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TECHNOLOGICAL SHIFT: A GRAPHICAL EXPLORATION OF PROGRESS FUNCTIONS LEARNING COSTS AND THEIR EFFECTS ON TECHNOLOGICAL SUBSTITUTION

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PREFACE

The innovation process, defined here to incorporate the full cycle from invention to full commercialization, is slow. It cannot be encompassed with time horizons of less than 20 years. Many innovations require half a century or more to reach commercial maturity.

Management of the innovation process is critical to the management of technology, but the slowness of the process makes it difficult for conventional economists or policy makers, who typically consider 15 years a long-term forecast or plan, to understand or control.

The situation, in short, is one in which the absence of theoretical understanding limits the effectiveness of manageri-al practice. Accordingly one appropriate niche for applied sys-tems analysis in this case is development, application and testing of theoretical models.

Toward this end the innovation task of IIASA's Management and Technology Area is studying the mechanisms of technological substitution. One phase of this work is being conducted through construction and analysis of a series dynamic simula-tion models, TECH1, TECH2 ...TECH.N.

The present working paper is one of a series describing these models. Its purpose is one of clarification, simplifica-tion and communication. It attempts, by use of static graphi-cal figures, to make the dynamic process described in the models more understandable. It is complementary to working papers by the same author entitled "Technological Shift: A Cybernetic Exploration", a semi-technical description of TECH1, and "Technological Shift: As Related to Technological Learning and Technological Change", a discussion of some theoretical and philosophical aspects of the structure posed in the TECH models.

Later papers in the series will describe TECH2, a variant of TECH restructured to assume a planned economy rather than free market competition, and application of TECH to historically observed technological substitutions.

In the first six months of 1980 the entire series of working papers will be collected into a IIASA Research Report. Various parts of the series are being adapted for separate journal publication. The author welcomes comments, questions, criticisms and suggestions on this or any related work.

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PROGRESS FUNCTIONS AND LEARNING COSTS: A GRAPHICAL EXPLORATION

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INTRODUCTION

The progress functions* of many technological developments have been studied (Yelle, 1979). In general data relating measures of performance--such as cost, factor productivity or speed--to measures of experience--usually cumulative output--yield respectable curves, often with good statistical fits. Indeed, learning phenomena are sufficiently ubiquitous and sufficiently regular that progress functions can be argued to have general law-like validity, and to deserve a place alongside supply curves, demand curves, Engle's curves and other tools of the economist trade. The law-like properties of learning curves have been argued by Sahal (1978, 1979) who in addition to fitting curves to industrial data has developed, using both probabilistic and deterministic reasoning, a general theoretical explanation of the progress function.

Given that engineers, management scientists, and others have proposed a new curve, what can economics do with it? Arrow (1962) has proposed that progress functions can be employed macroeconomically to account for the embarrassingly large portion of productivity growth that Solow (1957), Abramovich (1956) and others found could not be attributed to physically countable factors of production. Roberts (1978) has argued that learning curves could meaningfully be applied to such divergent phenomenon as automobile accident reduction and birth control and longevity, with the added proposal that global modeling might be improved by representing various system constraints as subject to progress functions.

*"Progress function" and "learning curve" are both used in the literature to designate relationships between performance and experience. In this paper progress function will generally be used to avoid the anthropomorphic connotations of the word "learning"

Here it is proposed that progress functions may also be useful in microeconomics. Specifically it is argued that just as demand, supply and Engle curves have been worked together into a theory of the interaction between income change and market behaviors, it may be possible to combine demand, supply and progress into a useful partial theoretical explanation of technological substitution.

In previous papers the author used a dynamic model of competition between product lines to point out that increase of performance with experience can critically affect the dynamics of technological substitution (Robinson 1979a, 1979b). Basically, it was observed that progress creates strong positive feedback loops. Experience leads to efficiency, efficiency leads to expansion of production and thus to further experience. It was further noted that the relative shapes and parameters of the old and new loops determine whether this loop turns out to be a vicious circle (poor efficiency → expansion → no progress → poor efficiency) or a snowball effect (increased efficiency → expansion → progress → increased efficiency). The dynamic picture was wonderfully and mind bogglingly complex. Here we seek simplicity and clarity through detailed investigation of the central static features of the model--relative and absolute progress functions.

