort the rate and direction of technical change.[39]

In an early contribution to what has become known as the "structuralist theory" [45, p. 209], de Janvry [109] incorporates price distortions in a model similar to that of Ahmad [2] and shows that socially optimal innovations may not be developed in such cases. This approach has been criticized by Mueller [347], who argues that removing the factor price distortion is no solution, since the IPC does not exist in developing countries without effective agricultural research institutions. Instead, there is only a labour-intensive traditional isoquant and a technically superior, capital-intensive modern isoquant "transplanted from other countries." Removal of the price distortion results in a minor substitution of labour for capital in the modern sector, but the dual economy persists.[40]

Moreover, inequalities in land ownership and farm size are likely to generate dual technologies. Griffin [188, p. xiii] argues that in LDCs there will not be one set of prices, but that different groups may face radically different sets of relative factor prices depending upon their economic position and political power. Adding duality to the induced innovation model, Grabowski [184] shows that large landowners with access to credit may have an incentive to pursue technological developments that require non-labour inputs, such as fertilizer and chemicals, which are less available to small farmers. Thus, unequal access to the inputs necessary for successful implementation of green revolution technologies can cause a worsening of the distribution of income even if the technologies themselves are inherently scale-neutral.[41]

De Janvry [110] emphasizes that the same inequalities of economic, social, and political power will distort the research activities of public sector institutions in favour of the dominant farm interest.[42] When the inputs of public research institutions are viewed as public goods, demands for particular lines of research depend on the expected payoffs to conflicting interest groups. The supply of innovations will depend on the political and bureaucratic structure, while socioeconomic position determines the actual payoffs. Guttman [201] further extends the public goods approach in a model in which agricultural research funds are allocated according to the votes of interest groups. The model explains the allocation of U.S. agricultural research funds for 1969. In an empirical analysis of the provision of extension services to Indian villages, Guttman [202] finds "political variables" to be important in addition to efficiency criteria.

A second, separate line of criticism questions the ability of such a broadly based theory to provide genuine research policy guidelines to suit the diverse situations of developing countries. Biggs [43, p. 22] argues that neither the induced innovation theory nor the structuralist theory "analyses the actual decision-making and behavioural processes within research institutions that generate and promote new technologies." The institutional approach of Biggs [45] stresses the importance of imperfect bureaucratic structures, institutional environment, communications, linkages, feedback mechanisms, dependency, and control in agricultural research systems, both at the level of the formal research institutions and at the level of non-formal on-farm research and development.

2.24 Induced Institutional Change

Though Hayami and Ruttan [219] focus on induced technical change in agriculture, they also consider institutional innovations, because much technical change had been produced by public sector institutions [450, p. 32]. The importance of institutional change was stressed by Polanyi [398], who maintained that institutional rather than technical change is the dynamic source of economic development. Following this line of thought, North and Thomas [370, 371] attribute the major sources of Western economic growth to changes in the institutions whose rules govern property rights, with the changes being brought about by the pressure of population against increasingly scarce resource endowments. Focusing on more recent economic history, Schultz [484] identifies the "rising economic value of man" during the process of economic development as the primary cause of institutional change.

Defining institutional innovation broadly so as to encompass organisational change (property rights and markets, as well as agricultural research and extension), Ruttan [449] follows de Janvry [110, 111] in stressing the interdependence and interaction of technical and institutional changes.[43] Institutional change may be induced by the demand for more effective institutional performance required for economic development, or it may result from advances in the supply of knowledge about social and economic behaviour, organization, and change.

Furthermore, Ruttan [449] has argued that sources of demand and supply for technical and institutional change are essentially similar. Hayami and Ruttan [222] identify two major sources of change in the demand for institutional change: firstly, the response to disequilibria in the allocation of the new income streams resulting from technical change, and secondly, the impact of changes in resource endowments and relative factor prices.[44] On the supply side there are also two major sources of change: firstly, the organization of group action to supply public goods, and secondly, advances in knowledge in the social sciences and related professions, which reduce the cost of institutional innovation.[45]

Though Hayami and Ruttan [222] have extended the induced institutional change model to include cultural endowments and Ruttan [453] has added a case study of the direct payment approach to U.S. farm income support, the model remains incomplete and difficult to test empirically.[46]

2.25 Growth Theoretic Approaches

The apparent importance of technical change in explaining economic growth (see Section 2.1) led to attempts to incorporate endogenous technical progress in modern growth models. The innovation possibility frontier (IPF) introduced by Kennedy [269][47] resulted partly from the author's dissatisfaction with the neoclassical production function, as did Kaldor's [257] earlier "technical progress function."[48] The IPF offers a theory of induced innovation and distribution (one aim was to explain the constancy of factor shares) that can be viewed as independent of the neoclassical production function.[49] It does not rely on changing relative factor prices, thus avoiding confusion between factor substitution and technical change.

In a two-sector model, technical change is assumed to occur only in the consumer goods sector, the rate of interest is constant, labour is homogenous, there is perfect competition, and the production function exhibits linear homogeneity. Using the factor-augmenting representation of Section 2.1, the proportional rate of reduction of the labour input due to technical change, $\hat{B} = \frac{\dot{B}(t)}{B(t)}$, can be raised only at the expense of less capital augmentation, $\hat{A} = \frac{\dot{A}(t)}{A(t)}$. Higher rates of labour augmentation require increasing sacrifices in capital augmentation. Thus the technology frontier (IPC) has the properties, $\hat{B} = f(\hat{A})$, where $\frac{d\hat{B}}{d\hat{A}} < 0$ and $\frac{d^2\hat{B}}{d\hat{A}^2} < 0$, which are shown in Figure 2.5. The entrepreneurs' objective is to maximize the one-period reduction in unit costs, $(\hat{C})$, which depends on the technical coefficients weighted by the factors' shares in total costs $(S_k,\ S_1 = (1-S_k))$. The objective function is

$$(14) \qquad \hat{C} = S_k\hat{B} + (1-S_k)\hat{A},$$

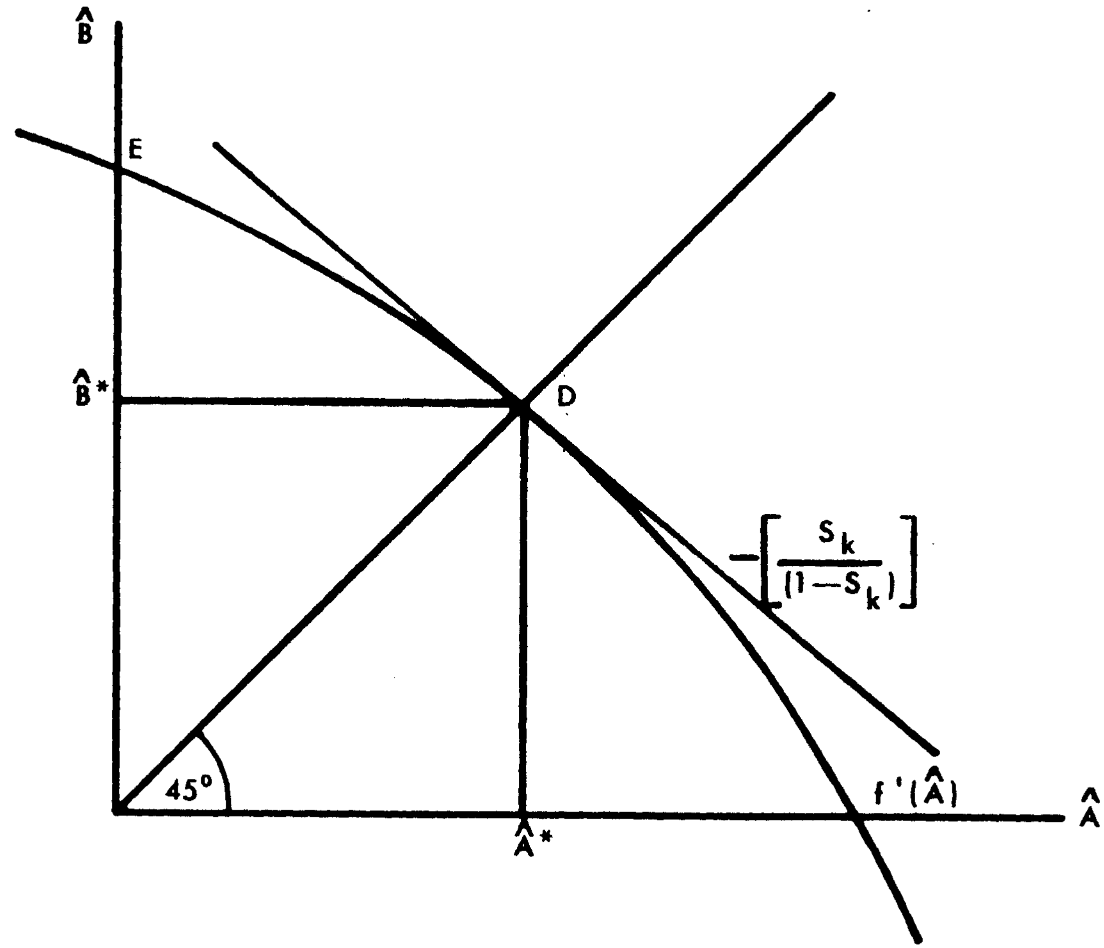

Figure 2.5 The innovation possibility frontier

and optimality is attained where

(15) $\qquad d\hat{B}/d\hat{A} = f'(\hat{A}) = -(S_k/(1-S_k))$,

which is the point of tangency between the IPF and the factor share ratio at point D in Figure 2.5.

The figure shows that a relatively high share of capital in total cost will lead to a greater value of capital augmentation, $\hat{A}$* (where * indicates the cost-minimising solution), than will a lower relative share. However, if technical change is not Hicks-neutral, ($\hat{A}^* \lessgtr \hat{B}^*$), then the weights, S_k and $(1-S_k)$, will change in the next period so that the economy converges asymtotically to an equilibrium where technical change is Hicks-neutral ($\hat{A}^* = \hat{B}^*$). Thus factor shares remain constant at the levels determined by the slope of the IPF on the 45° line in Figure 2.5. The slope of the IPF at this point indicates "the fundamental technological bias in innovation possibilities."

If technical change occurs in the investment goods sector as well,[50] equality of $\hat{A}$* and $\hat{B}$* will not result in constant factor shares. The share of capital in total costs (S_k) will fall continuously as technical change in the investment goods sector lowers the price of capital supplied to the consumption goods sector. In this case Kennedy [269] shows that when assuming a constant rate of interest and an elasticity of substitution of less than unity, there will exist a unique, globally stable balanced growth equilibrium, characterized by Harrod-neutral or labour-augmenting technical change and constant factor shares.[51] Intuitively, if r is fixed and the relative shares are written as

(16) $\qquad \dfrac{S_k}{S_l} = \dfrac{rK}{1-rK}$,

capital's share will fall relative to that of labour until $\hat{A} = 0$ and capital augmentation ceases at point E in Figure 2.5. Drandakis and Phelps [123] and Samuelson [464] integrated Kennedy's IPF into the standard one good neoclassical model, giving the required outcome. As Wan [557, p. 223] and Jones [247, p. 200] observe, the Kennedy approach offers an escape from the necessity of assuming Harrod neutrality for balanced growth to be possible; rather, it is a result of the model.

Clearly, maximizing the instantaneous rate of unit cost reduction may be shortsighted, but the Samuelson [463] version of the model minimizes unit costs T periods from the present and von Weizsacker [555] minimizes the total discounted cost of the future output stream. The more serious shortcoming, that technical change is costless or results from "exogenously supplied inventions" [122, p. 11], is tackled by von Weizsacker [555] by allowing the firm to allocate a variable amount of "indirect" labour to research and development.

When investment in research and development is incorporated in the model, the rate of technical change may be determined, along with its direction. The optimal rate of technical change is determined by Uzawa [548] and Phelps [393, p. 139], who state the "Golden Rule of Research" as calling for "equating the (marginal) rate of return from research to the growth rate." Nordhaus [366, 367] incorporates Uzawa's result in an induced innovation model, so that the IPC is pushed outward in a homogeneous fashion, with the magnitude of the shift a function of the level of research and development investment. Nordhaus [367, pp. 107-108] arrives at the same optimality condition as Uzawa, which he compares to the conclusion of Phelps and von Weizsacker before stating his own golden rule of technological change.

In an alternative model that includes both the rate and bias of technical change, Conlisk [93] allows fractions of both employed capital and employed labour to be allocated to the capital and labour-augmenting research sector (the allocation varying only with the capital/labour ratio to preserve linear homogeneity). Two main conclusions follow. Firstly, in contrast to the simple neoclassical growth model (with exogenous growth of labour) where the equilibrium rate of growth is not affected by the savings rate, including labour as an "endogenously produced" factor does make the equilibrium growth rate a function of the savings rate. Secondly, in contrast to the models of Samuelson [464] and Drandakis and Phelps [123], which have a fixed rate of technical change, the bias in technical change need not be Harrod-neutral.

Indeed, Conlisk suggests that this odd feature of the neoclassical model may vanish as technical change is made increasingly endogenous.[52] Hacche [204, p. 154] argues that because the savings decision endogenously fixes the position of the IPF, the rate of labour augmentation is dependent on economic decisions, even in steady states. Conversely, McCain [324, p. 923] attributes Conlisk's distinct, non-neoclassical results to his "technical progress frontier," defined in terms of <u>absolute</u>, not <u>relative</u>, increments in the productivity of the factors.

Similarly, Chang's [84, 85] studies of stability appear to show that $\sigma < 1$ is sufficient only for local stability of the Harrod-neutral equilibrium or that σ can take any value without affecting this result, <u>according to the particular manner in which the IPF is specified</u>. Thus, "the problem of choosing a particular type of frontier becomes fundamental. It is important to examine under what circumstances it will be correct to choose a particular kind of frontier" [85, p. 211]. We now turn to criticisms of the growth theoretic approach to induced innovation before discussing extensions of the model.

2.26 Criticisms of the Growth Theoretic Approach

Kennedy's theory appears to lead to a growth model [122] that incorporates technical change and leaves intact the neoclassical explanations of steady state, without needing to assume Harrod-neutrality. But the IPC approach raises several other problems. Innovation possibilities must be representable by an IPC of the type suggested by Kennedy and the IPC must be stable. Even then, it cannot explain behaviour unless it is known to decisionmakers [53, p. 37; 557]. Elster [127, p. 105] argues that Kennedy "invokes maximisation without a maximiser." He assumes that the innovation will occur at the point on the frontier that, at the ruling factor prices, permits the greatest reduction in unit cost, but he does not tell us how the entrepreneur is supposed to find the frontier and move along it until he finds a maximum, let alone how he is to find the global maximum. The theory lacks microfoundations.

Elster's statement is representative of the views of several critics such as Nordhaus [368] and Samuelson [464], who also question Kennedy's model for replacing exogenous technical change with an exogenously determined innovation frontier.

Ahmad's original critique shows how crucially the results depend on how the frontier is defined. Ahmad [2] argues that the IPF could equally well relate the amount of one factor saved per unit of output to the amount of the other factor saved. Ferguson [156] shows that the amount saved per unit of output is then $Z = uw + vr$, where u is the amount of labour, v is the amount of capital, and w and r are factor prices. The IPF is then $u = u(v)$, and cost minimization gives the result $du/dr = -r/w$. Thus factor prices, rather than factor shares, determine the bias, in conjunction with the slope of the frontier. Specifically, if the model is converted to factor shares, then in terms of the factor-augmenting production function of equation (1), $u = B(t)L$ and $v = A(t)K$. Thus, $A(t) = \frac{v}{K}$ and $B(t) = \frac{u}{L}$, which implies that the greater the labour input, the lower the level of labour-saving technical change.[53]

Another problem, originally raised by Drandakis and Phelps [123, p. 839] and attributed to Becker, is that a maintained rate of labour augmentation may exhaust the possibilities for further labour augmentation. Not only must the IPF be stable over time in the Kennedy model, but the unit cost reductions, $\hat{A}$ and $\hat{B}$, must be independent of past increments.[54] This is sufficiently unrealistic that Binswanger [53, p. 38] concluded, "No real world research process can lead to a Kennedy frontier that is independent of achieved $\hat{A}$ and $\hat{B}$ levels."

To rectify this defect, Nordhaus [368] assumes that there are limiting values of $\hat{A}(t)$ and $\hat{B}(t)$ and that it becomes increasingly difficult to decrease A and B as these values are approached. Allowing "technological possibilities" to drift over time, he shows that a balanced growth (Harrod-neutral) equilibrium is possible only if the "natural drift" of technology is always Harrod-neutral.[55] This would seem to be equivalent to the original assumption of Harrod-neutral technical change commonly made in simple neoclassical growth models.

More recently the problem of innovation possibilities depletion has been investigated by Magat [307] for the case of the competitive firm (following Kamien and Schwartz [261]). Depletion is allowed by incorporating "depletion factors," u and v, so that the augmentation terms defining the IPF become Au(A) and Bv(B). Then, Hicks-neutral technical change occurs only when labour-saving and capital-saving possibilities are depleted at the same rate (since the depletion factors shift the IPF and change its slope). On the assumption that "capital-saving technical advance is easier, or less depleted, than labour-saving technical advance," labour's relative share will increase even at a constant ratio of factor prices. Either this bias in depletion rates, or a falling relative price of capital (due to technical change in the capital goods sector), can explain the rising share of labour observed by some recent authors.

However, neither Magat [307] nor Skott [500], who criticize and extend the model, refers to Nordhaus [368] or attempts to evaluate his contribution. Skott [500, p. 983] argues that in the long run capital augmentation will increase due to "the fact that pure Harrod neutral technical progress would gradually alter the trade-off between the rate of capital augmentation and the rate of labour augmentation." This is true, given the rather arbitrary specification of the depletion factors, but the Magat-Skott model does not follow Nordhaus in considering how change in scientific knowledge determines the payoffs to research activities.

Earlier, Nordhaus [366, pp. 64-54; 367] pointed out that research and development expenditures are assumed to be independent of firm size, which, together with constant returns to factors, ensures decreasing costs and the elimination of competition. He argues that about the only case in which competition can be preserved is when "a new book of blueprints falls from the sky every period"; then the induced innovation model is reduced to "a disguised version of the neoclassical model with exogenous technical change." The alternatives he suggests are that the government must perform the research and transmit it at no cost to competitive firms, or the greater complications of monopolistic behaviour must be modeled, leaving little hope of a steady state. This issue of decreasing costs in models that incorporate either research expenditures or learning costs is not a criticism of the Kennedy model alone, but is quite general and frequently overlooked.

A very general cause for complaint is the equilibrium approach taken by growth theory. The literature on technical change abounds with terms such as bottlenecks and factor scarcity, which suggest disequilibria. Yet despite Bliss' [62] conclusion that "any interesting technical progress" is incompatible with steady state growth, Robinson [418] is the exception among theorists in considering disequilibria.

2.27 Extensions: Two-, Three- (and More) Sector Models

The growth-theoretic induced innovation model is extended by Chang [84] to the two-sector case by incorporating separate IPFs within both capital and consumer goods sectors. The basic result is that if the standard capital intensity condition[56] is satisfied and the elasticity of substitution in each sector is less than one, then the Harrod-neutral, steady state growth path is locally stable (subject to a standard savings assumption). The two-sector, two-IPF model is also investigated by McCain [324], but for the Kennedy-neutral[57] steady state growth path. As in the one-sector model, capital augmentation is zero in the capital goods sector, but in the consumer goods sector the rate of capital augmentation (or disaugmentation) must equal the increase (or decrease) in the price of capital goods. McCain is unable to make a general statement about stability, but Craven [96] proves stability for a simpler Leontief-type model that allows separation of price and quantity equations (and obviously precludes short-term substitutability).

Kennedy [271] generalizes McCain's results to a model with (m-1) capital goods and one consumer good (a crucial assumption), showing that "the rate of factor augmentation in any sector is equal to the rate of change of the price of the factor, if the product of the sector is used as numeraire" (p. 51). This means that although different output and input quantities can grow at different rates, all grow at the same rate in value terms. Commenting on the work of McCain [324] and Kennedy [271], Orosel [383] addresses the problem that if the capital goods are durable, then the continually changing capital goods prices would result in capital gains and losses. These will affect profit rates, which in equilibrium must be the same in all sectors. Orosel proves that there are cases in which capital gains and losses preclude profit rate equalization, but if equalization does occur, the dynamics of the steady state are such that it will be maintained. However, not all concave, differentiable technology frontiers are consistent with the steady state equilibrium.

Product, as opposed to process innovation, is incorporated in the Kennedy-von Weizsacker model by McCain [325] following Lancaster's characteristic approach to consumer theory. Allowing for the "quality" of goods to be augmented by new product innovation does not lead to fundamentally different results.

McCain [323] and Brewer [69] added a third non-producible factor (land[58] in the simple case, or several fixed resources, in Brewer's extension of the model), thus allowing consideration of the extent to which technical change can stave off the pessimistic forecasts of the classical synthesis. Though the classical stationary state is averted (in the case where population growth is exogenous), an economy with a higher rate of population growth will have a lower rate of growth of income per head. This occurs because in the steady state, the rate of capital augmentation will be zero, while the rate of output growth will equal both the rate of land augmentation and the rate of growth of labour in efficiency units (population growth plus labour augmentation). If population grows more rapidly, land augmentation must increase at the expense of the rate of labour augmentation, which is equal to the growth rate of per capita income.[59]

A third input is also added by Fixler and Ben-Zion [160], but in their model the new input is itself the innovation and the user is a monopolist. The effect on the level of employment of the two other factors depends, not surprisingly, on whether they are substitutable for, or complementary with, the new input. Given how frequently technical change is associated with a new intermediate input (fertilizer in LDC agriculture, for example), it is unfortunate that this case has received so little attention.

2.28 Applications: The Environment, Utility Regulation, and Class Warfare

McCain [327] provides an application of the Kennedy approach (and the Nordhaus isotech analysis) to environmental policy. In this case the third input is an unpriced collective good, which may be called "environmental capacity"; the model shows that in a growing economy, increasing pollution[60] will only be averted if the "price" (corrective tax, or an alternative measure) of pollution rises at least proportionally with the productivity of labour.

The notion that regulation of the rate of return on capital should lead to overcapitalization is suggested by the static resource allocation model of Averch and Johnson [19]. Following the approach of Kamien and Schwartz [260, 262], Smith [502] incorporates an IPF in the Bailey and Malone [22] model of the regulated firm and shows that the rate of return regulation will increase the labour-saving bias of technical change, adding dynamic misallocation of resources to the static inefficiency (an issue raised by Hayami and Ruttan [219, p. 151]. Okuguchi [378] proves that in the CES case, the usual condition of $\sigma < 1$ is necessary for this result, while Magat [306] shows that even in this case the result does not hold generally for the class of homothetic production functions.[61]

A third application of the model to growth cycles is provided by Shah and Desai [489], who incorporate Kennedy's frontier in Goodwin's [180] model of cycles in growth rates. Whereas in Goodwin's model the economy moves in cycles around the equilibrium, giving the capitalists an extra weapon in the form of choice of the bias in technical change leads to a locally stable equilibrium characterized by Harrod-neutral technical change. The authors suggest that the next task of theoretical research should be to model the worker's reaction to the labor-augmenting bias of technical change.

2.3 Estimates of Non-Neutral Technical Change and Tests of the Induced Innovation Hypothesis

The empirical investigations of the induced innovation hypothesis follow from the discussion of microeconomic approaches in Section 2.22. Kennedy's model and the many developments of it represent contributions to the modern theory of economic growth and do not lend themselves readily to empirical tests.[62] By contrast, many contributors to the microeconomic approach were mainly interested in developing a theoretical structure rigorous enough to impose restrictions on the parameters of the models sufficient to allow meaningful empirical tests. Several empirical contributions to the literature on biased technical change are included in Section 2.32, since in combination with knowledge of the trend in factor prices they provide useful evidence on induced innovation.

2.31 In Agriculture

The induced innovation hypothesis was first tested by Hayami and Ruttan [218, 219] against the historical evidence of productivity growth in Japan and the United States for the period 1880-1960. The analysis was extended by Wade [556] to include the United Kingdom, France, and Denmark and by Weber [559] to include Germany. The results for all six countries, with two time periods for Germany and France giving a sample of eight, are fully reported and discused in Yamada and Ruttan [577, pp. 522-528] and Binswanger and Ruttan [57, pp. 59-86]. The Japan and United States results are updated to 1980 in Hayami and Ruttan [222].

The model of biological technical change in Figure 2.3b suggests that a decline in the price of fertilizer relative to land will induce advances in crop technology, such as fertilizer-responsive crop varieties, characterized by the shift from point A on IPC_0 to point C on IPC_1. Thus there should be a strong negative relationship between fertilizer per hectare and the price of fertilizer relative to the price of land. Furthermore, there should be a positive relationship between fertilizer per hectare and the price of labour relative to the price of land, since a risng relative price of labour should induce farmers to substitute fertilizer and other chemical inputs such as herbicides and insecticides for more labour-intensive husbandry practices.