The paper proceeds as follows: First a simple construct of technical progress during competition between technological processes is postulated. This leads to graphical observation of the costs incurred in launching the new technology to a level of production efficiency where it can survive in market competition. Second, the construct is used to examine the way the progress functions form affects learning costs. Third, the problem of product (as opposed to production) learning is discussed. Finally, comments are made about the relationship between technological progress and technological innovation.

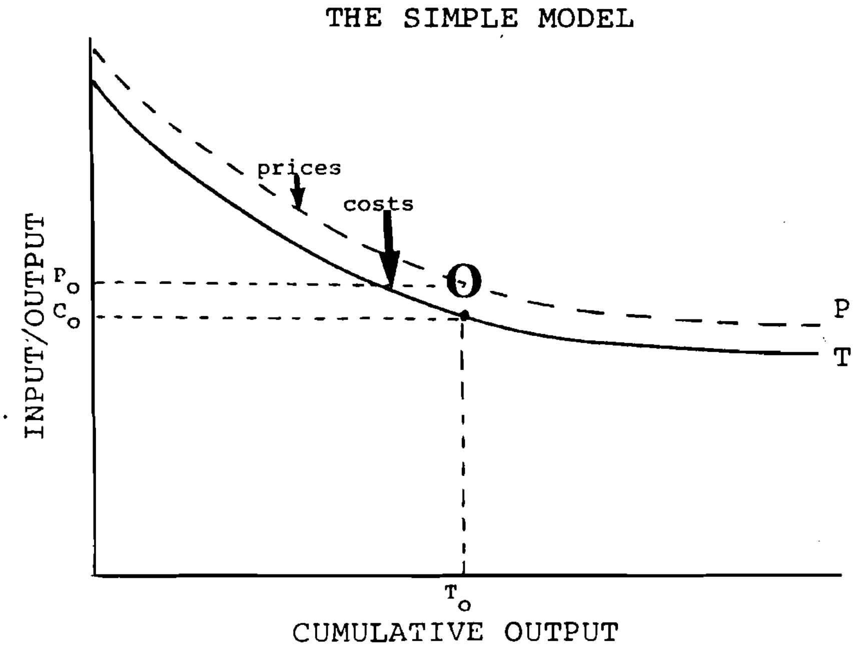

Figure 1. Established technology progress function and price curve. Given cumulative output T_o, technology T will face production cost of C_o and will offer its goods at P_o.

Let us begin with the progress function of an established technology T, putting total factor costs on the y axis and cumulative output on the x axis. For simplicity a simple downward bending curve is used, later more complex forms such as S curves are considered. Presuming prices are some margin above costs we can then draw a price curve P somewhat above the learning curve. Presuming T has a cumulative output of T_o units it will then be at point A along its progress function and have a unit cost of Y_a and a sales price of Y_p.

Let us now add to this figure the progress function of a new technology, T*, and follow what happens as T* accumulates production experience. Let us take the common and interesting case shown in Figure 2 where T* begins production at lower efficiency and higher costs than T, but has the potential to progress to higher efficiency through cumulative experience. Let us presume for the time being that T*'s product is indistinguishable from T's product, and thus that the price received for each technology's product will be the same at any given point in time. We give T* a price curve P*, to represent the prices T* would sell at if it were alone on the market and receiving a profit margin high enough to justify further investment. In T*'s early phases, however, it is clear that it will operate on a market dominated by T and will be forced to sell at a price substantially below P* as established by T's cost position.

In Figure 2 it is apparent that for T* to move down its efficiency curve to where it is cost competitive with T it will have to sell its goods below cost until learning brings its production costs below T's product price. This corresponds to a region such as the blackened region in Figure 2, whose upper bound is established by T*'s learning curve, and whose lower bound is