The tests[63] regressed the logarithm of the fertilizer/land ratio on the logarithms of the two price ratios, giving results that strongly support the inducement hypothesis.[64] Thirtle [539, p. 175] applies the same test to pooled data for the ten U.S. farm production regions over the period 1939-78 for wheat, corn, soybeans, and cotton. Again the results are almost entirely consistent with the hypothesis. Wade and Weber also apply the test to the relationship between feed concentrates and factor prices, since in animal agriculture food concentrates play a role analogous to fertilizer in crop agriculture. For the four equations fitted, all eight coefficients have significant signs supportive of the hypothesis.

The mechanical technology model in Figure 2.3a implies that both the land/labour ratio and the ratio of machinery to labour should be negatively related, firstly, to the price of land relative to the price of labor, and secondly, to the price of machinery relative to the price of labor. Tests of the machinery-to-labor relationship produce results that generally support the hypothesis. The coefficient of the machinery price/labor price ratio is always in agreement with the theory, while the coefficient of the price of land relative to the price of labor is contrary to the hypothesis in two of the eight cases.

However, the land/labor ratio equations fail to provide support for the hypothesis. Though the coefficient of the price of machinery relative to the price of labor is contrary to the hypothesis in only one case, the coefficient of the price of land relative to the price of labor fails to support the hypothesis in the majority of cases. Thirtle's [539, pp. 176-177] crop-specific results were clearer; in all eight equations the sign of the machinery price/labor price coefficient is consistent with the hypothesis, but in all cases the sign of the land/labor price ratio is contrary to the predictions of the theory [542].

Two explanations of these perverse results are offered. Ruttan et al. [455, pp. 62-64] attribute them to an "innate labor-saving bias" in technological possibilities. Thirtle [542] argues that the results are not damaging to the induced innovation hypothesis but suggest that the Hayami-Ruttan model should be reformulated. Specifically, if machinery replaces land in Figure 2.3a and technical change is depicted as in Ahmad's model [2], Figures 2.3a and 2.3b can be combined to form the four-quadrant diagram shown in Figure 2.4, which allows for interaction between the two groups of factors in equation (10). Thus an "innate labor-saving bias" can be explained by the rate of mechanical technical change reducing the input of labor faster than biological innovation reduces the input of land even at constant factor prices and with no direct substitution of land for labor.

These simple tests of induced innovation do not distinguish between technical change and factor substitution. Though this feature of the model appears to have worried some critics, Figures 2.3a amd 2.3b suggest that the shorter-run substitution from point A to point B becomes irrelevant in the secular period in which the IPC shifts and the final equilibrium at C is attained.[65] Thirtle [542] applies this reasoning to a four-quadrant model similar to Figure 2.4 but which includes Hayami and Ruttan's IPCs and changing factor prices. The entire substitution of machinery for labour is attributed to mechanical technical change, just as the whole decrease in the input of land per unit of output is attributed to biological technical change. This allows the labor-saving bias to be measured by the increase in the land-labor ratio.[66] Using estimates for four U.S. field crops, the more initially labor-intensive the crop, the greater the labor-saving bias of technical change over the period 1939-78. This result is entirely consistent with the induced innovation hypothesis.[67]

Later tests comply with the neoclassical orthodoxy by differentiating between factor substitution and biased technical change.[68] Thirtle's [540] model is actually simplified by this change, as is shown in Figure 2.4 and explained in the associated discussion. Applied to four U.S. field crops, this model also gives results that entirely support the induced innovation hypothesis. A further test showed that the labor-saving bias was greater for U.S. farm production regions with high ratios of labor to land than for less labor-intensive regions, again supporting the hypothesis.[69]

Ruttan et al. [455] compute the elasticities of substitution necessary to explain the observed differences in the land-labor ratios between countries, and the changes over time within countries, for the six-country sample discussed above. In cases where the required elasticity exceeds the econometrically estimated[70] actual elasticity by a sufficiently wide margin, the null hypothesis of neutral technical change is rejected.

The results indicate that four different game paths can be distinguished. Firstly, in 1880 the United States was on the same production function as France, Germany, and the United Kingdom, but after 1880 technical change in the United States had a strong labor-saving bias. Secondly, Continental Europe experienced neutral technical change until the 1960s, after which France and Denmark experienced labor-saving technical change. Thirdly, technical change in the United Kingdom was neutral until 1930 and strongly labor-saving thereafter, though technology remained more labor-intensive than in the United States case. Lastly, Japan began from an extremely labor-intensive position and showed neutral technical change, with a slight labor-saving bias in recent years. These results are largely consistent with the induced innovation hypothesis, but Japan, Britain, France, and Denmark all experienced periods when technical change had a labor-saving bias despite a falling ratio of wages to land prices. This is explained by either an "innate labor-saving bias" or by the international transfer of mechanical technology developed in the United States and not entirely suited to European factor-price ratios.

The tests described above, like many other recent contributions, use estimates of factor substitution possibilities that are derived from flexible functional forms and that exploit the duality relationships between production, cost, and profit functions. The most popular specification in agricultural economics has been the translog cost function, which gives rise to simple linear systems of factor share equations.[71] Binswanger's [50, 52, 56] many-factor tests follow this course. First, translog cost functions are estimated, using 1949-64 data, to determine the Allen partial elasticities of substitution for inputs of land, labor, machinery, fertilizer, and other inputs. Then the translog function is fitted to time series data for 1912-68 and the changes in factor shares are divided into two elements (using the elasticity measures): the change in factor shares attributable to factor substitution and residuals attributable to technical change. In terms of the factor share definition of bias (equation 8), technical change is found to be fertilizer- and machinery-using over the entire period, with a labor-saving bias discernible after 1948. When plotted against input prices, the technical change indices show trends and turning points consistent with the induced innovation hypothesis (see Ruttan [451, pp. 19-20] for a discussion). In an earlier study, Binswanger [48] derived similar results for the United States since the turn of the century and applied the same approach to Japanese agriculture (see below).

Binswanger's results are confirmed by Chambers and Lee [82], who fit a translog indirect production function to aggregate U.S. data for 1947-80. Technical change is found to be land- and labor-saving and capital- and material-using. These conclusions can be compared to those of Weaver [558], who applied a translog expected profit function to North and South Dakota wheat data for 1950-70. With inputs of labor, capital, fertilizer, petroleum products, and materials, Weaver finds technical change to be labor-saving relative to all other inputs (supporting the results of Lianos [294], but capital-saving relative to all inputs but labor. Additionally, technical change is fertilizer-using relative to all inputs and petroleum-product-using relative to all inputs except fertilizer.

However, Lopez [299] applies a modified generalised Leontief cost function to time series data for Canadian agriculture[72] over the period 1946-77. He does not impose constant returns to scale and finds that the null hypothesis of zero factor-saving technical change cannot be rejected. The constant returns to scale hypothesis, by contrast, is decisively rejected, suggesting that increasing returns are an important source of productivity growth.

Kislev and Peterson [276] are also critical of the inducement hypothesis and have estimated a model of the U.S. agricultural sector that accounts for increases in both land-labor ratios and farm size "by changes in relative factor prices without reference to 'technical change' or 'economies of scale.'" In response, Hayami and Ruttan [222, pp. 187-205] follow Binswanger [56] in developing a framework for decomposing the changes in factor shares into factor substitutuion and technical change components. Using a two-stage CES, they generate estimates that show both effects to be important.[73] Plots of factor prices against factor-using biases show clear negative relationships for labour, power, fertilizer, and land, thus offering clear support for the inducement hypothesis. The estimates of factor-saving biases are broadly consistent with Binswanger's [51] results except in the case of machinery, where Binswanger found a machinery-using bias combined with a rising relative price. Adjustment of the machinery price series for quality changes removes this inconsistency. Thirtle [541] follows the same methodology and finds biased technical change to be crucial in explaining mechanisation in U.S. corn production, while increases in fertilizer per acre can be largely explained by factor substitution. Again the results support the inducement hypothesis with technical change strongly labour-saving, machinery- and fertilizer-using, and neutral with respect to land.

For Japan, both the original Hayami and Ruttan tests [218, 219] and the comparisons of Ruttan et al. [455] are less convincing than in the U.S. case.[74] Several other studies should also be considered. Sawada [475] surveys the earlier literature and fits a CES function for the period before the First World War, the inter-war period, and the period since the Second World War, finding technical change to be land-saving and labor-using in the first two periods and land-using/labor-saving in the last period.

Binswanger [48] fits a translog cost function to Japanese data since the turn of the century for comparison with similar estimates for the United States. His results also offer some support for the inducement hypothesis. Technical change is found to be land- and machinery-saving. A fertilizer-using bias appears earlier than in the U.S. case, but after the 1920s, technical change is neutral with respect to fertilizer. For labor, the bias is labor-using before 1928 and labor-saving after that date.

The findings of other researchers appear to be contrary to the inducement hypothesis. Yeung and Roe [580] fit a CES function in which the exponential technical change parameters are a function of an index of the price of labor relative to the price of land and find technical change to be labor-saving. This conclusion is also reached by Nghiep [364], whose approach slightly modifies that of Binswanger [49]. Technical change is found to be considerably labor-saving and fertilizer-using for the period 1905-39. Slight machinery-using and land-saving biases are also apparent. However, Nghiep argues that these results <u>support</u> the induced innovation hypothesis since agricultural wages rose the most rapidly, followed by the prices of land, machinery, and other inputs, with fertilizer prices rising least.[75]

The studies considered above are based largely on national statistics that have been the subject of debate for the last twenty years [see 222, p. 164, for references]. Kako [256] followed Binswanger's translog cost function approach, but applied it to rice production data for 1953-70 in the Kinki agricultural district. His estimates of technical change are far more consistent with the inducement hypothesis. Innovation saves the scarce factors, labor and land, considerably, but fertilizer and machinery only slightly, thus helping to explain the increasing ratio of machinery to labor and fertilizer to land.

Lee [290] also used different data covering rice production in four prefectures for the period 1955-75 and identified three phases of technological change. From 1957 to 1960, technical change was land-using and labor-saving; from 1961 to 1967, the converse was true; from 1968 to 1975, technical change was again land-using and labor-saving. With respect to machinery, technical change was neutral until 1965 and has shown a remarkable machinery-using bias since that time. Lee argues that these results do support the induced bias hypothesis, though farm size, output price, and lags in innovation and diffusion must also be considered. There is also an anomalous result: technical change has been fertilizer- and pesticide-saving, despite a substantial decline in the relative price of these inputs.

With the benefit of hindsight, Hayami and Ruttan [222] tackle the data problems[76] and exclude the period of the Second World War and its aftermath in an application of their two-stage CES model. For all four inputs (labor, power, land, and fertilizer) their indices show a strong and consistent negative relationship between factor prices and factor-using biases that is entirely consistent with the inducement hypothesis.

The body of evidence is sufficient to substantiate the case for a relationship between factor prices and factor biases. Alderman [7] suggests that factor prices alone are not sufficient to account for the direction of factor biases and proceeds to include the effect on factor shares of research, extension, and infrastructure investment.

The available evidence has been extended to include other countries besides the United States and Japan and the limited information on the United Kingdom, France, Germany, and Denmark [455]. Investigations of non-neutral technical change and/or tests of inducement in agriculture include McKay et al. [329] on Australian sheep, corn, and beef production; Ahmad and Kubursi [3] on Egypt and Syria; Park [388] on Korea; Johnson [244] on New Zealand; and Godden [176] on the United Kingdom. The degree of agreement varies, but on balance these studies offer support for the inducement hypothesis. In addition, de Janvry's [109, 111] work on Argentina and Feeny's [143] study of Thailand extend the model to include social and political factors. Sanders and Ruttan [467] investigate the effects of price distortion, and Barlow and Jayasuriya [26] show that new technology in the Malaysian rubber industry tended to be capital-using and hence favoured the large estates relative to the smallholders.

Ruttan [451, pp. 20-21] suggests that much could still be learned by extending the tests to include countries that have invested heavily in the green revolution technology and by investigating recent relative price changes, particularly those for energy inputs and agricultural land.

However, the basic idea that factor biases are dependent on factor prices is well supported by a large body of evidence. Conceptual advances would seem to be required at this stage. Table I presents the work to date in an accessible form. The studies presented in Table I leave little doubt that there is a relationship between differences or changes in factor prices and the direction of factor-saving bias in technical change. Efforts should be made, however, to design more rigorous tests for induced innovation.

2.32 In Industry

Few direct tests of the induced innovation hypothesis have been conducted for the non-farm sector, but studies of biased technical change provide a considerable body of supporting evidence that will also be considered.

Using sample survey methods in an early attempt to determine the effect of union wage pressure on technological discovery, Bloom [63, p. 615] found little evidence that union wage pressure led to labor-saving changes, though it did seem "to have produced some increase in the total volume of discoveries." A similar study of the manufacturing sector by Piore [397], based on interviews with engineers, personnel, and industrial relations specialists, reached the same negative conclusion. Enos' [128] study of the petroleum industry found that inventions tended to be neutral, rather than saving the scarce factor, though there was some labor-saving bias at the development and improvement stage.

Early confirmation of non-neutral technical change in the United States was provided by studies such as Brown and Popkin [73], Resek [416], and Brown [72]. David and Van de Klundert [103] found that the U.S. private economy exhibited a significant Hicksian labor-saving bias during the first

Table Ia : Summary of Empirical Studies of Induced Innovation in Agriculture - USA (see notes at foot of Table Ic for meaning of symbols)

Study and Reference	Crop, Area and Time Period	Methodology	Factor Biases	Consistency of Results with Induced Innovation
1) Hayami & Ruttan [219]	National Aggregate, 1880-1960	Regression of factor ratios on factor price ratios	Not estimated	Consistent with induced innovation
2) Hayami & Ruttan [222]	National Aggregate, 1880-1980	" " "	" "	Consistent with induced innovation but not all coefficients are significantly different from zero
3) Binswanger [51], [56]	National Aggregate, 1912-1968	Translog cost function	LAND - (slight) LABOUR - (after 1948) MACHINERY + FERTILIZER + OTHER none	Consistent
4) Kislev & Peterson [276]	National Aggregate, 1930-1970	Implicit two stage CES production function	No technical change	Contrary in the sense that factor substitution explains all changes without reference to technical change
5) Weaver [558]	Wheat, North and South Dakota 1950-1970	Translog profit function	LABOUR - CAPITAL - FERTILIZER + PETROLEUM PRODUCTS +	Consistent
6) Thirtle [540, 543]	Wheat, Soybeans, Corn and Cotton, 10 US Farm Produc-Regions, 1939-1978	CES/Cobb-Douglas	LABOUR-SAVING BIAS	Consistent
7) Thirtle [541]	Corn, 10 US Farm Produc-Regions, 1939-1978	Two stage CES production function	LAND + slight LABOUR - strong MACHINERY + strong FERTILIZER + strong	Consistent
8) Thirtle [542]	Wheat, Soybeans, Corn, Cotton, 10 US Farm Produc-tion Regions, 1939-1978	Calculated from the data using 2 stage CES estimates of substitution elasticities	LABOUR SAVING BIAS	Consistent
9) Hayami & Ruttan [222]	National Aggregate, 1880-1980	Two stage CES production function	LAND - LABOUR - MACHINERY + FERTILIZER +	Consistent
10) Chambers & Lee [82]	National Aggregate 1947-1980	Translog indirect production function	LAND - LABOUR - CAPITAL + MATERIALS +	Consistent

Table 1b : Summary of Empirical Studies of Induced Innovation in Agriculture - Japan

Study and Reference	Crop, Area and Time Period	Methodology	Factor Biases	Consistency of Results with Induced Innovation
1) Sawada [475]	National Aggregates 1883-1963	2 factor CES production function	LAND - before 1931 LABOUR + LAND + after 1946 LABOUR -	Consistent
2) Hayami & Ruttan [219]	National Aggregates 1880-1960	Regression of factor ratios on factor price ratios	Not estimated	Consistent with induced innovation in two cases out of three
3) Hayami & Ruttan [222]	National Aggregates 1880-1960	Regression of factor ratios on factor price ratios	Not estimated	Consistent
4) Binswanger [48]	National Aggregates 1900-1970	Translog cost function	LAND - LABOUR + before 1928 - after *MACHINERY - FERTILIZER +	Mainly consistent
5) Yeung and Roe [580]	National Aggregates 1880-1940	Modified 2 factor CES	* LAND + * LABOUR -	Contrary to induced innovation
6) Kako [256]	Rice in Kinki District	Translog cost function	LAND - strong LABOUR - strong MACHINERY - slight FERTILIZER - slight OTHER - very slight	Consistent
7) Nghiep [364]	Rice, national, 1905-39	Translog cost function	LAND - * LABOUR - MACHINERY + FERTILIZER +	Mainly consistent
8) Lee [290]	Rice, 4 prefectures	Translog production function	LAND + 2 out of LABOUR - 3 sub-periods MACHINERY - strong * FERTILIZER - *& PESTICIDE -	Mainly consistent
9) Alderman [7]	National Aggregates 1902-1940	Translog cost function	LAND - * LABOUR - CAPITAL + CURRENT INPUTS + (Mainly Fertilizer)	Mainly consistent
10) Hayami & Ruttan [222]	National Aggregates 1880-1980	Two stage CES production function	LAND not clear LABOUR - MACHINERY + FERTILIZER +	Consistent

Table 1c : Summary of Empirical Studies of Induced Innovation in Agriculture - Other Countries

Study and Reference	Country	Crop Area and Time Period	Methodology	Factor Biases	Consistency of Results with Induced Innovation
1) McKay, Lawrence & Vlastuin [329]	Australia	Sheep and wool, crops, beef cattle, and other farm output in the Australian wheat/sheep zone, 1952-1977	Translog variable profit function	LAND - slight LABOUR - strong CAPITAL + strong *MATERIALS - slight	Mainly consistent
2) Lopez [299]	Canada	National Aggregates, 1946-1977	Generalised Leontief cost function	Increasing returns to scale and no technical change	Contrary
3) Ahmad & Kubursi [3]	Egypt & Syria	(For V. Ruttan to complete)			
4) Ruttan et.al. [455]	Denmark	National Aggregates, 1910-1965	Regression of factor ratios on factor price ratios	Not estimated	Mainly consistent, but the behaviour of the land/labour ratio in Denmark, France and the U.K. is not explained by the relative factor prices
	France	" 1870-1965	"	"	
	Germany	" 1880-1968	"	"	
	United Kingdom	" 1870-1965	"	"	
5) Ruttan et.al. [455]	Germany	Livestock Production 1880-1968	"	"	Consistent
	Denmark	" 1880-1925	"	"	
	United Kingdom	" 1870-1965	"	"	
6) Binswanger [52]	USA	National Aggregates, 1880-1970	International comparisons of residual measures of land and labour-saving technical changes	Labour-saving	General support
	Japan	" "		mainly neutral	
	Great Britain	" "		labour-saving	
	France	" "		slightly labour-saving	
	Germany	" "		"	
	Denmark	" "		"	
7) Park [388]	South Korea	Rice, 1963-1984	Regression of factor ratios on factor price ratios	Not estimated	Consistent
8) Barlow and Jayasuriya [26]	Malaysia	Rubber, 1922-1978	Cost calculations	LAND - LABOUR - CAPITAL +	Consistent, but a bias in favour of plantations relative to small-holders
9) Johnson [244]	New Zealand	National Aggregates, 1945-1967	CES production function	LABOUR - CAPITAL +	Consistent
10) Godden [176]	United Kingdom	National Aggregates, 1950-1980	General linear variable profit function	LAND - LABOUR - No Result PLANT + *MATERIALS -	Unclear, generally poor results

For attempts to examine the social and political aspects of induced innovation see de Janvry [96], [97], Feeny [127], Sanders and Ruttan [394] and de Janvry and Dethier (1985).

NOTES For factor biases (-) indicates factor-saving technical change and (+) indicates that technical change was factor-using. The symbol * against a factor bias indicates that it is either contrary to the direction indicated by the inducement hypothesis or explanation by the author is required to reconcile it with the theory.

half of this century. This result is confirmed by the more recent work of Sato [468], Takayama [531], Panik [387], and Zind [581]. At the industry level, Gupta and Taher [199] find the same labour-saving bias for post-war cotton textile production in the United States, as do Bergstrom and Melander [37] for nine Swedish manufacturing industries and Forsund and Jansen [161] for the Norwegian aluminum industry.

Subdividing the time period, David and Van de Klundert [103] found technical change in the U.S. private sector to be labor-saving for the 1900-18 period at a rate greater than for the full time span, neutral from 1919 to 1945, and labor-saving at a still greater rate from 1946 to 1960. However, Brown and Popkin [73] divided the period into three "technological epochs," 1890-1918, 1919-37, and 1938-58, and found technical change to be labor-saving between the first pair of epochs, but capital-saving between the second pair.[77]

The results of Morishima and Saito's [344] test of induced innovation partially agreed with both earlier studies, finding labor-saving change over the entire period, but with a heavy labor-saving bias before 1929 and a slight capital-saving bias thereafter. To test the induced innovation hypothesis, total technical change was divided into an induced component, an autonomous component, and the effect of changing industrial composition. Though the 1902-29 period was dominated by the growth of the industrial sector relative to agriculture, induced innovation was found to be capital-saving in the depression years of 1929-38,[78] when the labor force was increasing relative to the capital stock, and labor-saving for the period of high employment and rapidly rising wages from 1938 to 1955.

Fellner [155] also set out to investigate the induced innovation hypothesis, using U.S. data and arguing that increases in the capital-labor ratio would have increased labor's share of income but for offsetting effects. His regression results suggested that labor-saving innovations were one of these effects.

The recent introduction of flexible functional forms that can sensibly accommodate several inputs, together with the considerable change in relative factor prices caused by the energy crisis, has given a new lease on life to studies of non-neutral technical change. Berndt and Khaled [40] fit a generalised Box-Cox cost function to U.S. manufacturing data for the period 1947-71. Technical change is found to be capital- and energy-using and labor- and intermediate-material-saving. Woodward [575] applies Binswanger's [56] methodology to the postwar U.S. manufacturing sector and finds that labour augmentation is most pronounced, followed by capital augmentation, while the trends for energy and materials are far less clear. These results are not at all contrary to the inducement hypothesis, but those of Jorgenson and Fraumeni [252] are. They estimate biases of technical change for thirty-five U.S. industries. Technical change is labor-using for thirty-one industries, energy-using for twenty-nine, capital-using for twenty-five, and material-saving for thirty-three of the thirty-five industries.

Wills' [569] four-factor test of the inducement hypothesis, using data on the U.S. primary metals industry, is entirely supportive of the hypothesis. The rate of augmentation in descending order is labor, energy, materials, and capital, which corresponds exactly to the ordering of factor price increases. Moroney and Trapani's [345] four-factor study of six U.S.

natural-resource-using industries also produces results consistent with inducement. Berndt and Wood's [41] study of electric power produces a result similar to that of Wills [569]. Several other contributions on electricity generation reach similar conclusions [98, 178, 186], finding technical change to be capital- and labor-saving and fuel-using. Investigating the same industry, Stevenson [514] finds technical change to be capital- and labor-saving and fuel-using but argues that his "results failed to demonstrate the existence of induced technological bias" [514, p. 172]. Belinfante's [32] productivity study of U.S. electricity generation is also negative, finding evidence of technical change but little sign of bias.

For other countries the evidence is more limited, but Norsworthy and Malmquist's [369] study of the productivity slowdown is based on the translog production function and compares estimates of biased technical change in U.S. and Japanese manufacturing. For Japan, technical change is capital-using and labor-, energy-, and material-saving. The strong energy-saving bias for Japan contrasts with energy-using technical change in the United States and is attributed to high Japanese oil prices. Investigating the Japanese petrochemical industry, Lau and Tamura [286] apply a modified Leontief production function but cannot reject the hypothesis of zero technical change.

Rao and Preston [407] provide estimates of the factor-saving biases in many Canadian industries. For the majority, technical change is labor-saving, and capital-, energy-, and raw-material-using. Duncan and Binswanger [124] compare estimated rates of factor augmentation with rates of factor price change for data on Australian manufacturing industries and claim mild support for the inducement hypothesis. However, their translog study [125] of alternative sources of energy for five Australian industries over the period 1948-67 reaches negative conclusions. The price of fuel oil has fallen most relative to the price of other sources, yet oil expenditure shares are mainly neutral or factor-using. The price of coal gas has fallen least, but only one industry shows a reduction in the factor share.[79]

For the developing countries there have been few tests, but Lynk [301] studies a range of Indian manufacturing industries for the 1952-71 period. Technical change is found to be labor-saving and plant- and machinery-using. Levy's [293] productivity study of Iraq over the period 1961-67 also shows technical change to be labor-saving. However, he points out that this result is consistent with the induced innovation hypothesis, since wages were rising over the period and Iraq is neither labor-abundant nor short of capital, having oil resources and foreign Arab funds.

To date, the evidence of induced innovation in industry rests on a few deliberately constructed tests and a considerable body of information on the direction of technical change, which is sometimes explained by reference to input price movements. Table II provides an overall impression but is no substitute for a careful inspection of the available evidence. Although the weight of evidence from the industrial sector tends to support the inducement hypothesis, the evidence is less clear than from the studies in the agricultural sector. In part this is because many studies have been conducted within a simple two-factor framework. The lack of clarity may also be due to differences in the nature of technical possibilities among industries.

Table 11(a) : Summary of Empirical Studies of Induced Innovation in Industry

Study and Reference	Country, Industry and Time Period	Methodology	Factor Biases	Consistency of Results with Induced Innovation
1) Brown and Popkin [73]	US non-farm domestic sector, 1890-1958	Cobb-Douglas production function parameter estimates are used in comparisons of "technological epochs"	1890-1918 } 1919-1937 } LABOUR-SAVING 1938-1958 } LABOUR-SAVING	The labour-using result is clearly contrary to the induced innovation hypothesis.
2) Resek [416]	US non-farm domestic sector, 1919-1959	Regression of factor ratio on factor prices	LABOUR-SAVING	Consistent
3) David & Van de Klundert [103]	US private domestic economy, 1899-1960	CES production function	LABOUR-SAVING	Consistent
4) Ferguson [156]	Several US industries, 1949-1961	CES production function	GENERALLY LABOUR-SAVING	Mainly Consistent
5) Sato [468]	US private non-farm sector, 1909-1960	CES and CEDD (constant elasticity of derived demand) production functions	LABOUR-SAVING	Consistent
6) Takayama [531]	US non-agricultural private sector 1909-1960	Linear regression of several "simple formulas"	LABOUR-SAVING	Consistent
7) Panik [387]	US private domestic sector 1929-1966	CES production function	LABOUR-SAVING	Consistent
8) Zind [581]	US private non-farm sector 1909-1960	Linear regression estimation of coefficients of underlying relationships, similar to Takayama [444]	LABOUR-SAVING	Consistent
9) Gupta and Taher [199]	US textile industry 1949-1974	Translog cost function	LABOUR-SAVING	Consistent
10) Bergstrom and Melander [37]	Swedish Industry in aggregate and eight industries 1950-1973	Input demand functions from a CES	LABOUR-SAVING	Consistent
11) Forsund and Jansen [161]	Norwegian Aluminium industry 1966-1978	Comparison of cost-minimising factor ratios, as in Salter [390]	LABOUR-SAVING	Consistent
12) Morishima and Saito [344]†	US domestic economy 1902-1955	Differentiates between autonomous and induced innovation and includes structural change. A proper test of induced innovation based on the CES	Induced innovation is: PRACTICALLY NEUTRAL 1902-1929 CAPITAL-SAVING 1929-1938 LABOUR-SAVING 1938-1955	Consistent

Table II(a) continued.

Study and Reference	Country, Industry and Time Period	Methodology	Factor Biases	Consistency of Results with Induced Innovation
13) Fellner [155]†	US two digit manufacturing industries 1948-1957	Regression of increase in factor ratio on the rate of change of the factor price ratio	Suggests labour-saving innovations	Consistent
14) Berndt and Wood [41]	US manufacturing, 1947-1971	Translog cost function	CAPITAL LABOUR ENERGY MATERIALS Could not reject Hicks' neutrality	Inconsistent
15) Belinfante [32]	460 observations on 80 US steam-electric generating plants of 1947-59 vintage	Total factor productivity study based on Divisia indices	Little evidence of biases	Inconsistent
16) Wills [569]†	US primary metals industry, 1948-1974	Translog cost function	LABOUR - ENERGY - MATERIALS - CAPITAL +	Consistent. The rates of factor augmentation are shown in descending order; the ordering of the rates of price increase is the same.
17) Berndt and Khaled [40]	US manufacturing, 1947-1971	Generalised Box-Cox cost function	CAPITAL + LABOUR - *ENERGY + MATERIALS -	Mainly consistent
18) Stevenson [514]†	US electricity generating firms for 1964 and 1974	Translog cost function	*CAPITAL - LABOUR - FUEL +	The author finds no evidence to support the hypothesis but see (23).
19) Jorgenson and Fraumeni [252]	Thirty-five US industries, 1958-1974	Translog cost function	CAPITAL + (25) industries *LABOUR + (31) industries ENERGY + (29) industries MATERIALS -(33) industries	Contrary
20) Moroney and Trapani [345]	Six US natural resource intensive industries 1955-1974	Translog cost function	CAPITAL + (3) industries) LABOUR - (6) industries NATURAL RESOURCES + (5) industries SCRAP METAL + (2) industries (Scrap was used in only 2 industries)	The dominant pattern of labour-saving and natural resource-using technical change is consistent with relative input price movements.
21) Woodward [575]	US non-farm private sector, 1948-1978 US manufacturing sector, 1958-1977	Translog cost function	CAPITAL - strong LABOUR - strong ENERGY - weak MATERIALS - weak	Mainly consistent. Energy price have a slight effect.

Table II(a) continued.

Study and Reference	Country, Industry and Time Period	Methodology	Factor Biases	Consistency of Results with Induced Innovation
22) Greene [185]	US electric power companies 1955-1975	Translog cost function	CAPITAL - LABOUR - (since 1965) FUEL +	Unclear. The prices of capital and labour were rising relative to that of fuel almost to the end of the period.
23) Gollup and Roberts [178]	US electric power industry 1973-1979	Translog cost function	CAPITAL - LABOUR - FUEL +	Unclear.
24) Lau and Tamura [286]	20 Japanese petro-chemical plants of vintage 1958-1969	Input demand functions from a modified Leontief production function	CAPITAL LABOUR ENERGY MATERIALS Hypothesis of zero technical change could not be rejected	Contrary
25) Duncan and Binswanger [124]†	14 Australian manufacturing industries 1948-1967	Translog cost function	7 factors	Mild support, but results unclear
26) Duncan and Binwanger [125]†	Energy use in Australian manufacturing industries 1948-1967	Translog cost function	COAL - FUEL OIL unclear ELFCTRICITY + COAL GAS unclear	Perhaps mild support
27) Levy [293]	Iraq, industrial sector, 1961-1967	Translog profit function	LABOUR-SAVING	Not really contrary. Wages were rising and Iraq is not short of capital
28) Lynk [301]	15 Indian industries, 1952-1971	Generalised Leontief cost function	CAPITAL + PLANT + LABOUR -	Contrary
29) Norsworthy and Malmquist [369]	Japanese manufacturing 1965-1978	Translog cost function	CAPITAL + LABOUR - ENERGY - MATERIALS -	Unclear
30) Rao and Preston [407]	Canadian industries 1957-1979	Translog cost function	Predominantly CAPITAL - *LABOUR neutral ENERGY + MATERIALS +	Contrary
31) Daly and Someshwar Rao [98]	Ontario Hydro, 1967-1980	Translog cost function	CAPITAL - LABOUR - ENERGY + MATERIALS +	Mainly consistent

Table II(b) : Summary of Empirical Studies of Induced Innovation in Economic History

Study and Reference	Country, Industry and Time Period	Methodology	Factor Biases	Consistency of Results with Induced Innovation
1) Asher [17]	British and American textiles, 19th century	CES production function	LABOUR-SAVING BIAS in both countries	Contrary to the hypothesis since Britain had the greater labour-saving bias.
2) Uselding [545]	Springfield Armory 1820-1850	CES production function	LABOUR-SAVING BIAS overall	Weak support
3) Uselding and Juba [546]	American manufacturing 1839-1899	CES production function	LABOUR-SAVING BIAS overall	Weak support
4) Smith [503]	Springfield Armory 1820-1850	Translog cost function	LABOUR - Insignificant CAPITAL + MATERIALS -	Unclear. The author avoids making too much of the results
5) Cain and Paterson [78]	19 US manufacturing industries 1820-1919	Translog cost function	LABOUR - (14) industries CAPITAL + (16) industries NATURAL RESOURCES + (12) industries OTHER - (13) industries	Mainly consistent
6) Phillips [394]†	British coal industry, second half of 19th century	Translog cost function	LABOUR-SAVING BIAS except during the depression	Consistent
7) Phillips [395]†	Pig iron, cotton textiles, second half of 19th century	Translog cost function	Unclear	Contrary. Nearly all parameter estimates have the wrong sign.

NOTES Studies (1)-(12) are two-factor estimates of non-neutral technical change, rather than tests of induced innovation. Papers that explicitly address themselves to testing the induced innovation hypothesis are marked †.

The symbols (+), (-) and * have the same meaning as in Table I. In most instances "consistent" means only that the direction of the factor bias of technical change is the opposite of relative input price changes. The degree of correlation between the two variables may be high or low.

2.33 In History

The Rothbarth-Habakkuk thesis, discussed in Section 2.21, suggests that the high wage rate in the United States relative to Britain should have resulted in a greater labor-saving bias to technical change in the United States. This proposition was subjected to an empirical test by Asher [17], who fitted a CES function to U.S. and British textile data for the second half of the nineteenth century. Asher [17, p. 440] interpreted the results as showing a labor-saving bias in both countries, but with Britain having the greater labor-saving bias, clearly contradicting the hypothesis.[80]

Further evidence on the United States from a similar study of manufacturing industries over the period 1839-99 by Uselding and Juba [546] shows technical change to be labor-saving over the whole sample (in keeping with the rise in the wage/rental ratio), but finds a capital-saving bias for the decades of the 1840s, 1870s, and 1890s.

Uselding [545] analyses data from the Springfield Armory for 1820-50 and finds technical change to be labor-saving over the entire period (over which time the wage/rental ratio was rising). Division into subperiods shows that the labor-saving result held only for the 1841-50 period, when the relative wage was rising most rapidly. In addition, three-factor analysis shows some support for the Ames and Rosenberg hypothesis, since raw and intermediate material inputs appear to be important. This result is confirmed in the critique by Klingaman, Vedder, and Gallaway [279] of Uselding's approach, and Smith's [503] study, which applies a translog function to Uselding's data. Natural resource inputs were found not to be separable (defined in Section 2.22) for inputs and capital and labor, suggesting, in corroboration with the Ames and Rosenberg hypothesis, that natural resources must be considered along with labour and capital in evaluating U.S. technical change.[81]

Cain and Paterson [78] fit a translog cost function to data for a large range of U.S. industries over the period 1850-1919. Their results appear to support both the inducement hypothesis and the Ames and Rosenberg position. Over the period, the price of labor rose relative to that of both capital and raw materials. For the majority of industries, technical change was labor-saving and capital- and resource-using (though the results did not necessarily coincide). An individual industry could, for example, be both labor-neutral and capital-using.

The empirical evidence is less clear for Great Britain. Phillips [395] has investigated pig iron, cotton textiles, and coal mining [394] for the second half of the nineteenth century. No evidence of induced innovation can be found for pig iron. For cotton, technical change is labor-using during the period of the cotton famine (1854-72), but results for the other periods contradict the inducement hypothesis. For coal, induced innovation is evident except in the 1880s and early 1890s, the period once known as the "Great Depression."

2.4 Alternatives to the Conventional Approach

Dissatisfaction with the neoclassical approach to factor substitution and technical change was discussed in Section 2.1 above, but this survey shows the range of difficulties involved in analysing technical change. Partly, progress has been slow because of the breadth of the area, but technical change also raises problems such as market failure, interdependencies, historically contingent events, and the dynamics of change, which do not fit easily into the neoclassical framework. Nelson and Winter [360, p. 205] have been prominent among critics of the conventional methodology: "But what we know about technical change should not be comforting to an economist who has been holding the hypothesis that technical change can be easily accommodated within an augmented neoclassical model. Nor can the problem here be brushed aside as involving a phenomenon that is 'small' relative to those that are handled well by the theory; rather it relates to a phenomenon that all analysts (or virtually all) acknowledge as the central one in economic growth. The tail now wags the dog. And the dog does not fit the tail very well. The neoclassical approach to growth theory has taken us down a smooth road to a dead end."

If the neoclassical paradigm does prove to be a degenerate research programme in the area of technical change, the causes of the failure lie in its origins. Founded on classical physics and using mechanical analogues, the fundamental concept of neoclassical economics is that of equilibrium, the position to which the spring must return or the pendulum settle to rest. Variety is an unnatural state; the norm will prevail once the perturbations cease to disguise it. To neoclassical analysts, path dependence is an unfortunate complication; it is a "system of thought which in its pure form happens to be fundamentally ahistorical, if not actually anti-historical" [100, p. 11]. If time is dealt with, mathematical tractability is enhanced by seeking out stationarity, which definitionally makes history irrelevant. The failure to have a mechanism for explaining variety and the failure to come to grips with historically contingent events are at odds with the reality of technical change at the micro level. Firms differ, particularly in their technological characteristics, because they have different histories and different past experiences.

By contrast, the "neo-Schumpeterian approach is concerned above all with the process of economic change, as opposed to the analysis of equilibrium states" [163, p. 609]. "Economic progress, for Schumpeter, did not consist of price cutting among harness makers. The competitive behaviour that really mattered in the long run came from the innovative acts of automobile manufacturers which abolished harness making as an economic activity" [434, p. 5]. Schumpeter [485, p. 64] himself describes the irrelevance of equilibrium analysis eloquently: "What we are about to consider is that kind of change arising from <u>within the system</u> which so displaces its equilibrium point that the new one cannot be reached from the old one by infinitesimal steps. Add successively as many mail coaches as you please, you will never get a railway thereby."

Nelson and Winter [360] have produced an alternative, evolutionary theory of technical change that is not ahistorical[82] and avoids the neoclassical distinction between movements along a production function and shifting the production relationship. The neoclassical constructs of rational maximization and equilibrium are replaced by local search for, and selection of, techniques based on satisficing behaviour. Thus the model's intellectual heritage can be attributed to both Schumpeter and the behaviouralist approach of Simon [498].

It is particularly pertinent to this survey that even the early versions [356, 357, 362] of the model incorporate a simple price-inducement mechanism that can produce biased technical change in computer simulations. Firms produce with fixed proportion techniques that are retained if profitability is satisfactory, but if profits fall below the critical level, they search for new techniques (or imitate other firms) with a greater probability of finding techniques close to the original production point. In this sense the model is not ahistorical. New techniques, randomly selected, are tested for profitability and accepted if satisfactory. At a high wage/rental ratio, the probability of labor-saving techniques being accepted is greater than at a low wage/rental ratio.

Excess profits are invested, so that the growth of the capital stock is determined by the firm's total investments, with successful firms having the highest weights. The labor supply is inelastic, and firms begin from the same situation. The level of output, the wage/rental ratio, and capital accumulation rates are determined endogenously. Though firms will produce with different techniques, a higher wage rate will favour the choice of capital-intensive techniques, as described above, and lead to the expansion of capital-intensive firms relative to those with a lower capital/labor ratio. Thus, although the search for new techniques is random, in the aggregate the capital/labor ratio will increase if the wage/rental ratio rises.

Later models [357, 358] retain the uncertainty surrounding the research process, but explicitly introduce ongoing direct research (not dependent on inadequate profitability),[83] which adds a further inducement mechanism. At higher wage/rental ratios, the firm has an incentive to devote a higher percentage of its research effort to sampling the spectrum of capital-intensive techniques.[84]

Some of the computer simulation runs produce parameter values and time paths that appear to "explain" Solow's [506] historical data for the United States as well as the neoclassical analysis does. Indeed, neoclassical explanations or simulations explain the data equally well, leading Nelson, Winter, and Schuette [362, p. 117] to suggest an identification problem. Different theoretical structures can lead to similar statistical patterns so that "a world without a production function can, for example, mimic much of the behaviour of a world that has one."

Following Atkinson and Stiglitz [18] (discussed in Section 2.1 above), David [100] has developd an evolutionary model of technical change to investigate the labor scarcity hypothesis of Rothbarth and Habakkuk.[85] He argues that if the abundance of land did lead to an initially high wage rental ratio in the United States, then learning by doing would induce "locally neutral" technical progress, improving the capital-intensive techniques so that switching back to a more labor-intensive technique would not occur even if the factor price ratio changed. Thus, "there is some theoretical basis for seeking the origins of the modern configurations of a society's technology in the accidents of its remote factor-price history" [100, pp. 66-67].[86] Also, following Ames and Rosenberg [11], he argues that if the abundance of raw materials and prodigality in their use did foster more mechanized techniques in the United States than in Britain, the United States would indeed have initially followed a more capital-intensive path even if the wage/rental ratio were the same in both countries. The historical tests of the last section should be interpreted in light of this observation.

Radner [405] has developed a behavioural model that combines features of the Kennedy and Nelson and Winter approaches. At each point in time the satisficing manager's behaviour, called "putting out fires," requires allocation of his efforts to reduce the quantity of whichever input promises the largest expected cost reduction. Since this expectation depends on factor prices, the model contains an inducement mechanism and is an improvement on the Kennedy model, since innovation depends upon a real resource-using activity, even though the "budget" is fixed at one manager.

An increasing number of authors have now followed Nelson and Winter's lead in either recommending or contributing to the evolutionary or neo-Schumpeterian approach to technical change. See, for example, Elster's [127] methodological study, Metcalfe [334], Fransman [163], Kelly and Kransberg [267], Winter [571], and Iwai [238, 239]. But Nelson and Winter's [360] pioneering study shows that substantial difficulties will be encountered in pursuing the biological analogue. To begin with, the firm has some control over its own destiny that is lacking in an organism, and considerations of this nature prevent the simplistic imposition of biological notions in economics. It remains to be seen if their brilliant contribution will continue to develop and displace the neoclassical approach from its niche, or prove to be yet another dead end.[87]

3.0 THE ADOPTION AND DIFFUSION OF INNOVATIONS[88]

Parts 1 and 2 of this paper considered the process of innovation and the rate and direction of technical change. However, the term technical change is used to refer both to changes in the level of technology itself (often called technological change) and to the *effects* of those changes as they are reflected in productivity increases and the rate of economic growth [272]. Since advances in knowledge are inherently difficult to quantify, most empirical investigations follow the second route and concentrate on the effects of technical change on output levels.[89] Though innovation may determine the best practice technique, the speed of imitation or diffusion of the new knowledge will thus play a major role in determining the measured rate of technical change.[90] Indeed, whereas macroeconomic studies of technical change generally imply immediate diffusion of new technology, recent works on the "productivity slowdown" tend to show that other factors, including a decline in the rate of spread of technology, have been more important than the fall in R & D expenditures [504].

Part 3 of this paper concentrates on explaining the diffusion process, beginning with the best-known simple model, then proceeding to show why and how the theory has been developed. *Diffusion studies* do not consider the innovation process,[91] but begin at a point in time when the innovation is already in use. The earliest adopters may be called innovators, and the diffusion process is the spread of the new technique across the rest of the population. *Adoption studies* consider the reasons for adoption at one point in time, or the reasons for time of adoption for individual users. In contrast, most diffusion models are dynamic and study the behavior of the diffusion process over time. Thus, relative to adoption, *diffusion* may be viewed as a dynamic, aggregative process, over continuous time.[92] Alternatively, "if one can explain the date of adoption by individual firms, then by aggregation one should have the inter-firm or intra-sectoral diffusion curve" [522, p. 95].[93]

Diffusion research has been multi-disciplinary, as is shown by the historical account provided by Rogers [423] and from the heterogeneous list of references provided here. Indeed, since interest in diffusion began at the turn of the century [532], over 3,000 publications have appeared, with sociology, communications, education, marketing, public health, and geography all accounting for a greater proportion of the literature than does economics. An early review of the several traditions in the study of the diffusion process was provided by Katz, Hamilton, and Levin [265].

For simplicity of exposition, this part continues (Section 3.1) with a description of the "epidemic" diffusion model that has served as a basic research tool in most disciplines, including economics. This is followed (Section 3.2) by an account of the application of the epidemic model to the diffusion of techniques in economics. The procedure has been applied to diffusion within individual firms (intra-firm), between firms within an industry (inter-firm, or intra-industry, or intra-sectoral diffusion, also referred to as the rate of imitation), on an economy-wide level, and internationally.

Evaluation and development of the model follows, concentrating on the issues of interest to economists. Thus, Section 3.3 considers the manner in which different diffusion curves are generated when the stringent assumptions of the simple epidemic model are altered. Section 3.4 reviews adoption studies that explain why individual firms are leaders or laggards in the use of new techniques. Section 3.5 extends the analysis by considering recent attempts (threshold models and game theory) to provide a sound theoretical basis for the diffusion process. The next part considers the supply of innovations. In Section 3.7, aspects of the international transfer of technology are briefly considered. Finally, the Conclusion takes stock of the current state of knowledge, particularly from a methodological perspective.

3.1 The Epidemic Model

If personal contact is important in the adoption of an innovation by a limited population, the diffusion process may be viewed as formally akin to the spread of an infectious disease [16, p. 33]. One simple form of the epidemic model may be described by the differential equation,

$$(17) \quad \frac{dn_t}{dt} = \beta \frac{n_t}{N} (N - n_t)$$

where n_t is the number of individuals who have contracted the disease (adopted the innovation) at time t, N is the fixed population (of potential adopters), and β is the parameter reflecting the likelihood of contracting the disease. Thus the number of new infections (adoptions) at period t is equal to the number of uninfected persons (remaining potential adopters), $N-n_t$, multiplied by the probability of infection (adoption), which is the product of the proportion of the population infected (already adopters) at time t, n_t/N, and the parameter β, which is dependent upon factors such as the infectiousness of the disease (attractiveness of the innovation) and the frequency of contact, both of which are assumed to be fixed [105, pp. 9-10].

For constant β the number of adopters at any time t is clearly a function of the number that have already adopted the innovation, so that a basic characteristic of the process is imitative behaviour, or a bandwagon effect [459, p. 77]. However, the absolute increase in adopters at any point in time is the product of opposing forces, since as the proportion that has already adopted,

n_t/N, increases, the number of potential adopters, $N-n_t$, falls. This suggests a bell-shaped frequency distribution for numbers adopting over time.

The solution to equation (1) is:

$$(18) \quad n_t = N\{1 + \exp(-\alpha - \beta_t\}^{-1}$$

where α is the constant of integration. This is the cumulative density function of the logistic frequency distribution [522, pp. 69-70] shown in Figure 3.1a and is the equation of the sigmoid (S-shaped) logistic curve shown in Figure 3.1b.[94]

The curve is described by three variables. N is the upper limit, the ceiling approached when the process is completed; β may reasonably be called the speed of diffusion, though it is <u>not</u> the rate of growth[95] of diffusion [105, p. 11]; and α, the constant of integration, positions the curve on the time axis. The curve is symmetric around the inflection point, which occurs at time $-(\alpha/\beta)$ corresponding to 50 percent adoption, and approaches zero and N asymptotically, as t tends to minus and plus infinity.

Though several methods of fitting the logistic curve have been investigated [107, Ch. 11; 379, 550], most empirical investigations are straightforward, using linear regression analysis on the transformation of equation (18).

$$(19) \quad \log\left(\frac{n_t}{N - n_t}\right) = \alpha_t + \beta$$

This approach forms the basis of the first stage of Griliches' 1957 [190] study of hybrid corn and Mansfield's [313] investigation of twelve innovations in American industry.

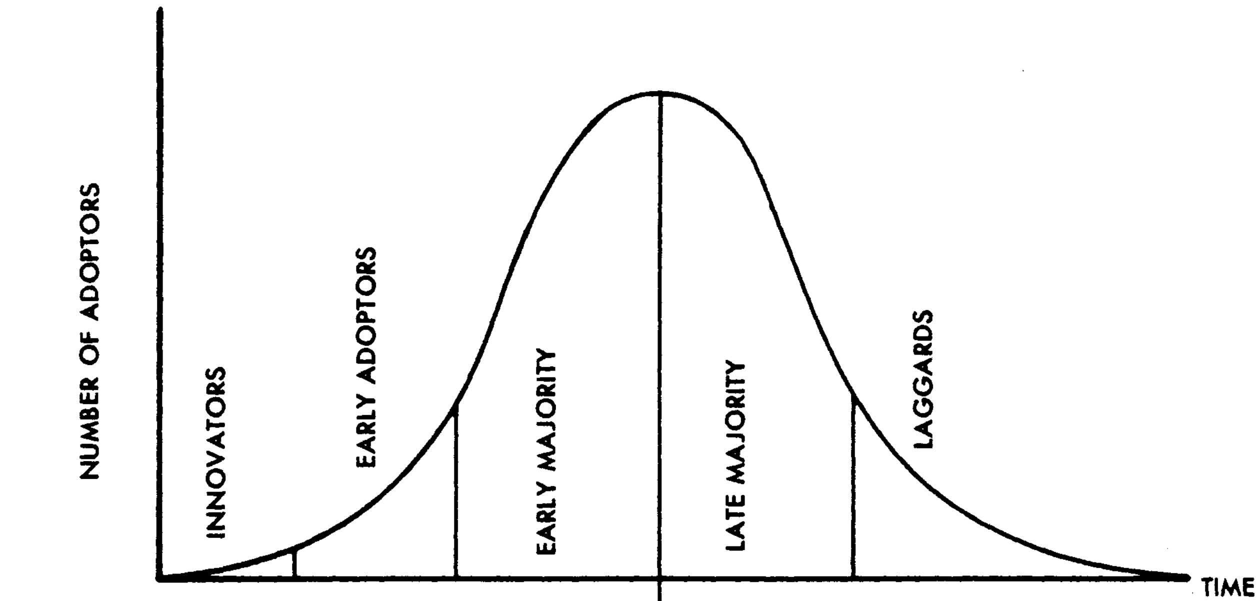

Figure 3.1a Adoptor categorization

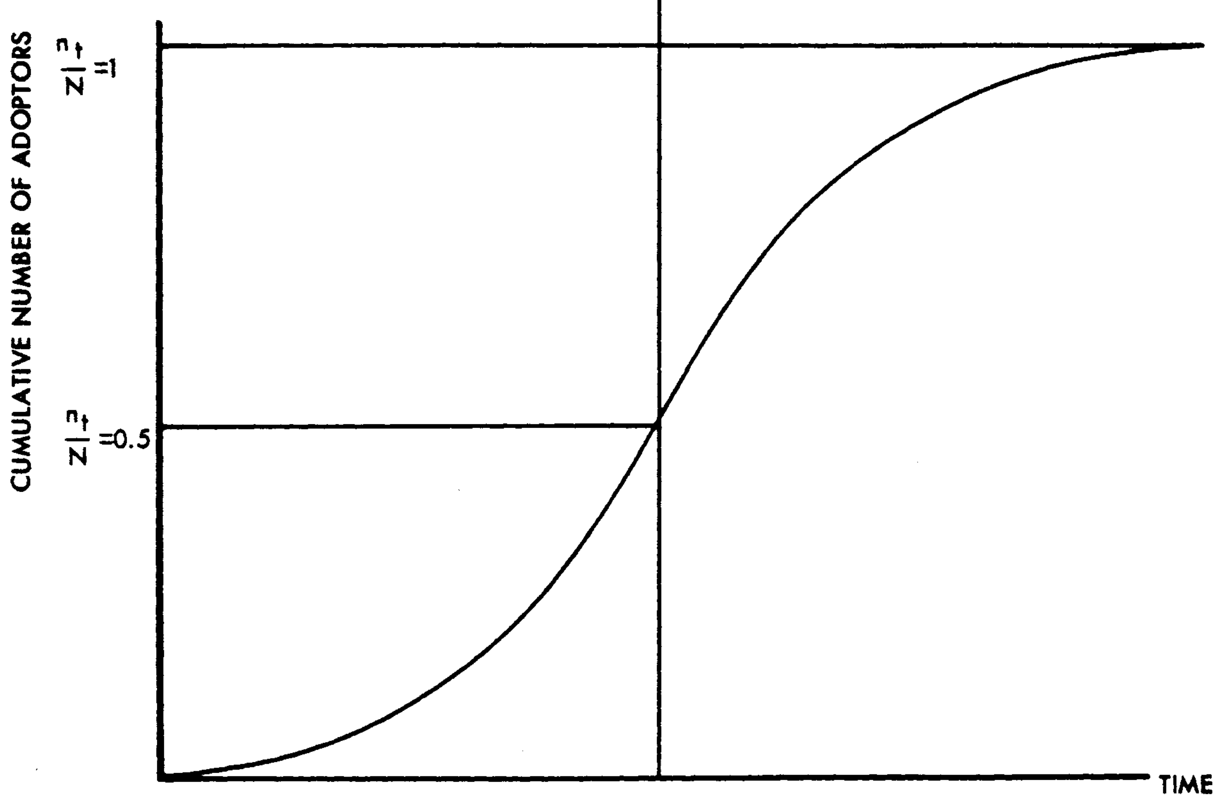

Figure 3.1b The logistic curve

3.2 Applications of the Epidemic Model

So far, the term diffusion has been considered only by analogy to the spread of infectious diseases. However, if the object of interest is a process innovation (often the spread of a new capital good), a reasonable measure of the extent of its diffusion would be either the proportion of the post-diffusion capital stock (S_t) currently accounted for by the new machines (s_t) or the proportion of the industry's output currently produced with the new process. Following Mansfield [313], Davies [105, p. 6] calls this concept the overall rate of diffusion.

The overall rate depends on both the rate of imitation (inter-firm diffusion), i.e., the proportion of firms that have adopted the innovation, and the level of use within each firm, determined by the intra-firm rate of diffusion--the rate at which particular firms substitute the new technology for the old once they have begun to use it [316, p. 173]. Following this convention, we consider first the overall rate of diffusion. Later, economy-wide and international diffusion are considered.[96]

3.21 The Overall Rate of Diffusion

One of the best-known diffusion studies in economics is Griliches' 1957 [190] investigation of the percentage of U.S. corn acreage planted with hybrid seed. The diffusion of agricultural technology had been intensively studied previously by rural sociologists (summarized in Rogers [423, pp. 57-59] and Summers [527]). Indeed, a particularly influential paper by Ryan and Gross [458] found that the diffusion curve for hybrid corn in Iowa followed a sigmoid pattern.

Griliches discovered graphically the same S-shaped pattern for individual states. He found the trends to be so strong that individual observations could not be explained by economic variables, as if they "had no antecedents." His solution was to fit logistic curves, not because any underlying model justified the logistic, but because curve-fitting reduced the mass of data for each state to just three parameters: origin, rate, and ceiling. In a second-stage analysis, these parameters were explained in terms of the profitability of adoption.

The logistic curve was chosen because it was the easiest to fit and interpret. Thus Griliches used ordinary least squares to fit the transformation of equation (18), shown as equation (19) above, to time series data for each of thirty-one states. The values of $N_i (i=1, \ldots, 31)$, the satiation levels for the thirty-one states, were chosen by visual inspection to give the best fit. Both the upper and lower tails of the distribution were excluded. At the lower extreme this was done by taking the point of origin to be 10 percent of the ceiling acreage.

This procedure generated estimates of β_i (the rate of diffusion), α_i (the origin, or year at which 10 percent hybrids were planted), and N_i (the final ceiling level), which were then "explained" by economic variables. The date of origin, α_i, was taken to represent the supply side of the problem, with the lag (relative to Iowa) before suitable hybrids became available being explained by varying profitability to seed producers (profitability diminished with distance from the Corn Belt). Differences in the ceiling level of use and speed of diffusion were attributed to demand factors and explained by the profitability of the shift from open pollinating seed to hybrid varieties.[97] Profitability was assumed to depend on corn acres per farm, pre-hybrid yield, and the difference in yields between open pollinating and hybrid varieties.

Athough Griliches succeeded in explaining a large proportion of the variance in the three parameters, a controversy resulted from his assertion that the variables considered by sociologists "tend to cancel themselves out, leaving the economic variables as the major determinants of the pattern of technological change" [190, p. 522]. In reply, Brander and Straus [68] produced evidence that in the case of hybrid sorghum adoption in Kansas, compatibility[98] appeared to be more important than profitability, and Havens and Rogers [212] and Rogers [420] argued against the importance of profitability in the case of hybrid corn in Iowa. Babcock [21] suggested that the economic and sociological explanations are complementary, and Griliches himself [192, 193, 195] responded by suggesting that the alternative explanations represented a "false dichotomy."[99]

3.22 The Inter-Firm Rate of Diffusion

Most diffusion studies consider the spread of an innovation among the firms in an industry (inter-firm diffusion) separately from the level of use within the firm (intra-firm diffusion). Mansfield's [313] seminal paper, which analyzed the inter-firm diffusion of twelve innovations in four U.S. industries, constitutes the conventional wisdom in the field [105].

Following Griliches, the diffusion process is treated as an initial situation of disequilibrium created by the innovation, which is corrected by the spread of the new technique up to a new equilibrium level of satiation. The model is developed from the initial proposition that the proportion of non-users who adopt the innovation in a given time period will increase with the profitability of the innovation (π) and the proportion of firms that have already adopted (n_t/N), but will be inversely related to the size of the investment outlay required (S), giving the equation:

$$(20)\quad (n_{t-1} - n_t)/(N - n_t) = f(\frac{n_t}{N}), \pi, S).$$

The function f is approximated by a Taylor's series expansion with third and higher order terms ignored, along with a quadratic term in (n_t/N). If the time period is sufficiently short, equation (20) may be written in differential equation form as,

(21) $$\frac{dn_t}{dt}\left(\frac{1}{N - n_t}\right) = \beta_0 + \beta_1 \frac{n_t}{N}$$

where

(22) $$\beta_1 \frac{n_t}{N} = a_0 + a_1\pi + a_2S + \varepsilon$$

and ε represents the error structure.

Assuming that the limiting value of n_t is zero as t approaches negative infinity, equation (21) has the solution,

(23) $$n_t = \frac{1}{1 + \exp(-\alpha - \beta_t)},$$

which is the logistic curve.

This result is hardly surprising, since once the limit condition has constrained β_0 to equal zero, the differential equation (21) is clearly the equation of the epidemic model (see equation (17) above). This has led Davies [105, p. 15] to argue that the model is no more than an ingenious application of the epidemic model and that no economic content would be lost in taking equation (21) as the starting point, since it is obtained from (20) by assumption and algebraic manipulation.

Davies [105, pp. 17-18] is also critical of Mansfield's fitting of equation (19) above by weighted least squares. The coefficient of correlation between the dependent variable and time exceeded 0.89 in all cases, suggesting that the logistic curve does fit the data well. However, the estimates are based on an average of only ten observations per innovation, and Mansfield's exclusion of smaller firms from the sample because of lack of information may lead to bias. In their study of thirteen innovations in the United States, Gold et al. [177] find such a diversity of variables and "special circumstances" that they are critical of "universal" models like Mansfield's. They suggest a broader analytical framework and concentrate on investigating the firm's decision-making process.

The second stage of Mansfield's study attempts to explain the estimates of β_1 for individual innovations by cross-section estimation of equation (22). Mansfield found that the coefficients (a_1 and a_2) of both independent variables were significantly different from zero and had the predicted signs. Though the equation fitted extremely well, the sample size of twelve innovations is too small for comfort. Further results suggested that diffusion was faster, the less durable the industry's capital equipment and the greater the growth rate of output.

Mansfield et al. [318] and Mansfield [317] have also applied the epidemic model to numerically controlled machine tools. Globerman [173] fitted the same model to Canadian data, allowing comparisons with both the Mansfield results and the further U.S. evidence generated by Romeo [426, 427]. Romeo found inter-industry differences in the speed of diffusion of numerically controlled machine tools to be partially explained by the number of firms in the using industry (positively) and the variance of the logarithm of firm size (negatively), suggesting that diffusion speed is increased by competition. Stoneman [522, p. 95] is critical of the small sample size and Romeo's version of equation (22), which is written in multiplicative form without explanation.

Although the authors make little attempt to extend the theory, the collection of papers in Nasbeth and Ray [350] provides a wealth of evidence on the diffusion of industrial processes in Western European nations. Particularly relevant are the papers by Lacci, Davies, and Smith applying the logistic curve (and alternatives) to tunnel kilns in brick-making and gibberellic acid in malting. Ray [410] has provided more results, updating the original studies.

Within the large marketing literature on technological forecasting and product innovations (see Section 3.32), Mansfield's model has been applied and developed by Blackman [58], Fisher and Pry [159], and Sharif and Kabir [492].

More recently, the Mansfield-Blackman model has been extended by Mahajan and Peterson [309] to integrate diffusion over both time and space (i.e., market regions). Sharif and Haq [491] identify no less than nine explanatory variables that can be added to Mansfield's list of factors explaining the rate of diffusion. Ayres' [20] "Schumpeterian" model of diffusion and profitability provides an alternative to Mansfield's approach.

3.23 Intra-Firm Diffusion of Technology

On intra-firm diffusion the standard reference is also work by Mansfield [314, 316, Ch. 9], which applies the methodology described above to the spread of diesel locomotives within thirty U.S. railroad companies between 1925 and 1960. The paper begins with the theoretical proposition that the increase in firm i's stock of diesels at time t as a proportion of the additions still to be made,

$$\left(\frac{s_{i(t+1)} - s_{it}}{S_i - s_{it}}\right),$$

will vary positively with expected profitability (π_i) and the firm's liquidity (C_i), negatively with the apparent risk (U_i), and also with firm size (I_i) (in a manner not specified a priori). Then, assuming risk to be lower for late adopters and to decline as satiation (S_i) is approached, U_i can be represented by the date of adoption (L_i) and the proportionate level of adoption,

$$\left(\frac{s_{it}}{S_i}\right).$$

Written in differential equation form, this gives:

$$(24) \quad \frac{dsit}{d_t} = g(.)(S_i - s_{it}),$$

where g(.) is a function of the variables listed above:

(25) $g(\cdot) = \phi_i \frac{s_{it}}{S_i}$ where

(26) $\phi_i = a_1 + a_2\pi_i + a_3L_i + a_4I_i + a_5C_i + \varepsilon_i$.

Manipulations fully described by Stoneman [522, p. 75] lead directly to the logistic curve equation:

(27) $s_{it} = \frac{S_i}{1 + \exp(-\phi_{it} - \alpha)}$.

Fitting the linear transformation of the logistic curve (using the weighted least squares method of Berkson [38]) generates estimates (ϕ_i) of the spread of diffusion for each firm. As in Mansfield's inter-firm study, described in the last subsection, these estimates become the dependent variables in cross-section estimation of equation (26) above. The estimated coefficients (a_i) had the predicted sign and were significant for all variables except I. About 70 percent of the inter-firm variation in the rate of dieselization is explained by this second stage analysis.

In criticising Mansfield's empirical methods (as opposed to theory), Stoneman [522, pp. 74-85] questions the manner in which the error term ε_i (see equation (26)) should be included in a logistic model. He argues that Berkson's weights and methodology may not be applicable to Mansfield's model.

Much of Stoneman's critique extends to the work of Romeo [426], who followed Mansfield's approach in studying the intra-firm diffusion of numerically controlled machine tools. Romeo's model differs from Mansfield's in taking as the dependent variable the proportion of the firm's <u>new machine tool purchases</u> at time t that are numerically controlled. Also, in the second stage analysis, the variables that explain the rates of diffusion are assumed to be linear in logarithms, rather than simply linear. Further empirical evidence on machine tools, some of which supports Romeo's assumptions, is provided by Nasbeth and Ray [350]. They analyze the intra-firm diffusion of special presses, the basic oxygen process, and continuous casting in steel. Although in many of these studies, curve-fitting is not actually attempted and the theory is not developed beyond the epidemic model [105, p. 26], they do provide detailed evidence for the diffusion of ten major process innovations in six countries, which facilitates international comparisons.

3.24 International Diffusion

Mansfield's methodology has been applied to the diffusion of synthetic rubber in twelve countries by Swann [529], who explains the parameters of fitted logistic curves for each nation by means of country-level variables such as output growth, rubber imports, rubber exports, and production of rubber per capita.

Neither Swan nor Nasbeth and Ray really tackle the problem of the transmission of technology between countries. Some aspects of international technology transfer are briefly considered in Section 3.7.

3.25 Nonprofit Firms, Regulated Industries, and the Public Sector

The U.S. hospital sector[100] includes a considerable proportion of non-profit firms, whose motivation for adopting new techniques must differ from the profit-orientation described above. Instead, improvement in the quality of medical care may be the primary motivation. However, Rapoport's [409] study of the diffusion of radioactive isotope use in U.S. hospitals compares parameters for the speed of diffusion across different states (using the results from fitted logistic curves) and concludes that the speed is greater where the environment is competitive, a result no different from the conventional wisdom for profit-seeking firms [263, 477].

The effect of regulation on the diffusion of innovations has been investigated by Capron [79]. Oster and Quigley [385] considered the effect of building code regulations on four innovations in housebuilding, finding that labor-saving innovations were less rapidly adopted than others. Key variables affecting diffusion speeds among jurisdictions were the extent of unionization, firm size, and the professionalism of local regulators (measured by education, background, and professional contacts). However, regulation should not be assumed automatically to retard diffusion. Sweeney [530] demonstrates the well-known result that in a situation of cost-plus-markup regulation, the existence of regulatory lag (the interval between cost reduction and price reduction) provides an incentive to the firm to adopt cost-reducing innovations to obtain excess profits. Ironically, inefficiencies in implementing the regulation system can encourage technical efficiency. Lastly, an appraisal of innovation and diffusion in the public sector is provided by Feller and Monzel [146].

3.3 Alternatives to the Epidemic Model

Though in several cases the logistic curve has provided a useful means of quantifying the diffusion process, it is merely one of a large class of S-shaped curves. Indeed, any unimodal frequency distribution will have a sigmoid cumulative density function, which need not be symmetric. Frequently, observed diffusion patterns exhibit an element of skewness and may be better represented by asymmetric functions such as the Gompertz curve or the cumulative lognormal.[101]

3.31 Asymmetric Diffusion Curves

The Gompertz is positively skewed with the inflexion point at $n_t/N = 0.37$. The cumulative lognormal can reproduce a whole family of S-shaped curves, since the inflection point is variable. It corresponds to the frequency distribution's mode, which is defined by $\mu - \sigma 2$, thus depending on both the mean and the variance of the distribution.[102]

However, no one, general form can represent all sigmoid curves as special cases. Nor can one general form subsume the most common candidates such as the logistic and the Gompertz [522, p. 71].[103] One curve may fit better than another or several may appear to fit equally well, making it impossible to discriminate on empirical grounds [459, p. 78]. Griliches [190] did not "want to argue the relative merits of the various S-shapes" and treated the curve-fitting stage of his analysis purely as a means of concentrating the data. Most later writers argue that the form of the curve should be determined by the theory of the diffusion process.[104] Thus, the appropriate form can be chosen on a priori grounds, and the curve-fitting exercise serves as an empirical test of the particular diffusion hypothesis.

The simple epidemic model described above rests on stringent assumptions concerning the population, the innovation, and the method of transmission. By relaxing these assumptions[105] and by tackling economic issues from which the epidemic approach diverts attention, it is possible to generate a wide range of diffusion models, several of which justify fitting non-symmetric functions.

To an extent, the epidemic model has been infused with economic content but remains unsatisfactory since only the demand side of the problem is included. The only economic issue that is taken up is the possible profitability of the innovation to potential adopters. Casual empiricism suggests that many innovations are supplied by firms that go to considerable trouble to ensure consumer awareness and availability of their products. Similarly, public agencies may induce innovation diffusion as a matter of policy. For example, the USDA's Federal Extension Service is the world's largest public investment in diffusion [423]. Brown's [70] "market and infrastructure perspective" is introduced with a solid argument for recognising the supply side. He reasons that first, diffusion agencies must be established, and second, a diffusion strategy must be implemented. These two elements of the process precede the actual adoption of the innovation. The next section shows how inclusion of supply side factors can explain positive skewness of the diffusion curve.

3.32 Incorporating Diffusion from a Constant Source: The Generalised Static Model

The assumption that diffusion depends on demonstration effects and learning from the experience of others is crucial to the epidemic/logistic model. But personal interaction between adopters and potential adopters may be unimportant. Instead, the innovation may be diffused from a "constant source." That is, the firm selling the innovation may rely on mass media propagation, salesmen, extension agents, etc. In such a situation, the instantaneous rate of diffusion will decline continually as the gap between the actual and the desired stock decreases at a constant proportional rate [23, p. 9]. Diagrammatically, the function, variously known as the waning exponential [291] or modified exponential [292], could be represented by the curve to the right of the inflection point in Figure 3.1a, since all that matters is the remaining distance to the saturation level.[106] This exponential curve has "received substantial empirical support" in marketing, where it has been referred to as the Coleman model, and in sociology [292, p. 364]. It has been extensively used in economics to study the demand for durable goods and product innovation (see Pyatt [402] and Bain [23] for reviews of early work on the diffusion of product innovations).

Lekvall and Wahlbin [292] refer to the passing of information by social interaction as the internal influence and that conveyed by the mass media or other promotional activity as the external influence, emanating from a source outside the group of prospective adopters.[107] They argue that for most innovations, both forces will be present in some combination and that the result will be a positively skewed curve, with the skew being greater for heavily advertised consumer products than for production innovations like a new seed, which would be much discussed among farmers.[108] The "two step flow of communication hypothesis" of Lazarsfeld, Berelson, and Gaudet [288] combines the idea of internal and external sources with a heterogeneous population. In their model a mass media message does not reach most receivers directly, but is first taken up by opinion leaders, who pass the word to others. The effects of heterogeneity of the adopter population were considered in detail by Coleman [92, Ch. 17] and formalised by Davies [105, pp. 12-13], who provides a simple demonstration that a heterogeneous population alone is sufficient to give rise to a skewed diffusion curve. Dividing the population into two groups, with different probabilities of adoption, the differential equation becomes,

$$(28) \quad \frac{dn_t}{dt} = \beta_1\left(\frac{n_t}{N}\right)(N_1 - n_{1t}) + \beta_2\left(\frac{n_t}{N}\right)(N_2 - n_{2t}),$$

which is shown to have an inflection point at $n_t/N < 0.5$ (i.e. a positive skew).

Both external and internal sources and a heterogeneous population are effectively combined in the "influential new product[109] growth model" for consumer durables introduced by Bass [28], and developed by Mahajan and Schoeman [312] and others. If the rate of diffusion is taken to be proportional to the number of potential adopters available, then a general form for the differential equation is

$$(29) \quad \frac{dn_t}{dt} = g(t)\ (N - n_t).$$

If g(t) is a simple linear function of the number who have adopted to date, then

$$(30) \quad g(t) = \beta_0 + \beta_1 n_t.$$

Substitution gives,

$$(31)\quad \frac{dn_t}{dt} = (\beta_0 + \beta_1 n_t)(N - n_t),$$

which may be written as

$$(32)\quad \frac{dn_t}{dt} = \beta_0(N - n_t) + \beta_1 n_t(N - n_t),$$

which combines equations (17) (the logistic) and the waning exponential[110] (equation A.3 in footnote 106).

The constant β_0 is the proportion of the population whose adoption decision depends on information from a central source. Similarly, β_1 is the coefficient of imitation, since the second term reflects adoption due to personal interaction [310, p. 130].

Equation (32) reduces to the logistic when $\beta_0 = 0$ and to the exponential when $\beta_1 = 0$. In all intermediate cases, it will produce an S-shaped curve that will mirror the skew of the data. In their useful survey of the development of new product diffusion models, Sharif and Ramanathan [493] refer to this approach as the "generalized model" while attributing the logistic approach to Dodd [119] and the decaying exponential representation to Coleman [92].

Since equation (32) can be written as

$$(33)\quad \frac{dn_t}{dt} = a_t = \beta_0 N + (\beta_1 N - \beta_0)n_t - \beta_1(n_t)^2 ,$$

Bass suggests the estimating equation,

$$(34)\quad a_t = \gamma_0 + \gamma_1 n_t + \gamma_2(n_t)^2$$

where

$$\gamma_0 = \gamma_0 N,\ \gamma_1 = \beta_1 N - \beta_0 \text{ and } \gamma_2 = -\beta_1.$$

Bass tested the model, using time series data for eleven consumer durables. He found that the model generally performed well in forecasting the magnitude and timing of the peak level of sales.

The manner in which the "generalized model" shown in equation (32) has been developed is summarized by Mahajan and Peterson [310]. Static models retain the fixed number of potential adopters (N) and operate on the function g(t) in equation (29), whereas dynamic models make N a function of relevant time-dependent variables (see next section). Thus Robinson and Lakhani [419] follow the first route, arguing that to enable firms to evaluate marketing strategies, β_1 must be developed as a function of the decision variables, such as price, advertising, and promotions. Similarly, Horsky and Simon [233] model β_0 in equation (32) as a function of advertising expenditures, and Bass [29] makes both coefficients functions of the level of adoption, n_t. Numerous permutations are defined by Mahajan and Peterson [310].[111] The main point is that the form of β_0 and β_1 in equation (32) implicitly assumes that the company or diffusion agency does not change its behavior during the diffusion period or product life cycle. Another solution to this problem is provided by Lilien [295], who incorporated a control variable by which the agency can influence the diffusion process.

Several other developments have helped to make diffusion models more realistic. For example, Sahal [459, p. 81] has stressed that "the diffusion of an innovation does not take place in isolation. Rather, it is very much a matter of actual substitution of a new technique for the old." Thus, Sahal expands a relatively early development of Mansfield's model by Fisher and Pry [159] in which the rate of adoption of a new product is proportional to the level of use of the old product being replaced. That innovations do not exist in isolation has also been addressed by Mahajan and Peterson [308], who include equations for the new product and an existing good that may be independent, complementary, contingent, or substitutable for the old good. Sharif and Kabir [492] apply the techniques of system dynamics in developing a "multilevel" model of technological substitution in which a particular product or technology is replacing an older one while it is itself being replaced by a still newer product or process.

The models considered above can be called "binomial" in the sense that the population is divided into two groups, adopters and potential adopters. Such models implicitly assume that the entire population eventually adopts the innovation and that, once adopted, the innovation is never rejected. These assumptions are avoided by Sharif and Ramanathan [494], whose "polynomial" model divides the population into four groups. These are adopters, rejectors, disapprovers, and the remainder, who are as yet uncommitted. The approach is also "multilevel" (as in Sharif and Kabir [492], above), analysing the substitution between an old, an intermediate, and a new product. This allows the full product life cycle to be modeled explicitly, with the empirical example showing the decline of black and white television as well as the growth of ownership of colour sets.

In Griliches [190] the spatial, as well as the temporal, aspects of the diffusion process are quite explicit. The work of the geographers, reviewed by Brown [70], has tended to build on the studies by Hagerstrand [205], refining the Monte Carlo simulation models he pioneered.[112] Both the temporal and spatial models of the phenomenon are considered by Sahal [459, Ch. 5], who discusses two "complementary" models. The temporal model appears best to represent technological substitution in cases where the adoption process is measured in terms of annual sales of the new product, whereas the spatial model is more appropriate where the diffusion data refer to a stock variable.[113] Mahajan and

Peterson [309] integrate the time and space dimensions of the diffusion process in a model that incorporates the distance of the subject region from the location where the product is first introduced. This "neighborhood effect," whereby the "innovation waves" spread from the center to the periphery, is added to the general model.

To summarize, the "general static diffusion model" incorporates diffusion both by word of mouth and by diffusion from a central source. It has been expanded to include explicitly the effect of economic variables such as product prices, advertising expenditures, and demonstration efforts.[114] The technological substitution process has also been explicitly incorporated, including the case where several technologies are involved. The population has been divided into more than two groups, allowing for rejection of the innovation and the effect on the diffusion process of persons who actively disapprove of the innovation. Lastly, geographical space has been included in the models. We now turn to the work of authors who have rejected the assumption of a fixed population of adopters.

3.33 Dynamic Models

While the "generalized static model" (equation (28)) can mirror any degree of skewness in the data and provide reasonable estimates for technological forecasting, it may be misleading even in this application. The most obviously unrealistic assumption is that of a fixed population of adopters and, by implication, no post-innovation improvements. This is unfortunate, since the historical literature reviewed by Rosenberg [435, Ch. 1] suggests a "view of technical progress as consisting of a steady accretion of innumerable minor improvements and modifications, with only very infrequent major innovations" (p. 7).[115] This emphasis on the importance of follow-up improvements is supported by studies such as Enos [128] on petroleum technology, Miller and Sawers [338] on aircraft, and Sahal [459] on tractors and other machinery.

Kuznets [283, pp. 337-338] divides the product cycle into phases called "initial application," "diffusion," and "slowdown and obsolescence." He argues that for many innovations, such as television, automobiles, and computers, substantial ongoing quality and cost improvements cause extreme difficulty in defining the end of the diffusion phase in terms of an upper limit in numbers.

The problem is well illustrated in a recent paper by Dixon [117] repeating Griliches' [190] work on hybrid corn and especially by Griliches' [195] reply. Dixon found that in twenty-one of the thirty-one states studied, a positively skewed diffusion curve (the Gompertz) was "more apt" than the logistic curve used by Griliches. However, the skewness arises largely because data subsequently available showed that adoption had exceeded the "ceilings" assumed by Griliches. Griliches [195, p. 1463] replied that he would not fit an asymmetric curve but "would now respecify the model so that the ceiling is itself a <u>function of economic variables</u> that change over time." This proposition is developed further by Metcalfe [332, pp. 349-350], who argues that "instead of a single diffusion curve, we have an envelope of successive diffusion curves, each appropriate to a given set of innovation and adoption environmental characteristics, each with its own value of N and β. While any given set of characteristics generates a logistic process, the envelope need not conform to the logistic pattern and its exact shape will depend on the temporal incidence of the changes in its characteristics." A model of this type for consumer durables has been developed by Mahajan and Peterson [308]. The endogenous and shifting ceiling is incorporated by including in the equations the growth of housing starts.[116] The result is a "product growth curve" that is the envelope of the appropriate portions of a whole series of diffusion curves for a series of increasing ceilings. Over time, this product growth curve approaches the cumulative market potential curve and finally coincides with it.

Hernes [224] criticized Lekvall and Wahlbin for attributing the skewness of the diffusion curve to "external and internal forces" and offered the following alternative classification of causes: first, structural heterogeneity, when some variable such as purchasing power is differentially distributed among the population; second, dynamic heterogeneity, when the population changes during the diffusion process (rising income levels would be an obvious example); and last, changing stimulus over time, which includes changes in the quality of the product itself. His own model incorporated the last of these three factors.[117]

By now it should be apparent that there are fundamental difficulties with the basic approach to diffusion followed thus far. It assumes an economic system in which the original equilibrium has been disturbed by the introduction of an innovation. The diffusion process is viewed as the adjustment from the old to the new equilibria. Adjustment is not instantaneous because of the asymmetric distribution of information. Griliches [195] explains that "if all variables describing individuals and affecting them were observable, one might do without the notion of diffusion and discuss everything within an equilibrium framework. Since much of the interesting data are unobservable, time is brought in to proxy for at least three sets of distinct forces." There are (1) declining real costs of the technology due to cumulative improvements and learning by doing (or by using); (2) the scrapping of old durable equipment, making way for the new; and (3) risk reduction due to the spread of information about the operating characteristics, workability, and profitability of the new technology. As Griliches suggests, the alternative to his own disequilibrium approach is to model these economic determinants explicitly.[118] We turn now to that challenge beginning with vintage capital (Griliches' second point) and stock adjustment models.

3.34 Vintage and Stock Adjustment Models

The vintage capital model explains the co-existence of old and new techniques, allowing the time element to enter the model while retaining the notion of equilibrium. Indeed, Salter's [462] book, which is the example discussed by both Davies [105] and Stoneman [522], calls the vintage approach "a model of the delay in the utilisation of new techniques of production."[119] The "delay" is caused because only the plants most recently built will embody the latest technology appropriate for current factor price ratios. With a continuous stream of technical advances, the spectrum of plants in existence at any one time provides a fossilized history of technology. New "best practice" plants[120] will be added to the leading edge of this spectrum and plants at the trailing edge will be scrapped, but only when revenues no longer cover viable operating costs.

Despite its obvious attractions, the vintage model has not been fully developed as a framework for the study of diffusion.[121] However, it has been applied by Sumrall [528] in conjunction with the ideas of Tobin and Brainard [544] on investment theory. Sumrall's model adds to earlier studies, comparing rates of return on five vintages of basic oxygen furnaces (BOF), electric furnaces, and open hearth furnaces, testing the hypothesis that "firms adopted the BOF at an optimal rate." The hypothesis is rejected, leading to the conclusion that large firms trailed their smaller counterparts in adopting the BOF. This finding is incompatible with the Schumpeterian hypothesis that large firms are more technologically progressive.

The investment theory concept most extensively applied to the diffusion of product innovations is the stock adjustment model (see Stone and Rowe [517] for an early example). More recently, the model has been applied to the diffusion of computers by Chow [89] for the United States and by Stoneman [519] for the

United Kingdom. Beginning from the epidemic approach, Chow [89, p. 1118] postulates that the growth of computer usage at time t will be proportional to the difference between the actual stock n_t and the equilibrium stock N_t. Chow suggests two alternative differential equations,

$$(35) \quad \frac{dn_t}{dt} = \beta \; n_t(N_t - n_t) \text{ and}$$

$$(36) \quad \frac{dn_t}{dt} = \beta \; n_t(\log N_t - \log n_t),$$

which yield as their solutions the familiar logistic and Gompertz curves (see Section 3.1 and footnote 101). Though the similarity to the epidemic model is clear, the stock adjustment does give the model a theoretical base. Stoneman [522, pp. 115-117] shows that diffusion curves can easily be derived using the stock adjustment concept. He provides a simple derivation of the logistic equation by assuming maximization of profits subject to a given production function constrained by adjustment costs. Both models are improved by dynamic formulations. N_t is not a constant, but a function of the relative price of the new technology and the level of GNP. In addition, Stoneman defines β (the speed of adjustment) as a function of economic variables. The better results of both the U.K. and U.S. studies, derived by fitting Gompertz curves, are reported and discussed in Stoneman [522, pp. 135-140].

In terms of the classification system developed, both studies are of the "overall" rate of diffusion at the economy-wide level, making no distinction between inter-firm and intra-firm diffusion, which Davies [105] regards as a serious limitation. However, models based on investment theory clearly do provide an economic explanation of the delay involved in the diffusion of techniques. So too can macroeconomic growth theories, as Hicks [228, Ch. 2] has shown. Much new process technology is embodied in investment goods. The rate at which investment can proceed must be limited by the rate at which savings can be increased and by factor shortages, which will themselves give rise to technical changes. These are Hicks' "induced inventions" discussed in Section 3.1 above.

3.4 Adoption Studies

In this section we review the literature on differential adoption.

3.41 The Social-Psychological Tradition

Since the diffusion curves described in early sections are intended to model the behavior of firms in aggregate, it is inevitable that they cannot explain why some firms adopt innovations faster than others [105, p. 15]. This was recognized by Mansfield [315, 316, Ch. 8], who investigated "the speed of response of individual firms."[122] He argues that the length of time a firm waits before using a new technique tends to be inversely related to its size. A large firm is better able to handle the costs and risks involved and is more likely to have both an early need to replace equipment and operating conditions suited to the new technique. Similarly, the length of time before adoption may be expected to be inversely related to the profitability of adoption by the firm.

Assuming that the relationship is multiplicative, these propositions lead to the testable hypothesis,

$$(37) \quad d_{ij} = Q_i \, S_{ij}^{a_{i2}} \, H_{ij}^{a_{i3}} e^{e_{ij}}$$

where d_{ij} is the number of years the jth firm waits before using the ith innovation, S_{ij} is its size, H_{ij} is a measure of the profitability of the investment in the innovation, u_{ij} is a stochastic error term, the a_i's are parameters, and Q_i is a scale factor that varies across innovations. Equation (37) was fitted to data on 167 firms for fourteen innovations. Measurement difficulties allowed H_{ij} to be included for only five of the innovations, and it was statistically significant for only two of these. However, the coefficient of S_{ij} is consistently negative and statistically significant, though Davies [105, pp. 22-23] shows that interpretation is difficult. For instance, this result would emerge if industry A, with a few large firms, adopted an innovation more quickly than industry B, with many small firms, even if there were no correlation between early adoption and firm size <u>within</u> either industry.

Mansfield extended the empirical analysis to include as explanatory variables the firm's rate of growth, its profitability, the age of its president, its profit trend, and a measure of its liquidity. He also allowed for different types of innovation (for instance, highly costly or relatively cheap). Unfortunately the coefficients were not statistically significant.

Mansfield's approach has been applied to several industries by other authors. Examples are Nasbeth's study of six innovations in Sweden (in Williams [564]); Hastings' [211] investigation of the adoption of four process innovations in the Australian wool textile industry; Oster's [384] study of the adoption of the basic oxygen furnace in the United States; and Benvignati's [34, 35] studies of adoption in the cotton textile industry. The last of these works reaches the conclusion that the diffusion of domestic innovations is more rapid than for foreign advances. A further source of information on adoption is the Nasbeth and Ray [350] volume, especially the papers by Hakonson and Smith, which study innovations in which the diffusion process is incomplete, and hence not all the d_{ij}'s are known. This problem has also been tackled in the diffusion context by Jarvis [241], who has applied techniques similar to those used by Griliches [190], to the diffusion of pasture improvements in Uruguay.

Both Stoneman [522] and Davies [105] point out that Mansfield's adoption model appears to be unconnected or even inconsistent with his diffusion models and indeed bears no relation to ideas of information-gathering and uncertainty, which underlie his earlier approach. This is unfortunate, since aggregation of the d_{ij}'s for each industry should give the inter-firm diffusion curve. Intuitively, the determinants of adoption at any moment in time should be expected to be the independent variables for which time served as a proxy in diffusion curve-fitting. However, the variables chosen by Mansfield do not seem to reflect adequately the determinants of diffusion suggested by either Hernes [224] or Griliches [195] in Subsection 3.33.

Mohr's [340] methodological contribution offers an explanation of this poor correspondence between diffusion and adoption models. Whereas diffusion models are categorized as process theory, adoption models of the Mansfield type are an example of variance theory. (These terms are defined in footnote 93.) Mohr [340, pp. 57-58] considers the effects of imposing a "degenerate" variance theory where a process theory is appropriate, and his quotations (pp. 68-69) demonstrate the confusion that results from unwittingly mixing diffusion and adoption approaches.

Mansfield's pioneering diffusion and adoption studies defined the conventional wisdom on the subject until recently. Stoneman [522] refers to Mansfield's diffusion model as the "psychological approach," and indeed Mansfield [316] does argue that "there exists an important economic analogue to the classic psychological laws relating reaction time to the intensity of the stimulus." The "psychological approach" is displayed most strongly in the work on adoption described above, in which "attitudinal" variables and variables intended to take account of the <u>attributes of innovations</u> are to be found. In this, the adoption studies more closely resemble the work of other social scientists who have emphasised these "non-economic" variables. Kelly and Kransberg [267, pp. 127-129] consider the "Social-psychological Tradition in Diffusion Research," concentrating on the importance of social networks, studies of resistance to change, and the effects of education on adoption. The discussion of the effects of education shows that attempts at classification are somewhat arbitrary, since they concentrate on the work of Nelson and Phelps [355] and Hayami and Ruttan [219], all of whom would be more at home classified under "the Economic Perspective" (the other alternative is "Spatial Diffusion").

Feller's [147] classification of differing approaches to innovation includes an interpretation of the argument between Griliches and the rural sociologists and a discussion of the importance of the "sociological variables" that determine entrepreneurial attitudes. Rogers [423] provides a comprehensive summary of the non-economic literature.[123] The core of his book comprises chapters on the adoption-decision process (broken down into five stages), the origin and attributes of innovations (see footnote 98), categorization of adopters, information networks, and the role of the change agent.[124] Adopters are categorized as idealized types, according to time of adoption, as shown in Figure 3.1b. Innovators are described as respectable local opinion leaders. The early majority follow with deliberate willingness, while peer pressure is necessary to convince skeptical late adopters. The laggards are traditionalists who cling to the past.

3.42 Agricultural Adoption Studies

Though the extensive adoption literature outside of mainstream economics cannot be described adequately here, a brief summary of common methodologies follows, drawing examples from agricultural economics, and rural sociology where such studies proliferate.[125] This is because "diffusion is the dominant mechanism for the spread of a new technology in sectors where the firms are small compared with the market as a whole and where, for a variety of reasons, they are unable to expand their market share rapidly. Farming is the archetypical example" [354, p. 1050]. This contrasts with industries in which firms do their own R & D and where the expansion of innovators and the contraction of laggards can be major factors in the spread of a new technology (see Metcalfe [332] for example).

Many early adoption studies used simple statistical techniques to investigate relationships.[126] For example, Gross [196] studied attitudes toward hybrid rice adoption, finding that 42 percent of farmers thought profitability was of primary importance, 38 percent thought farmer-specific factors such as experience and education to be most important, and the remaining 20 percent thought credit availability predominated. Hypothesis tests based on chi-square contingency tables were used extensively, for example by Wilkening [563], to investigate the effect of family decision-making processes on the adoption of hybrid corn in the United States. Although these tests establish that the relationship between the variables is (or is not) statistically significant, the relation is not quantified. Various simple correlation techniques have been applied to a wide range of problems. For example, Rogers [420] found a positive relationship between farmer contact with the agricultural extension agent and adoption, for a United States sample. Williams [566] performed a similar operation using Nigerian data. Both found contact with the extension agent to be more important than the mass media. These few examples are drawn from a sample of several hundred, more than 460 of which are listed in an early survey article by Jones [246], to which the reader is referred. Less common methods include factor analysis, used by Greene [185], who found that 6 out of 53 explanatory variables explained 52 percent of the variation in quantity of fertilizer used by Thai farmers; and discriminant analysis, used to classify observations in one category or another using several explanatory variables [578].

Not surprisingly, the most common approach to determining the quantitative importance of various explanatory variables has been simple regression analysis, which often attempts only to explain adoption versus non-adoption rather than the extent or intensity of use of an innovation.[127] Unfortunately, ordinary least squares estimation of equations with a dichotomous or otherwise limited dependent variable is not appropriate since the error structure is heteroscedastic; the parameter estimates are inefficient. Nor can classical hypothesis tests be applied since the error terms for a limited dependent variable will not be normally distributed [10, 305, 396]. Additionally, if a dichotomous variable is to be explained by the exogenous values of an attribute, it is convenient to be able to interpret the expected value of the dependent variable as the probability of adoption. For the simple linear probability model, predicted values of the endogenous variable may well lie outside the interval (0,1), which violates the probabilistic interpretation [396].

The solution is to apply a transformation that will ensure that all values of the dependent variable lie in the (0,1) interval. The obvious candidate is the cumulative probability function, which may be written,

$$(38) \quad P_i = F(\alpha + \beta X_i) = F(Z_i)$$

where F represents the cumulative function and X is stochastic. If the index Z_i is assumed to be uniformly distributed, the result is the constrained linear probability model. If Z_i is taken to be normally distributed, the result is the probit model, and if F is taken to be the cumulative logistic curve (with which this survey began), the result is the logit model.

Agricultural adoption studies abound, frequently mixing economic and "sociological" explanatory variables. Hill and Kau [230] applied the probit model to the use of corn dryers in U.S. agriculture. Feder and Slade [141] have fitted a logit model to the adoption of new techniques by Indian rice farmers. Jamison and Lau [240] used a logit model to analyze the adoption of chemical inputs by Thai farmers and found that education, age, and extension activity all had positive effects on adoption. Rahm and Huffman [406] applied a similar model to the adoption of reduced tillage by Iowa corn farmers. Gerhart [166] applied probit analysis to explain adoption rates of hybrid corn in three regions of Kenya. His use of the presence of drought-resistant crops as an indication of high risks raises a further econometric issue. Feder, Just, and Zilberman [138] point out that the planting of drought-resistant crops is itself an endogenous variable. Thus, its inclusion as an independent variable raises the issue of simultaneous equation bias, which also arises when the adoption of improved seed varieties is explained by fertilizer use, where these are really simultaneous decisions. The logit analysis of the adoption of several innovations in Philippine agriculture by Nerlove and Press [363] is a pioneering attempt at dealing with interactions of this nature.

Dichotomous choice models do not explain the <u>intensity of use</u> of the innovation, which may often be of greater importance [488]. Many studies have investigated the <u>intensity</u> of adoption by creating a dependent variable with values in the interval (0, 100), which may be interpreted as the percentage of the total population that have adopted. Specification difficulties include avoiding predictions that fall outside the interval and treatment of truncated variables, such as those that cannot take negative values. Feder, Just, and Zilberman [138] suggest a two-stage procedure for problems such as fertilizer use. A dichotomous choice model could be used to determine the probability of fertilizer use; then, given adoption, the level could be explained by a conditional model with the log of fertilizer use as the dependent variable. Alternatively, the Tobit model can estimate both the probability of adoption and the intensity of use. It has been used by Akinola [5] to explain chemical input use levels on Nigerian cocoa farms and by Shakya and Flinn [490] for fertilizer intensity in rice production in the Nepal Teroi.

Lastly, if knowledge of technologies depends on experience, the new must be more uncertain than the old, and the adoption decision will depend on the potential adopter's attitude toward risk. The literature on risk in agricultural economics spans several decades [13]. Relatively recently it has been applied to the problem of new technology, producing models that study farmers' optimization problems (profit or utility maximization) as an allocation decision involving a traditional technology and an uncertain modern alternative requiring commercial inputs such as fertilizer, pesticides, and irrigation [138].

Hiebert [229] investigated the effect of imperfect information (represented by a random element in the effect of fertilizer on yields) on the adoption of a modern production technique. He found that the risk-averse farmer used less land and fertilizer in modern production than one who is risk-neutral. Though his model is static, Hiebert reasoned that learning would shift the conditional distribution of net income from the modern technique, making adoption more likely. Feder [136] analyzed the effects of risk, risk aversion, farm size, and credit constraints on input use, output scale, and crop mix decisions, using for the modern process a stochastic production function suggested by Just and Pope [253]. With no credit constraint, the level of fertilizer per acre using modern techniques was not affected by risk aversion, uncertainty, or farm size, but greater risk resulted in a smaller allocation of land to the modern technique.

Just and Zilberman [254] extended the analysis to encompass all inputs and included the covariance of net income per hectare under modern and traditional techniques, which proved to be an important determinant of adoption intensity. Feder [137] discussed the introduction of two explicitly interrelated innovations. Feder and O'Mara [139] and Just, Zilberman, and Rausser [255] incorporated fixed transaction costs and information acquisition costs for the new technology, leading to the crucial result that farms below a critical level of size will not adopt the new technology. Returns to scale may prevail in adoption even if the modern technology itself is scale-neutral.

The predictions of these models are dependent to some extent on their initial assumptions, which include concave and well-behaved utility functions. Feder, Just, and Zilberman [138] report that rather different results are obtained from "safety first" models, in which the utility of income is assumed to be zero below a "disaster level" and unity above it [33, 403, 440].

3.5 Theoretical Developments

Although the disequilibrium "epidemic" model has frequently produced good empirical results and may adequately describe the spread of diseases, fashions, and gossip [105, p. 10], critics such as Stoneman [522] stress its lack of economic content and doubt its general relevance.

3.51 Threshold or Probit Models

The static probit and logit models, introduced above in a statistical context, make adoption a function of the characteristics of adopters at one point in time. If the exogenous "stimulus" variables that explain adoption change over time, then an increasing proportion of the population will cross the "threshold" and adopt. The result of these dynamic "probit" models is a diffusion curve that is a function of the actual explanatory variables, rather than a function of some proxy variables such as time. These are equilibrium models, since the system has adjusted to the particular values of the variables at each point in time, rather than being out of equilibrium and approaching a distant final ceiling level of diffusion.

Models of this type have only recently been applied to process innovations but have a long history in the study of the diffusion of consumer durables. Pyatt's [402] impressive contribution to this area includes a brief survey of earlier work. Bain's [23] study of television ownership, which begins with a useful survey, argues that the actual growth curve will be an envelope of short-run lognormal diffusion curves (see the discussion under "Dynamic Models," Section 3.33). Cramer [95], himself a pioneer in this area, provides an introduction to the theory and estimation of lognormal Engel curves. The basic approach can be illustrated by reference to Bonus [66]. Suppose that the income of household i at time t is lognormally distributed

(39) $y_{it} \sim \Lambda(M_t, \sigma_t^2)$

and so is the "critical level" of income ($\overline{Y}_{it}$) required for adoption to occur:

(40) $\overline{y}_{it} \sim \Lambda(\overline{M}_t, \overline{\sigma}_t^2)$.

It follows that the probability that the household will own the product (P_{it}) is given by $P_r(\overline{y}_{it} \leq y_{it})$. Thus, the probability of ownership will be related to income by a "quasi-Engel curve" that will be cumulative lognormal, assigning "at a given point of time and to each income level, the corresponding fraction of actual owners" [66, p. 657]. Aggregating the quasi-Engel curve over the income distribution for each time period generates the diffusion curve that results as the distribution of income levels and adoption thresholds both change over time. Recent examples of applications of this "probit" model include Dagenais [97] (automobiles) and Wilton and Pessemier [570] (electric vehicles).

The rationale of probit (or logit) models as a description of the diffusion process has been stated by David [99]. "Whenever or wherever some stimulus variate takes on a value exceeding a critical level, the subject of the stimulation responds by instantly determining to adopt the innovation in question. The reason such decisions are not arrived at simultaneously by the entire population of potential adopters lies in the fact that at any given point of time either the 'stimulus variate' or the 'critical level' required to elicit an adoption is described by a distribution of values, and not a unique value appropriate to all members of the population. Hence, at any point in time following the advent of an innovation, the critical response level has been surpassed only in the cases of some among the whole population of potential adopters. Through some exogenous or endogenous process, however, the relative position of stimulus variate and critical response level are altered as time passes, bringing a growing proportion of the population across the 'threshold' into the group of actual users of the innovation."

This approach allowed David [101] to offer an appealing explanation of the twenty-year lag between Obed Hussey's first sale of his mechanical reaper and the first wave of popular acceptance in the mid-1850s. The "stimulus variate" is farm size (S), since adoption will take place only if the saving in wages due to the reduction in labor use exceeds the cost of the reaper. Thus adoption will be profitable for farm i at time t if,

(41) $w_t(L^0_{it} - L^N_{it}) > P^N_{it}$

where w_t is the wage rate, P^N_{it} is the annual cost of the mechanical reaper, and L^0_{it} and L^N_{it} are the annual labor requirements for the old and new techniques respectively.[128] Let

(42) $L^0_{it} = a_1 S_{it}$

and

(43) $L^N_{it} = a_2 S_{it}$,

where the coefficients a_1 and a_2 are determined by the technology and S_{it} is farm size. Substitution gives the result

(44) $S_{it} > \frac{P^N_{it}}{w_t} \left(\frac{1}{a_1 - a_2}\right)$,

which suggests that diffusion will occur if <u>either</u> S_{it} increases, or if the wage rate rises relative to the price of the reaper (both old and new technologies remaining unchanged). Figure 3.2 shows the relative frequency distribution of farm size. If S^*_{it} is the "critical level" above which the reaper is adopted at time t, an increase in wages relative to the cost of the reaper will shift S^*_{it} to the left[129] as time passes. Simultaneously, the distribution of farm size moves to the right. Thus a sigmoid diffusion curve is generated.

David's approach has been criticized by Olmstead [380, p. 328], who argues that "if farmers could share or rent reapers and mowers, then the threshold argument, as presently constituted, is rendered inoperative." Olmstead also stresses that there were numerous small improvements to the reaper that gradually raised its productivity (i.e. a_2 in equation (44) was not constant).

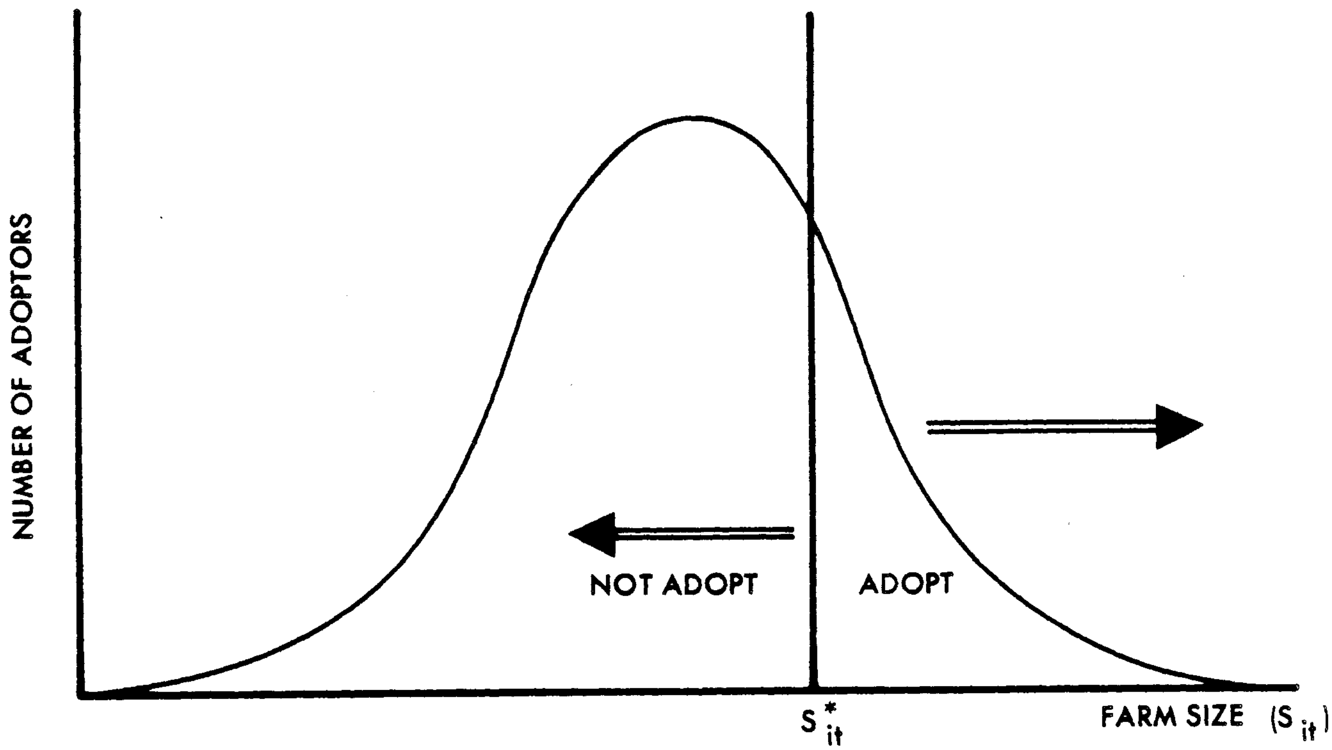

Figure 3.2 The threshold model

The model developed by Davies [105] is similar, but has the advantage of taking post-innovation technical improvements into account. He suggests that firm i will adopt by time t if

(45) $E(R_{it}) < R^*_{it}$

where $E(R_{it})$ is the expected payoff period and R^*_{it} is the "critical level"--the maximum payoff period that firm i finds acceptable. Again, firm size is emphasized, with both the expected payoff and the critical level being defined as multiplicative functions of firm size, other factors representing the technical attributes of the firm, and an error term. Both the error structure and firm size are assumed to be lognormally distributed.

The characteristics of the innovation are modeled by considering two types of new technology. Group A innovations are reasonably cheap and simple, while those in group B are expensive and complex. Thus post-innovation improvements decline for group A during the diffusion period as do the returns from information search, whereas for group B these factors remain constant. This assumption results from the difference between the learning possibilities for simple and complex innovations [106, p. 158]. This difference is modeled by defining the diffusion curve[130] for group B innovations to be the symmetric cumulative normal, while that for group A is the positively skewed cumulative lognormal. The slope of the curves, or speeds of diffusion, will depend on the variances of the distributions. The parameters representing the speeds of diffusion are b_1 and b_2 in the estimating equations,

(46) $\frac{n_t}{N} = a_1 + b_1 \log t$

(47) $\frac{n_t}{N} = a_2 + b_2 t,$

where $\frac{n_t}{N}$ is the proportion of the population that has adopted. Applied by Davies to 22 innovations (8 classified as group A, 7 in group B, and 7 "unclassified"), the model appeared to be consistent with the data, tending to perform better than the logistic curve alone and giving poorer results when the "wrong" curve was fitted for the classified innovations. The sign of b_i was positive and this parameter was significant in all cases, meaning that larger firms do adopt more rapidly. This is consistent with Davies' reasoning, which stressed returns to scale.

A second-stage analysis then attempts to explain differences in the speeds of diffusion, b_1 and b_2. The parameters are interpreted to suggest that diffusion will be faster:

(i) the greater the growth rate of the industry;

(ii) the greater the profitability of the innovation;

(iii) the greater the labor intensity of the industry;

(iv) the more important are post-invention improvements;

(v) the more effective is information search;

(vi) the smaller are inequalities in firm size; and

(vii) the smaller are inter-firm differences in expected profitability.

Conceptually, the diffusion mechanisms may be viewed as analogous to the David model schematized in Figure 3.2. Thus, as firm size may be expected to increase with industry growth, (i) will shift the frequency distribution of <u>firm sizes to the right</u>. Factors such as post-invention improvements (iv) and information search (v) will shift the "critical value" R^*_{it} to the left. However, R^*_{it} itself has a frequency distribution, rather than being a single value, so that the diffusion process rests on the interaction of these two frequency distributions, moving in opposite directions.

Variations on the David/Davies approach can be found in Von Tunzleman's [554] analysis of the diffusion of steam power (reported quite thoroughly by Stoneman [522, Ch. 10]), and in Gutkind and Zilberman [200], whose model has a fixed frequency distribution for firm size. Their sigmoid diffusion curve results from the falling capital cost of the innovation and from increased profitability, due to learning by doing, both of which lower the adoption threshold.

Davies' model has been described in some detail, since it does represent a major advance, but several criticisms remain. First, though post-innovation improvements are attributed to learning by doing and information search is frequently mentioned, the learning process is not explicitly modeled. Second, the model concentrates on demand-side phenomena, with the diffusion process in part being driven by exogenous changes in factor prices. These are endogenized in Section 3.6, where the supply of the innovation is discussed.

3.52 Learning Models

Stoneman [522, p. 76] considers the "driving force" of Mansfield's [314] approach to intra-firm diffusion to be the reduction in perceived risk resulting from usage. Learning by doing, or more accurately, learning by using (Rosenberg [437, Ch. 6], plays an uncertainty-reducing role in many diffusion models.

An early attempt at explicitly modeling the learning process is the study by Kislev and Shchori-Bachrach [277] of agricultural innovations. A knowledge function in the production relationship depends on both initial levels of skill and "Arrow-type learning by doing." The more highly skilled producers are more efficient in acquiring knowledge and are early adopters, but because learning by doing is communal (dependent on the industry's cumulative aggregate output), the less skilled can over time acquire sufficient knowledge to adopt.[131] As adoption spreads, the increase in supply depresses the price of the product and the more skilled, whose labour has a higher opportunity cost, are driven out. They move on, adopting the next new product or new technique, thereby generating an "innovation cycle" that owes something to both Cochrane's [91, Ch. 19] "technology treadmill" and Vernon's [551] "product cycle" in international trade. A similar "learning by doing" process relaxes the farmer's subjective constraints that limit adoption of new techniques in the programming models of Day and Singh [108] and in Feder and O'Mara's [140] simulations that lead to a familiar S-shaped diffusion curve. Feder and Slade [141] have further distinguished between the passive acquisition of information and active accumulation, which entails costs.

Though these models produce sensible results that appear to be empirically supported, the relationship between learning, decision-makers' uncertainty regarding production parameters, and the actual adoption decision is not made explicit. Stoneman and Ochoro [526] apply a mean-variance approach to intra-firm diffusion, showing that different learning processes produce different diffusion paths, but again without justifying any of the learning mechanisms. Several promising models allow experiences with the new technique to yield sample information that decision-makers use to adjust their subjective probabilities, consistent with the spirit of Bayes' theorem. Thus, in adoption studies such as O'Mara [382], prior beliefs are modified on the basis of observed performance, generating a Bayesian posterior distribution. Feder and O'Mara [140] use Bayesian learning to justify the inclusion of the cumulative use of the innovation in the adoption function. This relationship was included by assumption in earlier studies such as Kislev and Shchori-Bachrach [277].

Pursuing the Bayesian approach, Lindner, Fischer, and Pardey [297] have studied the "innovation assessment lag," which is defined to be the passage of time between initial awareness of the innovation and actual use. In year zero, the risk-neutral farmer has a negative expectation of the normally distributed mean profit from using the innovation. A limited amount of information is collected in each period and the adoption decision is based on accumulated knowledge. Under this formulation, the innovation lag will be lengthened by greater variance of actual profit. Fischer and Lindner [158] have extended the model to allow for differences between farms, while Lindner [296] has shown that even if the innovation is scale-neutral, larger farms will adopt more quickly. This result has far-reaching implications and may be viewed as an extension of Nordhaus' [366] observation that perfect competition is incompatible with a system in which firms undertake their own R & D. Even if innovations are supplied free of charge by the public sector, the ability of larger firms to spread learning costs over a greater output will have the same consequence. The effect of farm size on the adoption of modern high-yielding seed varieties is crucial to appraising the effects of the green revolution. The considerable empirical literature, surveyed in some detail by Feder, Just, and Zilberman [138], suggests that larger farms do adopt more quickly. This result appears in one of the seven "generalizations" in Ruttan's [448] summary of the green revolution experience.

Bayesian learning processes have been applied to the diffusion of non-agricultural techniques by Stoneman [521] and Jensen [243] for the intra-firm case, and by the same authors (Stoneman [520], Jensen [242]) for the inter-firm situation.[132] Stoneman [521] develops the mean variance approach of Stoneman and Ochoro [526] by adding a Bayesian theory of learning and adjustment costs. The interaction of learning and the procedure for choice of technique, plus adjustment costs, generates a diffusion curve. Let α_t be the proportion of the firm's output produced by the new technique and α_t^* be the desired level, with returns to both old and new technologies perceived to be normally distributed.

(48) New: $N(\mu_{nt}, \sigma^2_{nt})$

(49) Old: $N(\mu_{ot}, \sigma^2_{ot})$.

Returns are additive, so at time t the firm will have a mean and variance of actual returns (following Stoneman's notation),

(50) $\mu_t = \alpha_t \mu_{nt} + (1 - \alpha_t) \mu_{ot}$ and

(51) $\sigma^2_t = \alpha^2_t \sigma^2_{nt} + (1 - \alpha_t)^2 \sigma^2_{ot} + 2\alpha_t(1 - \alpha_t)\sigma_{not}$,

where σ_{not} is the covariance term. α_t is chosen by maximizing a utility function subject to an adjustment cost constraint. With no adjustment costs, the solution for the desired value α^*_t is a function of the mean and variance terms in equations (50) and (51) and a parameter representing the firm's attitude toward risk. Then, adjustment costs are defined to be an increasing function of the rate of change of α_t and a decreasing function of the starting level α_{t-1}. Maximization of utility subject to this cost function leads to the equation,

(52) $$\frac{d\alpha_t}{d_t}\frac{1}{\alpha_t} = \frac{1}{\theta}(\mu_{nt} - \mu_{ot} + b(\sigma^2_{ot} - \sigma_{not})\left(\frac{\alpha^*_t - \alpha_t}{\alpha^*_t}\right).$$

The parameter Θ represents the adjustment cost, b is the firm's "risk coefficient," and $\sigma_{not} \equiv \rho\sigma_{ot}\sigma_{nt}$ is the covariance, which may also be expressed in terms of the correlation coefficient σ.[133]

Though the parameters of the old technology are known with certainty, Bayesian learning is assumed to change the anticipated values of α_t and α^*_t, where the time path of α_t is the diffusion curve and α^*_t is the final level.

The approach of α_t to the ceiling value follows the logistic curve in the special case where there is no learning and diffusion is governed by adjustment costs. This result goes some way toward integrating investment theory and the diffusion literature. When learning is included, the model can generate a sigmoid diffusion curve and can explain the failure of some innovations, since although the estimate of the variance of the new technique falls with learning, the estimated mean profitability of the new technique may either rise or fall as knowledge improves. The rate of diffusion will be greater, the higher is the true profitability of the innovation, but will also be influenced by attitudes to risk (b), the initial uncertainty (σ^2_{nt}), adjustment costs (Θ), and the covariance between returns to the old and new techniques (ρ).

By way of contrast with this broad approach, Jensen's [243] theoretical paper proves that differences in prior beliefs among firms are sufficient to generate a sigmoid diffusion curve even in the absence of external information derived from the activities of other firms. Jensen's [242] decision theoretic model of adoption and inter-firm diffusion reaches the same conclusion, that "firms will adopt at different dates if and only if their original beliefs differ." Reinganum [414] uses a similar model. Stoneman's [520] inter-firm model follows a methodology similar to Stoneman [521], leading to a threshold model of the adoption decision. The assumption that the mean and variance of returns to the innovation are lognormally distributed gives a cumulative log-normal diffusion curve.

3.53 The Game Theoretic Approach[134]

Jensen's result, that differences in prior beliefs are sufficient to generate a diffusion curve, contrasts with the classical diffusion model in which the process results from asymmetric information and with threshold models that rely on physical differences between firms. Recently, the problem of the timing of adoption in duopoly models, addressed earlier by Scherer [476] and Rao and Rutenberg [407], has attracted renewed attention.

Two contributions by Reinganum [413, 414] demonstrate that even if firms are identical and information on a capital-embodied innovation is perfect, strategic behavior alone can lead to a Nash equilibrium of different adoption dates, and hence a diffusion curve. This is demonstrated in a duopoly game [413], or an oligopoly game [414] that also shows that an increase in the number of firms can delay adoption. Fundenberg and Tirole [164] argue that Reinganum's model rests on the assumption that firms must precommit themselves to adoption dates. This rules out preemptive behaviour, which is studied in their own model.[135]

3.6 The Supply of New Products

Since economists tend to rely on the interaction of supply and demand in the solution of most basic problems, it is odd that the diffusion theories discussed above pay so little explicit attention to the supply of new products in which innovations are embodied. The models considered thus far concentrate on the profitability of the innovation to the user and pay little attention to the supply side. Thus, the supply of innovations appears in Griliches' [190] early study as the "date of origin" of the diffusion process. This was taken to depend on availability of seeds, which was in turn explained by profitability to seed producers. In other studies, such as David [101], the supply side appears in exogenous price and quality changes that affect the diffusion process but are not explicitly modeled.

3.61 Product Innovation

As Blaug [61] pointed out, the product innovations of the machine-goods industries are the process innovations of the consumer-goods industries. Thus the diffusion problem cannot be described effectively without attention to the behavior of the suppliers of the innovation as well as the users. An early move in this direction of including the behaviour of suppliers is found in Glaister's [172] study of optimal advertising policy for new consumer goods. Glaister follows epidemic model arguments to justify the derivation of a "logistic" equation that differs in one crucial point: the speed of diffusion coefficient β is a function of the product price. If β depends upon price and the price is chosen by a monopoly supplier (with constant unit costs and a constant price elasticity) in order to maximize future receipts, then at any instant in time the firm chooses from a whole family of logistic curves. The resulting diffusion path is not logistic, but positively skewed. This is the same outcome as the "generalized static model" that also arose from a combination of diffusion by word of mouth and from a constant source (i.e., advertising), but the route by which Glaister reaches the result is different.[136]

Bass [29] provides a more fully developed version of the generalized static demand-side model [28], which incorporates an industry supply curve that falls over time due to learning by doing.[137] Thus, the suppliers' marginal cost for the qth unit at time t is,

$$(53)\quad \frac{\partial C_t}{\partial q_t} = k\ E_t^{-\lambda},\ \lambda > 0$$

where E_t represents the cumulative output. The demand relationship is

$$(54)\quad q_t = f(t)\ \gamma p_t^{-n}$$

where q_t is output, n is a constant elasticity, and f(t) shifts the demand curve over time. Choosing price so as to maximize profit subject to the constant demand elasticity gives

$$(55)\quad p_t = (\frac{n}{n-1})\ k\ E_t^{-\lambda}.$$

Substitution of (55) into (54) and manipulation lead to the expression

$$(56)\quad q_t = \left(\frac{m}{1-\lambda_n}\right) f(t)\ F(t) \left(\frac{\lambda n}{1-\lambda_n}\right),$$

where m is the final level of sales and F(t) is the integral of f(t). Then f(t) is defined to be the differential equation of the generalized linear model,[138]

$$(57)\quad f(t) = B_0 + (B_1 - B_0)\ F(t) - B_1\ (F(t))^2.$$

Substitution of expressions for f(t) and the solution for F(t) into (56) lead to a diffusion model in which learning by doing lowers costs and hence price, while the demand side diffusion process simultaneously shifts the demand curve. The overall diffusion curve (the path of q_t) thus depends on both the shifting of demand and the effect of the falling price.

Several other studies have emphasized the behavior of the industry supplying a product innovation, paying little attention to the demand side or the diffusion curve. Spence [509] considers the strategic interaction among firms during the growth phase of a new industry. In a model that does not take account of the effects of learning by doing or of uncertainty, he finds that firms invest in capital equipment as rapidly as possible up to some target level and then stop. This result occurs quite generally because a firm that gets ahead can preempt the market, increasing its share and deterring entrants. A learning curve is added in Spence [510], with unit costs depending on accumulated output. This gives an advantage to early entrants and creates barriers to entry. More entry occurs if the learning effects spill over, rather than being firm-specific, and the industry growth rate is increased when demand-side learning is added to the model. The interesting point is that diffusion is not the object of attention. The aim, following in the footsteps of Schumpeter [485], is to develop "a model of competitive interaction and industry evolution." Neo-Schumpeterian models of this type, for oligopolistic industries, now constitute a literature that is quite distinct from the study of diffusion in competitive industries such as agriculture.

In a similar vein, Gort and Konakayama [182] examine "diffusion in the production of an innovation." This is defined as the increase in the number of producers of a new product (i.e. cumulative entry, less exit). In a study of seven innovations, entry was found to depend on the demonstration effect, technical change, dynamic adjustment costs, and the growth of transferable experience (i.e., as old-firm personnel move to new entrants). Existing firms apparently had poor endowments of intangible capital (measured by patent rate and the accumulated stock of experience of producers). Using the same definition of diffusion, Gort and Klepper [181] investigated the evolution of forty-six new product markets. They found a positive correlation between entry and technical innovation. In a manner reminiscent of Kuznets [281], they identified five stages in the evolution of the industries. These are

i) first commercial use, up to
ii) period of sharp increase in the number of producers
iii) period with a net entry of approximately zero
iv) period of negative net entry
v) a second period of net entry of approximately zero.

Their evidence suggests that this "product cycle" is clearly related to product innovation, with the growth phase (ii) corresponding to rapid rates of innovation emanating from firms <u>outside</u> the industry.

3.62 Process Innovation

The contribution of Metcalfe is decidedly less neoclassical than the works discussed above. Metcalfe [332, 333] develops a neo-Schumpeterian model that is explicitly intended to broaden diffusion analysis to encompass theories of industrial growth and structural change.[139] With this aim, Metcalfe surveys the contributions of Schumpeter [487], Burns [76], and Kuznets [281, 282] on industrial growth and retardation, Hicks [228, Ch. 2] on innovation-induced impulses to economic growth, and Pasinetti [390] on structural change. The standard diffusion model does not attempt to incorporate economic contributions of this type.

To close the gap, Metcalfe specifies a logistic relationship for the proportional growth of demand,

$$(58)\quad \frac{dq}{dt}\frac{1}{q} = B(m(p) - q_t).$$

The model is dynamic in that the equilibrium demand, m(p), is a function of price and may also be affected by post-innovation improvements. For simplicity,

$$(59)\quad m(p) = c - a\ p_t.$$

On the supply side, the rate of growth of production capacity is taken to depend on the rate of profit (as in Cambridge growth models). Hence,

$$(60)\quad r_t = \frac{p_t - w_t \ell - \gamma v}{v},$$

where r is the ratio of profits to capital, v is the capital-output ratio, ℓ is a unit input requirements coefficient, w_t is the price of a composite input, and γv is depreciation. The price of the composite input increases with output (x_t),[140] so

$$(61)\quad w_t = w_0 + w_1\ x_t$$

and capacity growth is a function of the rate of profit,

$$(62)\quad \frac{dx_t}{dt}\frac{1}{x_t} = \theta(1 + \mu)r_t,$$

where θ is the fraction of profits reinvested and μ is the fixed ratio of external to internal funds invested.

Combining the last three equations and simplifying the notation gives

$$(63)\quad \frac{dx_t}{dt}\frac{1}{x} = \frac{p_t - h_0 - h_1 x_t}{k}.$$

If there are no post-innovation improvements, the growth of supply will also be logistic, with the saturation level being reached when the prime cost terms in h are equal to the output price p_t.

The role of price in equilibrating supply and demand is apparent, since the saturation levels of both equilibrium demand (m(p)) and the supply of productive capacity depend on the innovation's price. If p_t were too low, the growth of demand would exceed the growth of supply, which would limit the rate of diffusion in a closed economy, unless p_t rises to correct the imbalance.[141]

Metcalfe combines the demand and supply side equations and solves for the balanced diffusion path of output, which is found to be logistic when there are no post-innovation improvements. When these are included, the saturation level will shift upwards over time yielding a positively skewed curve. The industry's <u>rate</u> of growth drops asymtotically toward zero (the retardation result) as profits fall because of rising costs and a falling innovation price. In keeping with Schumpeter's views, innovators make only a temporary profit. Profit is, "at the same time the child and the victim of development" [485, p. 154].

Though Metcalfe succeeds in generating several results in the Schumpeterian spirit, his model is deficient on the supply side, having only a representative firm and only one innovation. A model of Schumpeterian creative destruction and industrial evolution must allow for differences and competition between both firms and industries. A step in this direction has been taken by Metcalfe and Gibbons [336], who modified the earlier model to let two new industries appear as a result of innovations. The industries compete for resources and markets, giving rise to possible trajectories in which the growth of one industry occurs at the cost of decline in the other. Thus, possible patterns of structural change and industrial evolution are examined.

The broad scope of Metcalfe and Gibbons' approach prevents them from paying detailed attention to the modeling of the Schumpeterian firm's decision rules. Stoneman and Ireland [525] proceed in this direction with a model that adds a monopoly supplier subject to learning economies to a threshold model of the David [99]/Davies [105] type. Rather than being driven by exogenous changes in prices and firm size, the model makes the innovation's price ((P^N_{it}) in equation (44)) endogenous. Since the supplier maximizes discounted returns, early profits are attractive, but this tendency is balanced by rising marginal costs at any moment in time and falling costs over time due to learning. The solution to this problem determines price, which declines over time. Stoneman and Ireland show that learning economies are necessary to produce a sigmoid curve. However, no exogenous forces are required to generate the diffusion process, whereas in the David and Davies models wages were rising and technology changing.

When the monopoly supplier of the capital good is replaced by oligopoly, the stock of new machines rises and the capital goods price falls. The price will be lower, the greater the number of suppliers, but the number of suppliers does not affect the speed of diffusion.

Stoneman and David [524] consider the effects of information provision and adoption subsidies in a model that includes expectations and supply considerations and integrates the epidemic and threshold approaches to diffusion.

They find that information policies are effective under perfect competition but that a monopoly supplier's reaction may negate this outcome. Subsidies to adoption will increase usage in both cases.

3.7 Aspects of the International Diffusion of Technology

This survey has concentrated on the development of analytical models of the diffusion process. It draws on disciplines outside economics only to the extent that they contributed to the evolution of these models. However, many of the factors that have now been incorporated in formal models were originally investigated by economic historians and other scholars such as Rosenberg [432, p. 1], who have shown "a willingness to step outside of the limited intellectual boundaries of this mode of reasoning."

3.71 In Economic History

The majority of Rosenberg's contributions are available in two volumes of collected papers [432, 434] that discuss, from a historical perspective, issues such as post-innovation improvements, complementarity between innovations, the importance of (and difference between) learning by doing and learning by using, and the improvement of old technologies that the stimulation of competition from new techniques can cause. Rosenberg's work, that of historians such as Kenwood and Longheed [273], and of critics like Rosegger [428] show that many important elements in the extremely diverse process of diffusion have not yet been included in formal models.

In an immature literature such as that on the international diffusion of technology where formal modeling is as yet limited,[142] historical studies account for a significant proportion of current knowledge. A minority of the issues raised by the historians are considered here. For instance, David [102] extends the threshold model of the adoption of agricultural machinery to the transfer of agricultural technology from America to Britain. The slow rate of diffusion is largely explained by factors not normally included in diffusion models, such as the inappropriate topology of the English landscape, the legal and institutional arrangements, and possibly the penalties of England's early start in the accumulation of agricultural machinery. Such considerations remain relevant in the international transfer of agricultural technology at the present time.

Temin [535, 536] accounts for the slow diffusion of coke smelting from British to American iron producers largely by reference to the difference in resource endowments (wood was plentiful in America) and the unsuitability of American coal. This again calls to mind the location-specific nature of innovations and the influence of factor endowments as an <u>inducement mechanism</u>. These same influences appear in the relatively rapid change from wooden to iron ships in Britain as compared with America (studied by Harley [209]) and the mechanization of gun-making (Ames and Rosenberg, and Blackmore, both in Saul [474]). Blackmore's study of Colt's London armory also stresses that the international diffusion of techniques required the international movement of skilled labor. In the extensive literature on the entrepreneurial failure of Victorian Britain, Sandberg [465] absolved the Lancashire cotton industry of blame for the slow diffusion of ring spinning because it had less need to economize on labor. However, Lazonick [289] attributed Lancashire's decline to a failure to make the transition from competitive to corporate capitalism. The complexity of factors affecting diffusion, often missing from mathematical models, is clear in these works and is reinforced by Allen's [9] study of iron and steel. A survey of "entrepreneurial failure" in several industries is provided by Sandberg [466] and is a main topic of McCloskey's [328] conference volume.

From this brief excursion into economic history, it is difficult to avoid the conclusion that such aspects of technical change as induced innovation, the effect of market structure, appropriate technology, diffusion, and technology transfer interact in a complex manner, especially in the context of international diffusion.[143]

3.72 In Agricultural Development

The international diffusion of agricultural technology is not a recent phenomenon. Ruttan and Hayami [456] cite the classical studies of Sauer [472] and Vavilov (in Chester [87]), which document the international diffusion of plants, animals, tools, and husbandry practices. But Evenson [129] warns that the transfer of agricultural technology is far more complex than diffusion models in economics and sociology imply. The fundamental difficulty in agricultural diffusion is locational specificity, which is defined to mean that the value of a technique depends on soil, climate, and economic conditions. This limits returns to scale in agricultural research and raises adaptive research to the status of a prerequisite for diffusion.

These difficulties are illustrated by Evenson, Houck, and Ruttan's [131] prototype study of sugar cane varieties[144] and its extension by Evenson [129]. Evenson and Binswanger [130] stressed three findings: (1) International diffusion of new varieties was related to climate and plant disease incidence with widespread diffusion occurring only after important technological advances. (2) Early attempts to develop indigenous technologies were largely unsuccessful but did lead to screening techniques that later facilitated the diffusion of varieties from Java and India. (3) After a while, indigenous research programs were successful in adapting the Javanese and Indian varieties to local conditions in a wide range of countries.

Drawing on the same earlier work, Hayami and Ruttan [222] identified three stages in the international transfer of technology. The first, called "material transfer," is the simple importation of seeds, plants, and other materials that are adapted to suit local conditions largely through trial and error by farmers. The second phase is "design transfer," characterized by the import of journals, books, and blueprints that allow the copying and domestic production, with minor modifications, of the foreign designs. The final phase is the transfer of "capacity" and scientific knowledge, entailing an indigenous research capability that can adapt foreign prototypes to local conditions and increasingly create a truly indigenous technology.

Ruttan [447] argued that institutional transfer and innovation are essential elements in the development of capacity, and Ruttan and Binswanger [454] discussed the relationship between induced technical change and institutional change. However, developments of such complexity cannot be expected to occur automatically or rapidly. The establishment of the international agricultural research institutes represents the single most far-reaching attempt to increase both research capacity and the rate of diffusion. The structure of the international research system, its role in adaptive research, and its relation to developed and underdeveloped country national research systems are discussed by Ruttan [452]. Biggs and Clay [47] suggest that the international system has "filled the gap on the neglected subject of foodcrops."

Hayami [214] provides the historical background with an account of the development and transfer of new rice varieties in Asia. His account is extended to include the green revolution in Ruttan and Hayami [456]. The paper by Evenson and Binswanger [130] represents a move in the direction of formal modeling, reporting the results of the Evenson and Kislev [132] empirical investigation of technical change and diffusion in cereal grains. Many studies on national and international agricultural research and productivity are drawn together in Arndt, Dalrymple, and Ruttan [14].

Though the literature has concentrated on basic technology transfer issues, a minority of authors have investigated the transfer and development of capacity in the production of particular inputs necessary to the success of the green revolution. Thus Ghatak [167] studied the transfer of fertilizer production technology and Morehouse (in Stewart and James [515]) considered the Indian tractor industry. The seed industry has been investigated by Godden [174, 175], who concentrated on the concept of plant breeders' rights. The role of multinational companies in the international supply of modern seed varieties has been raised by Mooney [343].

The international diffusion of agricultural technology raises most clearly the question of how technology transfer and the development of indigenous capacity interact. In a largely critical survey, Biggs and Clay [47] argue that the conventional wisdom on agricultural technology diffusion amounts to a center-periphery model, entailing notions of dependency. In this they follow Rogers [423], who maintains that in the classical model, the innovation originates from an expert source, such as an R & D organisation, and is diffused as a uniform package to passive potential adopters. This centralized, vertical model is contrasted by Rogers [422] to a decentralized model in which innovations evolve as they diffuse. Drawing on the work of Schon [482], Rogers suggests that a decentralized model is more appropriate to situations in which users develop the innovation. A high degree of <u>reinvention</u>[145] can lead to adopters becoming their own change-agents and active participants in the horizontal dissemination of innovations.

Rogers [423, p. 346] concludes that most diffusion networks contain elements of both centralized and decentralized systems, which can be combined to give a uniquely appropriate representation. In international agricultural development, this suggests that the analysis could incorporate on-farm research and allow for farmer (user) participation in developing appropriate technology (CIMMYT economics staff, in Eicher and Staatz [126]). Ruttan [452, p. 135] has also argued that some elements of farming or cropping system research are essential to provide feedback to the research institutions on the technical and environmental constraints faced by farmers. A centralized/decentralized analysis would be capable of incorporating the informal, farm-level R & D network stressed by Biggs and Clay [46] and would emphasize that research should be aimed at solving farmers' problems (Biggs, in Stewart and James [515]).

A method by which these approaches can be combined arises from Rosenberg's [437] distinction between "learning by doing" and "learning by using." "Learning by doing" advances with cumulative output of the capital goods industry supplying the innovation, leading to lower costs and product prices. "Learning by using" refers to learning by the <u>users</u> of the capital good in the consumer goods industry and can take two forms. The resultant technical change may be of a disembodied nature (better results from using an unchanged innovation), or the innovation itself may need to be changed. In the second case, "what we are describing is a feedback loop" [437, p. 123], and the improvement must be embodied in the innovation by the producer. If we read "agricultural research institution" for "capital goods industry" and "small-scale farmer" for "consumer goods industry," the feedback loop is the proportion of technical change generated by informal R & D that requires embodiment in the innovation.

4.0 CONCLUSION

Addressing the American Economic Association in 1966, Boulding [67] chastised the profession for neglecting technical change to the point where economists were incapable of answering many of the most important questions of the day. Boulding's concern has been echoed in several subsequent reviews [263, p. 223; 354].

This review documents major advances in our understanding of the process of technical change, but a number of inadequacies remain to be resolved. Part 1 raises the issue of our inadequate understanding of how science interacts with technology. Unicausal explanations, such as the science push or demand pull models of technical change, are clearly inadequate.

This view is confirmed in the review of the literature on induced technical change in Part 2. Categorisations of commonly used concepts like factor substitution and technical change rest on an arbitrary definition of the isoquant. While the induced innovation hypothesis has met with some success in explaining the direction of technical change, the relationship between the rate of technical change, profitability, and research and development expenditures, is far less clear, as is the relationship between rate and direction of technical change.

The discussion of diffusion in Part 3 also raises definitional problems. If the distinction between (major) innovation and post-innovation improvement or re-invention is arbitrary, so too is that between innovation and adoption [423, pp. 175-182]. This is made worse by reliance on the sequence of invention-innovation-improvement that misses the point that much of the firm's technological activity is neither acquired from nor transferred to other firms. Nor have we in this survey been able to weave the component parts into a coherent whole. The linkages between the process of cumulative synthesis and induced innovation and between induced innovation and diffusion remain unresolved.[146]

Many important problems do not fit neatly into the confines of a single discipline or even related disciplines. This is clearly true of both our attempts to understand the sources of technical change, which lie at the interface of the social and physical sciences [127], and our attempts to understand the diffusion and impact of technical change, which require a more adequate understanding of the other sources of institutional change. It seems apparent, as Kuznets [283] has argued, that we continue to inadequately capture many of the costs associated with technical change with the result that the benefits are often exaggerated relative to the costs.

The induced innovation section began with the presumption that the tradition of treating technical change as exogenous to the economic system made inadequate use of the power that economics can bring to bear on understanding the process of technical change. A similar argument can be made in the case of institutional change, which until recently has also been treated as exogenous. Substantial progress has been made in treating institutional change as at least partially endogenous [412]. But we share with Field [157] the view that it will not be possible to endogenize fully either technical or institutional change. Both the rate and direction of technical and institutional change will be influenced by forces that are exogenous to the economic system.

We have documented the substantial progress that has been made in the attempts by economists to understand the process of technical change. But progress has been slow. The analysis of technical change involves problems such as market failure, interdependencies, historically contingent events, and the dynamics of change, which do not fit easily into the neoclassical framework. However, we do not agree with Nelson and Winter [360, p. 205] that the use of the augmented neoclassical model has led to a dead end. The power of the analytical methods and the advances in knowledge reviewed in this paper have provided too much insight into the process of technical change to accept readily the Nelson-Winter conclusion. But this should not blind us to the limitations of the neoclassical approach as we attempt to extend our knowledge. Neoclassical analysis is a "system of thought which in its pure form happens to be fundamentally ahistorical, if not actually anti-historical" [100, p. 11]. When time is dealt with, historical reality is often sacrificed to mathematical tractability. The failure to come to grips with historically contingent events is at odds with the reality of technical change at the micro level.[147] Firms differ in their technological characteristics, in part because they have different histories and different past experiences.

By contrast, the "neo-Schumpeterian approach is concerned above all with the process of economic change, as opposed to the analysis of equilibrium states" [163, p. 609]. An increasing number of authors have now followed Nelson and Winter's lead in either recommending or contributing to the evolutionary or neo-Schumpeterian approach to technical change [127, 267, 334]. These evolutionary studies draw their inspiration from biology rather than classical physics. Social science applications of evolutionary concepts date back to Smiles.[148] In economics, Marshall [322] recommended the biological analogy before proceeding to foresake notions of life and movement for the simpler and more tractable approach of mechanical equilibrium.[149] A limited form of the evolutionary process has been applied successfully by Alchian [6] and others, but the effective application of evolutionary models to the study of technical change awaits a more rigorous development of the methodological foundations of this branch of economics.

The advances in our understanding of the role of demand and supply side forces in influencing the direction and diffusion of technical change have important implications for economic policy. The demonstration of the powerful role of economic forces in inducing technical change places a major burden on the efficiency of both market and nonmarket resource allocation systems. The theory of induced innovation and the historical research conducted within the induced innovation perspective are consistent with the inference that when either factor-factor or factor-product price relationships have been distorted, either through market or nonmarket interventions, the innovative behavior of both public research institutions and private research and development organizations will be biased.

The impact of bias in the allocation of research and development resources is particularly serious because of the long lag between the allocation of resources to research and the impact of the new technology generated by research and development on production. If rates of return to research were low, the cost of such distortions would also be low. But because the rates of return to research have been very high [319, pp. 144-146; 452, pp. 237-261], the costs of distortion are also very high.

This implies that assuring the efficiency of the institutions through which resources are allocated to research and development must be a central element in policies designed to speed the process of economic growth.

The advances in our understanding of the linkages between research and development and diffusion processes are also adding importantly to our capacity to design effective technology transfer policies. The effective diffusion of new technology is dependent on the capacity to invent and reinvent new technology. This means that a country or region that wants to acquire access to the new income streams generated by technical change must go beyond reliance on simple technology transfer and invest in the capacity to adapt the technology for its own resource and institutional environment. And when it has acquired the capacity to effectively transfer, adapt, and diffuse technology it will also have the capacity to invent technology that is appropriate to its resource endowment and institutional environment.

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FOOTNOTES

1. Rosenberg notes, "This view has the disconcerting aspect, at least for the economist, of appearing to make the central feature of modern economic growth an exogenous phenomenon. . . . Economists have had much more success in dealing with the consequences of technological change than with its determinants" [434, p. 141].

2. Although Smiles' portrait of the character and accomplishments of the early British engineers was cast in the heroic mode, he was sensitive to the political, economic, and social forces that influenced their accomplishments [234, p. 5].

3. Both Ogburn and Gilfillan emphasized that inventions generally occur incrementally as a result of the accumulation of experience, rather than as dramatic breakthroughs. Ogburn, however, placed primary emphasis on the rate of advances in knowledge and on the state of "material culture" while Gilfillan placed greater emphasis on the response to demand [169, 170, 171, 375, pp. 30-102; 376, pp. 775-810; 377].

4. Alfred North Whitehead has argued that "the great invention of the nineteenth century was the invention of the method of invention" [562, p. 96].

5. After an extensive review of the history of a number of major innovations, Rosenberg asserts that "the normal situation in the past, and to a considerable degree also in the present, is that technological knowledge had preceded scientific knowledge. . . . It is still far from unusual for engineers in many industries to solve problems for which there is no scientific explanation, and for the engineering solution to generate the subsequent scientific research that eventually provides the explanation" [434, p. 144].

6. The proposition that the rate of invention in the capital goods industries in the United States is closely associated with the rate of capital investment was established by Schmookler [481, pp. 104-163] and confirmed by Scherer [478].

7. This literature has been critically reviewed by Mowery and Rosenberg [346, 434]. See also the review by Kamien and Schwartz [263, pp. 31-47].

8. Rosenberg and Mowery argue that much of the research that purports to demonstrate the plausibility of the demand pull hypothesis can more appropriately be interpreted as evidence that private profitability or social utility (or need) are inducements to the allocation of private and public resources to research. But profitability and utility are also enhanced by advances in scientific or technical knowledge that reduces the cost of technical change. See also Nelson [351].

9. This view has also been characteristic of much of the anti-technology movement literature. For an extreme view of the autonomy of science see Mishan: " . . . science is not guided by any social purpose. . . . As a collective enterprise science has no more social conscience than the problem solving computers it employs. Indeed, like some ponderous multipurpose robot that is powered by its own insatiable curiosity, science lurches onward . . ." [339, p. 129].

10. This area has been reviewed by Nadiri [349]. More recent developments are discussed in [268] and [121]. Few productivity studies are referred to in this paper since the typical objective of such work is a total factor productivity index that describes the rate but not the <u>bias</u> of technical change.

11. Productivity growth and technical change were assumed to be synonymous, but productivity is also affected by increasing returns to scale and improvements in the allocation of resources, such as structural change [508, p. 93].

12. If the production function is homogenous of degree one (constant returns to scale), it can be represented by any single isoquant and the two measures will be identical.

13. This measure is suited to process innovations, which may be thought of as better ways of making existing goods. Product innovation, encompassing both the appearance of new goods and improvements in quality, while very important [283, pp. 339-346], has proved less tractable. Thus, theories of induced innovation are confined to process innovation. This serious limitation is mitigated by the fact that the product innovations of the capital and intermediate goods industries can be viewed as process innovations in the industries using their output [61].

14. The production function is taken to embody "all previously known techniques" [272].

15. This definition is suitable for micro studies since the individual firm can treat prices as exogenous. If the firm is using the cost minimising input combination before and after the change, both situations will lie on the expansion path.

16. Augmentation is a particular repesentation of technical change in the production function, not an explanation of causation or transmission. For example, labour-saving technical change may result from and be embodied in a technically superior machine, such as a new model typewriter. Following the usual convention, the dot notation repre-

sents derivatives with respect to time. The two-factor case is used to introduce the concepts.

17. They point out that Hicks did not hold factor ratios constant, but required that the firm should remain in a position of "internal equilibrium." This is interpreted to mean "expansion path preserving." If the product function is not homothetic, a shift from A to a point like F on the non-linear expansion path OFA is Hicks-neutral by their definition but labour-saving according to the fixed factor proportions approach.

18. If marginal products and factor prices are equal, the factor share definition can be written in terms of output elasticities. If Y is output, the output elasticity for capital is the ratio of the marginal to average product, or capital's share in output,

$$\left(\frac{\partial Y}{\partial K} \cdot \frac{K}{Y} = \frac{rK}{Y}\right).$$

Robinson's [417] diagramatic analysis exploits the relationship between marginal and average product.

19. Obviously if there are n factors, there will be n measured biases, whereas for the pairwise ratios of equations (6) and (7) there will be

$$\frac{n!}{2(n-2)!}$$

combinations of bias parameters and associated difficulties of interpretation.

20. It is in fact the only definition of neutral technical change that has this property. This was recognised by Robinson [417] and proved by Uzawa [548]. Jones employs simple heuristic argument to explain the problem.

21. In terms of factor augmentation, Harrod neutrality is the equation (4) case, previously referred to as purely labour-saving under the Hicks classification. In Figure 2.1, if labour (L) is replaced by $\hat{L} = B(t) \cdot L$, so that labour is measured in efficiency units, what used to be Hicks neutrality becomes Harrod neutrality.

22. For technical change to be both Hicks- and Harrod-neutral the production function must be Cobb-Douglas. If the capital input and its price are unchanged relative to output, yet the input of labour is decreased, the rising wage must exactly compensate for factor shares to remain constant. The unitary elasticity of the Cobb-Douglas was originally intended to give this constancy of shares. To show Harrod neutrality in Figure 2.1, rotate the isocost line around point P until it is tangential to I_1 at point G. Then capital remains at $\overline{K}$, output is unchanged and so is the price of capital [204, p. 122].

23. This was recognized by Blaug [61], who considers that the effects of changing relative prices and commodity substitution constitute a "fatal objection" to the Hicks-Robinson classification of technical change.

24. In terms of the factor-augmenting production function, this is the purely capital-augmenting case of equation (5).

25. David's critique of the methodology of neoclassical economics and that of Nelson and Winter appear in the final section of this paper as a prelude to the evolutionary models they propose as an alternative.

26. In Temin's [538] application of the three-factor, two-sector model, land is specific to agriculture and capital to manufacturing, with labor common to both.

27. Induced innovation in Ahmad's model becomes factor substitution under Salter's definition of the isoquant.

28. Salter's rejection of induced bias is equivalent to Ahmad's assumption that the IPCs shift Hicks neutrally [204, p. 126]. Both are unwarranted assumptions. In particular, Ahmad postulates neutrality of the shift of the IPC also in the sense that it is independent of the technique actually used in the previous period [368, p. 212].

29. To avoid repetition, Ahmad's diagram is omitted; see the diagrammatic explanation below of the Hayami and Ruttan model, which follows Ahmad's reasoning.

30. Griliches [194, pp. 241-245] has suggested that these two processes may be regarded as "somewhat independent (of each other), at least over a certain range."

31. Though the model explains the direction of the factor-saving bias of technical change, the rate of technical progress remains exogenous.

32. The diagram is clearly a simplification and is not intended to represent fixed factor proportions between land and power.

33. This account is close to that in Hayami and Ruttan [222]. The original version in their first edition is more simplistic. That of Ruttan, Binswanger, Hayami, Wade, and Weber [455] adds further complexity by differentiating between the short run (in which existing capital leads to nearly fixed proportions); the long run (in which substitution along the neoclassical isoquant occurs); and the secular period (in which, given the current state of scientific knowledge, a set of IPCs can be developed, each corresponding to a different research budget).

34. Definitionally, the function is separable if,

$$\frac{\partial[\frac{F_i}{F_j}]}{\partial[X_k]} = 0 \text{ for all } i,j \quad N \text{ and } K \quad N.$$

where, for this two-group case, N denotes either group of factors, and F_i, F_j are the marginal products of X_i and X_j. Hence, separability requires that the rate of substitution between two factors in one group should be independent of the level of factor inputs in the other group.

35. The model presented here is a simplification in the sense that it requires only conventional neoclassical isoquants that shift Hicks neutrally. The same four-quadrant approach can obviously incorporate IPCs and non-neutral technical changes in the spirit of the Hayami and Ruttan model [541].

36. If the parameters are fixed, payoffs to applied research will be rapidly exhausted. Basic research is required to change the state of scientfic knowledge and hence μ and/or σ so that the process may be continuous.

37. Note that each research process reduced both augmentation coefficients, but in different proportions. Also, these functions are not specific to the factor-augmenting form of the production function. Indeed, Binswanger [55] retains these same functions, but with A and B as parameters of the production function.

38. Binswanger [54, 55] studies many other issues, including the effects of market structure, induced bias in the output mix, the effect on the bias when the technical change is embodied in an intermediate input, demand conditions, a budget constraint on total research resources, and the effect of varying degrees of patentability for different factor improvements.

39. Though this is clearly a serious issue, justifying the following discussion, in some sense the real problem is the distortions themselves, not the inadequacy of the theory of induced innovation.

Distortions clearly have biased technical change, for example, in the case of rice in Japan during the 1960s and 1970s and tobacco in the United States [452, pp. 88-90, 338-340]. Public research institutions could tailor research to efficient shadow prices, but if farmers face distorted relative prices, the research output will not be appropriate to farmers' perceived needs [451, p. 24].

40. The concept of the "dual economy" has taken on several meanings. Here it can be taken to mean the coexistence of modern and traditional techniques and the lack of unique factor prices. Mueller implies that dual technologies may be the inevitable outcome of the technology gap and the international diffusion of technology rather than the result of duality in factor prices.

41. This possibility has attracted considerable attention. Hazell and Anderson [223] provide an up-to-date review of many contributions and offer explanations for the divergence of conclusions.

42. The development of irrigated rice varieties by IRRI might be taken as evidence of such a bias, since farmers with irrigated land are asserted to be more prosperous than those who rely on rainfall (see Biggs [43], p. 27).

43. De Janvry and Dethier's [112] "structuralist theory" of induced innovations stresses the importance of institutional forces in modifying the market outcome. Ruttan [449] summarises the findings of Ruttan and Binswanger [453] on the green revolution by observing that the wide diffusion of an institutional innovation--the socialization of agricultural research--has generated technical change that in turn has created new income streams and a disequilibrium that are a powerful source of further institutional change. As a result, property rights

in land, as well as many other institutional arrangements, are being modified.

44. Hayami and Kikuchi's [217] Philippine study provides an example of both demand side sources. They argue that rapid population growth, combined with irrigation and high-yielding rice varieties, has led to institutional innovations in the form of subleasing and labor contracts that require weeding services as a precondition of participation in the harvesting operation. See also Feeny [144] and Feeny's [145] response on delayed irrigation projects in Thailand, in which he suggests the importance of politics and "returns to the men in government."

45. Hayami and Ruttan [222] and Ruttan and Hayami [456] cite the communal arrangements in Japanese villages, designed to prevent depletion of common property, as an example of the first case and the role of social science knowledge in the design of more efficient commodity markets, land tenure institutions, credit, and marketing arrangements as examples of the second.

46. However, an attempt to test the hypothesis suggested by Schultz [484] has been made by Stauffer and Blase [512].

47. A similar model was simultaneously developed by von Weizsacker, who is accorded joint credit in much of the literature.

48. Kaldor's approach is not pursued here, as it is the rate of technical change that he endogenised in a way that avoids difficulties by drawing no sharp distinction between technical change and capital accumulation, on which its rate depends. Arrow's [15] "learning by doing" is similar in depending on investment and concentrating on the rate of change.

49. The production function is made explicit in the explanation offered here, which is attributable largely to Jones [251, Ch. 8].

50. This gives a two-sector, one-good model, "or what is the same, to restrict the analysis to a one sector model" [156].

51. This statement synthesizes several contributions. Kennedy [269] assumes a constant rate of interest and derives the Harrod neutrality result. Samuelson's [463] assumptions differ and he does not reach the Harrod neutrality result. His analysis introduces a factor-augmenting production function and facilitates the investigation of the stability conditions, especially the crucial importance of $\sigma < 1$. Any tendency for the share of labour to rise will make labour-augmenting technical change more profitable, and the introduction of technology with a labour-saving bias will reduce labour's share provided that the elasticity of substitution is below unity. Further analysis of the stability conditions can be found in Drandakis and Phelps [122], Wan [557], and Chang [84, 85]. Using the notation of Section 2.1, Drandakis and Phelps define the bias (B) in terms of the elasticity of substitution and the augmentation parameters as $B = [(1-\sigma)/\sigma][\frac{\dot{B}(t)}{B(t)} - \frac{\dot{A}(t)}{A(t)}]$.

52. However, this result is also contrary to the findings of Nordhaus [366, 368], who does endogenise the rate of change yet concludes that the Harrod-neutral equilibrium is achieved if $\sigma < 1$. See also Kamien and Schwartz [261], who also consider both the rate and direction of technical change in the context of a profit-maximizing firm with a Kennedy frontier. They conclude that the equilibrium is Hicks-neutral (the micro approach is equivalent to no technical change in the capital goods sector) and stable if $\sigma < 1$, unstable otherwise, for both the myopic and dynamic maximization problems.

53. Hacche [204, pp. 129-132] discusses Ahmad's critique in detail, including the relationships between the IPC and the IPF. There is also a simple derivation of the Harrod-neutral equilibrium.

54. Compare this with the Evenson snd Kislev sampling procedure (Section 2.22) in which the payoff from applied research depends on a gap between existing techniques and scientific knowledge. Repeated sampling quickly exhausts the payoff. If this or a similar view of the research process is accepted, then for the IPF to be stable over time, scientific progress would be required to proceed in such a manner as to replace innovation possibilities at the rate they are "used up." For a discussion of the interaction of science and technology see Rosenberg [438, Ch. 7], who argued that much scientific progress is indeed in response to technical change that has outpaced scientific understanding.

55. The term natural drift is attributable to Samuelson [463, p. 353]. It is important to note that the Nordhaus result applies only to balanced growth equilibria (requiring that the main economic variables remain in the same proportion to each other). The result is damaging because the Kennedy frontier appeared to offer an escape from the assumption of Harrod-neutral technical change. However, for many purposes, a stable equilibrium (that is not on a balanced growth path) is sufficient. Indeed, Magat [307] and Skott [500], discussed below, do derive a stable equilibrium with innovation depletion.

56. The result depends on the relative shapes of the IPFs, since capital intensities affect factor shares and factor shares are relevant to the determination of technological biases. Following Jones [249],

Harrod neutrality in both sectors is imposed as a condition of the steady state path.

57. "Technical progress is neutral in the sense of Kennedy if the capital-output ratio is constant in value terms, in the consumer goods sector" [324, p. 921]. See Burmeister and Dobell [95, pp. 139-146] for a discussion of Kennedy neutrality and a comparison with Harrod neutrality in the context of two-sector models.

58. Fellner [154, p. 1083] raised the issue of the treatment of land, but considered that capital can be substituted with sufficient ease to make the two-factor model applicable. For an informative discussion of fixed resources and technological change, see Rosenberg [434, Chs. 13 and 14].

59. McCain [323, pp. 498-499] carries the argument further. If population growth is a non-decreasing function of income per capita (in keeping with the classical approach), then the long-run equilibrium is Malthusian, with zero rates of capital and labor augmentation and consequently a constant (subsistence) wage. Brewer points out a problem with disaggregation. In his model, as in McCain [324] and presumably Kennedy's [271] generalization (which does not address the stability issue), the results depend on all $\sigma < 1$. The problem is that "one might reasonably guess that increasing disaggregation to a larger number of factors would make it very likely that at least some elasticities would exceed unity, for example, between two similar types of land in nearby locations" [69, p. 292].

60. Market failure may lead to technical change biased in the direction of environmental pollution. See the critiques of the microeconomic

approach in the last section, which emphasise that if the induced innovation model relies on market forces when there are serious distortions, it will lead to suboptimal solutions.

61. Magat then proves that for both the regulated and nonregulated cases, technical change will be Hicks-neutral and stable if $\sigma < 1$. But for all homothetic functions, Kr/Lr > Ku/Lu, where r stands for regulated and u for unregulated. Though Magat does not comment on this point, it would appear to mean that technical change will exactly maintain the initial (static) overcapitalization. Regulation is not confined to utilities. Hayami and Ruttan [219, pp. 151-152] argue that the commodity programs (especially acreage allotments in tobacco) have distorted research resource allocation in U.S. agriculture.

62. Binswanger [53, p. 38] attributes the demise of Kennedy's approach to its lack of microfoundations and particularly to the difficulty of conceptualizing an empirical counterpart of the IPF. However, Woodland [574] takes the IPF to be the dual of Diewert's [116] revenue function and constructs an empirical model. Even so, it is the Ahmad/Hayami and Ruttan approach to which most empirical work refers, probably because the theory is a modificaion of a favourite empirical tool, the production function.

63. The results reported are from Binswanger and Ruttan [57]. Extending the Japan and U.S. data to 1980 causes two sign changes [222].

64. See Sahota's [460, pp. 727-728] review article for a methodological critique of these simple tests; he argues that assumptions have replaced implications in this formulation. The functions tested are ad hoc in the sense of not being derived from a specific production relationship.

65. Hayami and Ruttan [222, pp. 178-187] consider that their tests of the behaviour of factor ratios in response to factor price changes relate to movements along the IPC or its production function equivalent, called the metaproduction function.

66. Net of direct substitution of land for labour (in the northwest quadrant), calculated by applying the actual change in the wage rental ratio to estimates of the elasticity of substitution of land for labor.

67. If the initial production function is labor-intensive, that is, if it requires large amounts of labour relative to capital, expected discounted wage costs will be higher than if the initial production function is capital-intensive. Hence, for given factor cost ratios and innovation possibilities, labor-saving research is more attractive if one starts from a labor-intensive point than if capital intensity is already high [54, p. 105].

68. Thirtle [543] also considers returns to scale.

69. At face value this reasoning is directly opposed to that of Hayami and Ruttan. The two are reconciled by noting that Binswanger is considering a single crop or industry in a developed economy, whereas Hayami and Ruttan have in mind the factor endowment of the entire economy over a long period. Hayami and Ruttan treat the factor intensities as fixed, whereas for Binswanger they are the target variables.

70. The estimated elasticities are from Binswanger [49]. The data used were for U.S. agriculture 1949-64. These estimates of the elasticity of substitution are used in cross section tests for 1880, 1930, 1960, and 1970 and are applied to all six countries in the time series tests.

71. See Wyatt [576, pp. 98-101] for a better explanation and some applications.

72. In one unusual application, Klein and Kehrberg [278] develop a method of evaluating agricultural research projects based on the innovation hypothesis. They apply it to an existing Canadian animal breeding project.

73. Kislev and Peterson [275, 276] argue that the mechanisation of agriculture is technical change in the farm machinery industry and factor substitution in agriculture.

74. The data used by Hayami and Ruttan [218, p. 1117, Table 1] show that the price of labor relative to land was rising in the United States and falling in Japan for the entire period 1880-1960. However, Figure 1, p. 1118, shows a slow rise in the Japanese land/labor ratios, which would account for the "wrong" sign when their simple test was applied to the Japanese data.

75. Nghiep's price data are clearly different from the series used by Hayami and Ruttan. In particular, the price of land is a rent, rather than a land value. In discussing the partial elasticities of substitution, Nghiep does not mention the oddest result--that land and fertilizer appear to be complements. See also Hunt [235], who suggests that the translog function may be inappropriate in this case and that the parameter estimates may be biased.

76. See Hayami and Ruttan [222, Ch. 7] and also a paper by Kawagoe, Otsuka and Hayami [266], on which this work is based. Their measurement of labour is in work hours, whereas Nghiep [364] used number of workers.

77. A more complete survey of early two-input studies is provided by Kennedy and Thirlwall [292].

78. This is supported by Uselding and Juba [546], who found total technical change to be capital-saving during the decade of the 1930s.

79. The authors point out that technical change did appear to be coal-saving and electricity-using, suggesting that if external costs such as pollution were included the test results might better fit the inducement hyothesis.

80. David [100, Ch. 1] shows that Asher's measure of bias ($B = \lambda L - \gamma K$, where λL is the labor augmentation parameter and γK that for capital) depends on the rates of technical progress. He argues that a relative measure of the bias, $B^* = (\lambda L - \gamma k)/\lambda L$, would be more appropriate. However, inspection of Asher's results [17, pp. 439-440] indicates that the rate of technical change in Britain would have had to be practically double the U.S. rate for cotton and triple the U.S. rate for wool for the conclusions to be reversed.

81. Smith appears to reject factor-price-induced, biased technical change. His results indicate that labor-saving technical change was not significant, but that there is significant capital-using and natural-resource-saving technical change.

82. David [100] argues that the Nelson and Winter approach is not historical, but this reasoning has been questioned by Elster [127, pp. 156-157], who also provides a brief introduction to evolutionary theories. His illustrations cover animal tool behaviour and the technology of fishing boats. On the methodological foundations of the evolutionary approach to economics, see Winter [572, 573].

83. Binswanger [53, p. 32] criticized the assumption that search only begins when profits are unsatisfactory. This assumption is contrary to Schmookler's [481] evidence that increasing demand, and hence higher profitability, leads to more innovation rather than less.

84. More recent developments of the model, such as by Nelson and Winter [359], concentrate on Schumpeterian hypotheses rather than induced innovation.

85. See Williamson [568] for a useful critique of David's approach.

86. Rothbarth [439, p. 387] argued that once established, American superiority became self-reinforcing and operated independently of its original historical cause. David's analysis provides a theoretical basis for this claim.

87. The biological concept of niches has been added to the economics literature by Mark, Chapman, and Gibson [321].

88. This part owes much to two recent studies of diffusion by Davies [105] and Stoneman [522]. Similarly, the discussion of adoption draws heavily on a survey of agricultural adoption by Feder, Just, and Zilberman [138]. It is beyond the capabilities of the authors to do justice to the voluminous literature on diffusion from all the contributing disciplines. We have borrowed freely, since many important developments occurred in other subject areas, but the paper is written for economists. A guide to work in other disciplines is provided by the extensive bibliography in Rogers [423].

89. Though this approach may capture the more direct effects of technical change, the important and wide-ranging social, organisational, and institutional changes that can be caused by major technical innovations tend to be neglected. Kuznets [283] argues that these resultant changes would have to be identified and taken account of if we are to calculate the <u>net</u> contribution of innovation to economic growth.

90. The relationships between best practice techniques, diffusion, and productivity growth have been investigated by Shen [495, 496].

91. This is arguably a shortcoming; Rogers [423, Ch. 4] states that "events and decisions occurring previous to this point have a considerable influence upon the diffusion process."

92. In statistical terms, the S-shaped "diffusion curve" represents a cumulative distribution, obtained by integrating a unimodal frequency distribution of adopters arranged on a time scale. See Stoneman [522, pp. 96-97] and Figures 3.1a and 3.1b.

93. This statement does disguise the fact that adoption and diffusion studies are examples of two distinct modes of explanation in social science research. Mohr [340] argues that adoption studies are an example of variance theory, in which the independent variables are simultaneous, necessary, and sufficient to explain the variance of the dependent variable. This approach, common in neoclassical economics, is contrasted with process theories, such as diffusion, that predominate in the other social sciences. In process theory, which deals with discrete states and events, the precursors are necessary for the outcome to occur, but are not sufficient, since the process is probabilistic and the outcome only follows a particular time sequence of precursors. See Section 3.4 of this part, where adoption studies are discussed, and the Conclusion, which considers methodological issues.

94. Yeomans [579, Ch. 5] provides a general discussion of mathematical trend curves that explains the logistic in a forecasting context. Davies [106, p. 158] points out that though the tails of the two curves are slightly different, it is reasonable to assume a "rough equivalence" between the logistic and the cumulative normal curve.

95. See also the derivation and discussion of the logistic curve in van Duijn [550].

96. A concise account of applications of the logistic curve to product and process innovations is provided by Bain [23, Ch. 2]. Davies [105] and Stoneman [522] arrange their surveys according to the level at which diffusion is being studied. This approach is avoided here since it leads to repetition.

97. Bogue [65, p. 24] raises the point that by the logic of Griliches' model, the fundamental breakthroughs in the development of hybrid corn should have been made at Corn Belt experiment stations, not in Connecticut, an area of "low market density." However, the key individuals had previously worked on corn breeding in the Midwest.

98. Rogers [423, p. 211] lists the attributes of innovations as (1) relative advantage (which includes profitability), (2) compatibility, which is consistency with "existing values, past experience and needs of adopters," (3) complexity, (4) trialability, and (5) observability. The basic argument is that less complex, observable innovations that can be tested first will be more readily adopted than those that lack these attributes.

99. Griliches also noted that the disagreement is in part semantic. Terms such as <u>compatibility</u> or <u>congruence</u> can be translated into economic variables with the inclusion of imperfect information and risk preference, which are not at odds with profitability. In the original paper [190, p. 522], Griliches argued that area characteristics and personal characteristics are highly related. That is, low yields are often correlated with low education, low status, low income, and other socio-economic variables.

100. The diffusion of hospital technologies is considered by Russell and Burke [442] and Russell [441].

101. The Gompertz curve may be expressed as:

$$\text{(A.1)} \quad \frac{dn_t}{dt} = \beta_1 n_t(\log N - \log n_t),$$

which is similar to the logistic (see equation (1)). If $y = \log x$ is distributed normally, $x=e^y$ has the lognormal distribution. Maddala argues that "since many variables in economics cannot take negative values, and also do not have symmetric distributions as the normal, the lognormal distribution may be more appropriate in some economic applications than the normal" [304, p. 33]. The linear approximation of the lognormal is given by,

$$\text{(A.2)} \quad \frac{dn_t}{dt}\frac{1}{n_t} = \frac{\beta_2}{t}\left(\frac{N - n_t}{N}\right), \ \beta_2 > 0$$

[526, p. 25].

102. Cramer [95, pp. 30-31] comments that use of the normal distribution can always be defended by appeal to the central limit theorèm.

103. A survey of studies using asymmetric curves can be found in Bain [23, Chs. 2 and 3], who fits a lognormal curve (also used by Davies [105]) to data for television ownership in the U.K. Dixon [118], discussed below, applies the Gompertz (see also Hernes [224]) to hybrid corn data.

104. While this view may appeal to economists, some of the diffusion functions used in marketing literature deliberately impose no prior constraints on the data.

105. Davies [105, pp. 11-13] demonstrates that if β varies over time, positively and negatively skewed diffusion curves are generated according to whether $\beta(t)$ decreases or increases.

106. The equation for this "waning exponential" curve is:

$$\text{(A.3} \quad \frac{dn_t}{dt} = \frac{\beta}{N}(N - n_t).$$

107. Alternatively, in the literature on the economics of advertising, Gould [183] refers to the exponential case, arising from an impersonal advertising medium [539], as a <u>diffusion</u> model, whereas the epidemic word-of-mouth case discussed by Ozga [386] is called a <u>contagion</u> model. He investigates optional advertising policies for both types of process.

108. Bain's [23] survey does show that, whereas early studies of process innovations relied on the logistic curve, several pioneering papers on product innovation did apply skewed curves. Advertising is much more intensive in consumer goods industries than in the capital goods sector.

109. Stoneman [522] argues that the general principles of analysis applied to process and product innovations are very similar.

110. Skiadas [499] describes an equation of this form as a linear combination of the Blackman/Fisher-Pry and Coleman models. His paper provides a useful list of equations for many of the models discussed here, supported by graphs of their frequency distributions.

111. A complete survey of the development of diffusion models in the marketing literature, including several applications, is now available in Mahajan and Peterson [311].

112. See also Brown and Lentnek [71] for an example of a spatial diffusion study with economic content. In spatial diffusion, Grigg [189, Ch. 11] draws a distinction between "migration" diffusion and "stimulus" diffusion.

113. In the marketing literature particularly, the reader should be wary of the distinctions between <u>stocks</u> and <u>flows</u> such as sales, between durable and non-durable goods, between first-purchase and replacement sales. See particularly Olsen and Choi [381], whose graphs decompose total sales into first-purchases and repeat buying, showing the curves to be very different.

114. These models include aspects of supply in the diffusion equation, often by making a coefficient a function of the (exogenous) supply price or advertising expenditure. The distinction can be a little arbitrary, but really they do not attempt to model the pricing and output decisions of the suppliers of new technology. Studies that do have an explicit supply model are considered in Section 3.6.

115. Rosenberg [432, Ch. 11] discusses improvements to innovations and other factors affecting diffusion that are difficult to model. One intractable difficulty is that innovation is continuous and the potential adopters' technological expectations will crucially affect the adoption decision [436, Ch. 5]. Technological expectations have been modeled by Balcer and Lippman [24].

116. Just as car ownership influences tire production, increasing the housing stock increases the stock of new consumer durables. United States housing starts had tripled between 1950 and the time of writing, making the static model inappropriate [308].

117. A further contribution by Dodson and Muller [120] explicitly introduces advertising expenditures in a dynamic model.

118. Stoneman [522, Ch. 5] provides a detailed, if abstract, comparison of the views of diffusion as an equilibrium or disequilibrium concept.

119. This is actually the title of Chapter 4 of Salter's book [462], in which the model is developed. See also Nasbeth and Ray's verbal account of the economic reasons for a slow start to the diffusion process, neatly summarised in Kelly and Kransberg [267, p. 125]. Brown [70, pp. 191-192] offers an alternative set of reasons for a slow start.

120. That new investment is assumed to be in machinery of the latest type is a disadvantage, since the evidence suggests that this is often not the case. See especially Gregory and James [187] and Gomulka [179].

121. Davies [105, p. 30] argues that threshold models such as the one developed by David [101] rest on a view of decision making that is not dissimilar from Salter's vintage model. Models of this type are considered in Section 3.5. See also David [102], who frequently refers to Salter's book.

122. The "second stages" of the studies by Griliches [190] and Mansfield [313, 314] explain the rates of diffusion for different areas and industries and within different firms. Here, we consider individual firms within one industry, rather than comparing industries.

123. Economists may be confused by his terminology. Though his book is called The Diffusion of Innovations, it is predominantly about adoption. Rogers and Eveland [424, p. 283] make his usage of the term diffusion quite clear, stating that "correlation analysis of one-shot survey data is overwhelmingly the favourite methodology of diffusion investigators." In this paper, work of this type has been called adoption, whereas non-economists use the terms interchangeably.

124. There is also a chapter on innovation and adoption in organisations. Although economists do not differentiate between the decision-making processes of individuals and of organisations, Rogers suggests some important differences. For instance, the adoption decision and its implementation may be quite separate processes in an organisation. To adequately explain adoption by organisations the work of behavioural scientists must be incorporated [424]. The distinction is made more important by the fact that

most new product adoption may depend on individual (or family-group) decision-making, whereas process innovations are usually adopted by organisations.

125. Rogers [420] provides a comprehensive survey of the earlier literature. Fliegel and van Es (in Summers [527]), give a brief history of the adoption and diffusion literature in the particularly active area of rural sociology. Feder, Just, and Zilberman [138] provide a useful survey of agricultural adoption in developing countries.

126. These statistical methods commonly used by social scientists are described in Yeomans [579, Ch. 6].

127. Several of the huge number of agricultural development studies of the adoption of new techniques, modern inputs, and improved seed varieties are discussed in Feder, Just, and Zilberman's survey [138].

128. This formulation is from Davies [105, pp. 30-31].

129. Note that this is consistent with the notion of induced mechanical innovation in U.S. agriculture studies in Part 2 of this survey.

130. Davies [105, pp. 75-80] fully explains the relationship between the probability of <u>adoption</u> (P_i in equation (22)) and the <u>diffusion</u> curve. "Conceptually the link between P_{it} and n_t/N is straightforward. n_t/N is simply the weighted sum of all possible values of P_{it}, where the weights are the probabilities that each firm size will actually occur." In other words, to derive n_t/N, the P_{it} must be integrated over the firm size distribution.

131. That there are externalities among adopters in models of this type has attracted little interest, except for Allen's [8] application of Markov random field models.

132. Stoneman's work is emphasised here partly because his textbook account [522] is accessible to a wider readership than Jensen's elegant papers and partly because his approach provides insights on the earlier literature.

133. If $b > 0$, then the firm is risk averse. The implication of the term containing b is that if the variance of the new technique is less than that of the old and/or if the old and new techniques are less than perfectly correlated, then diffusion of the new technique will reduce risk and will be faster for a risk averse firm than for one that is risk neutral.

134. The meaning of the terms <u>decision theoretic</u> and <u>game theoretic</u> and the way in which these models have been applied in the study of innovation are covered by Kamien and Schwartz [263, pp. 105-108].

135. An unpublished survey by Stoneman [523] offers further interpretation of the models considered in Section 3.5, which are updated to include "several" developments still at the discussion paper stage.

136. There is also common ground with Bain [23], whose skewed curve is the envelope of short-run lognormal curves and the other envelope approaches discussed in Section 3.33.

137. Comments on the Bass model and a summary are provided by Horsky [232], while Russell [443] provides a diagrammatic derivation of the diffusion curve.

138. This is equation (17), with $n_t = F(t)$, $N = 1$, and $a_t = f(t)$.

139. In evolutionary or neo-Schumpeterian models, technological progress depends on both innovation and imitation. Iwai [238] does not model the supply of innovations but does use an array of logistic curves to describe the imitation process and evolution of the industry with co-existing production methods. A second paper [239] extends the analysis to consider the

evolution of technology under the combined pressures of imitation, innovation, and economic selection.

140. Stoneman [522, pp. 126-127] suggests that this proposition is not supported by the empirical evidence. For major innovations, such as the railways, Hicks [228, Ch. 2] does argue that the rate at which building occurs will be limited by scarcity of factors such as skilled labour and capital.

141. In an open economy, differences between supply and demand represent imports or exports, allowing separate diffusion curves for innovation demand and the supply of productive capacity. Thus, in a model developed by Metcalfe and Soete [337], diffusion forms an explanation for international trade that is logically independent of technology gap models of the Posner [399] type.

142. Formal modeling of technology in trade theory and empirical tests of such relationships have been reviewed by Pugel [401] and Cheng [86].

143. A major gap in the literature, which we have not attempted to fill, is in the implications of recent advances in our understanding of the process of technical change for international trade. In the literature on international trade, major attention has been given to the effects of productivity growth on the terms of trade, on trade patterns, and on the partitioning of the new income streams generated by productivity growth [250, pp. 73-92; 348, pp. 22-26, 46-59]. But, except for an early article by Chipman [88] and a more recent article by Hamilton and Soderstrom [207], the relationship between the theory of induced innovation and international trade theory remains almost completely unexplored. In the standard Hechscher-Ohlin-Samuelson model, differences in resource endowments are the primary determinants of trade. In the theory of induced innovation, the

path of productivity growth is directed toward releasing the constraints on growth imposed by factor constraints. To the extent that technical change can release the constraints on growth resulting from inelastic factor supplies, the power of the differential factor endowment explanation for trade is weakened [250, p. 80]. And to the extent that trade can release the constraints of factor endowments on growth, the theory of induced innovation loses part of its power to explain the direction of bias in productivity growth. Yet these two bodies of literature have not yet been adequately integrated [86, p. 184].

144. This example is a crop-biological technology. The other categories defined by Evenson are animal-biological, chemical, mechanical, and managerial.

145. This is Rogers' [423, pp. 175-184] term, "defined as the degree to which an innovation is changed or modified by a user in the process of its adoption and implementation." The crucial point is that adopters play an important role in the process rather than being merely passive recipients of the innovation.

146. Methodological problems must be expected in integrating induced innovation, a variance theory firmly based in neoclassical economics, with diffusion theory, an evolutionary or process theory [340].

147. Macro analysis of economic growth and technical change at the sector or economy-wide level has left crucial questions unanswered. The analysis must be a search for micro-foundations (the firm is the basic organism). This, Elster [127, p. 23] suggests, is "a pervasive and omnipresent feature of science."

148. See Hirschleifer [231] for a consideration of the current relationship between biology and economics.

149. Schumpeter's [486] review of Marshall's _Principles_ stresses this aspect of his contribution to economics.

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