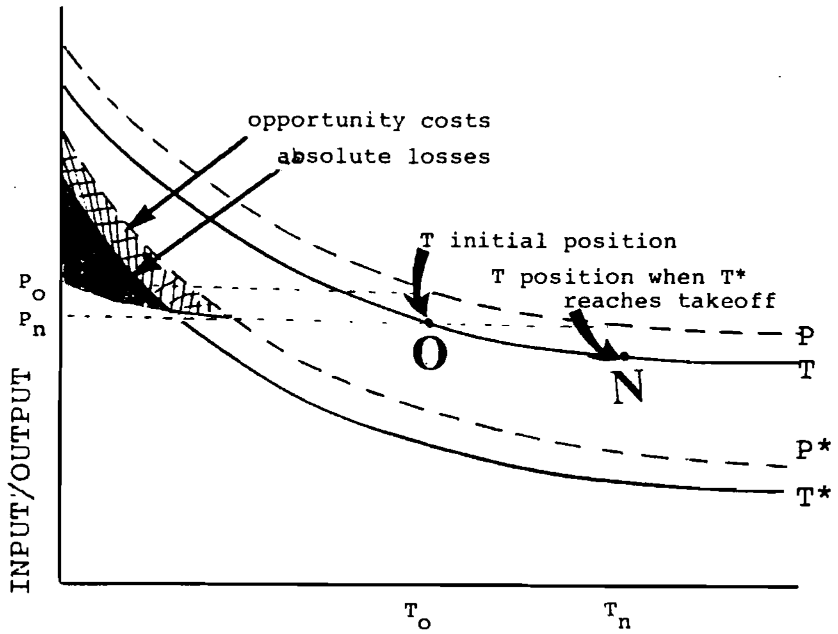

Figure 2. Old and new technology progress functions.

established by T's price trend as mapped onto T*'s progress down its progress function. In addition T* will forego a normal profit margin whose upper bound is established by the new technology price curve P* and whose lower bound follows T's prices. This corresponds to the cross-hatched region in Figure 2.

The entire shaded area, that is, the sum of absolute losses plus foregone profits, we shall term relative learning cost*. As relative learning costs appear in the next seven diagrams, the reader is advised to note the features of the area carefully. In particular it should be noticed that the lower bounds of the learning cost region are determined by T's prices mapped onto T*'s cumulative output--i.e., the price at which T* sells--and that the upper bounds are determined by the curve P*--that is, the prices T* would anticipate if it were not competing with an established technology.

Dynamic Context

Static computations can only show part of this picture. The magnitude of learning costs is highly susceptible to dynamic factors arising from the interaction of supply, demand, price, profitability and investment. As capacity accumulates the rate of output accumulation, and thus of technical progress, also accelerates. This process tends to be slow under high learning cost conditions as T*, when showing large losses, fails to draw investment, and may prevent substitution altogether. If progress continues, however, a turning point is eventually reached.

As shown in Figure 3, when T* reaches the point on its progress function where costs equals price it begins to show a profit, and when it reaches a cumulative output such that its costs

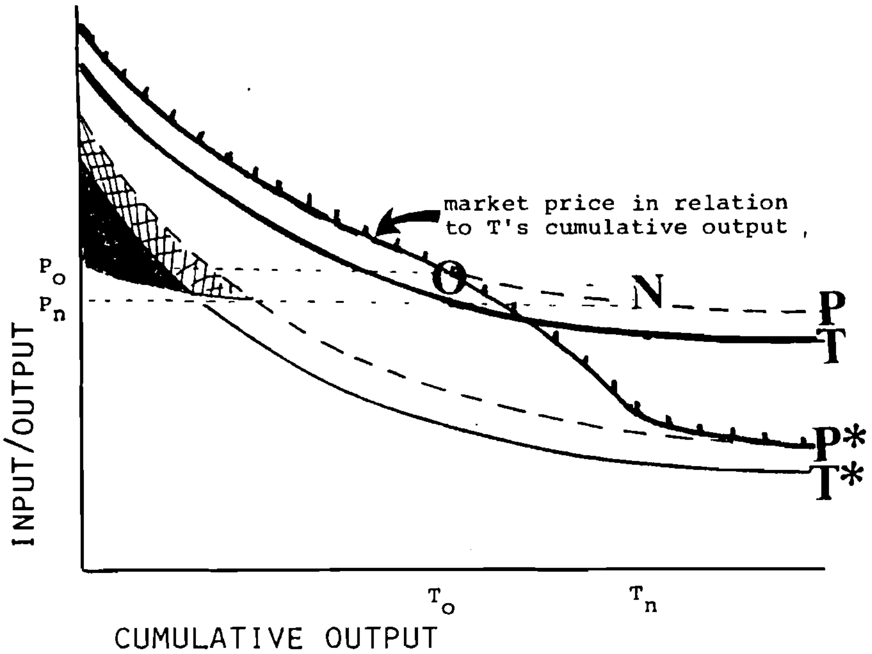

Figure 3. Price behavior in the context of T* and T progress.

In consistent terminology we would have to say progress costs. "Relative" because the area is established for T curves relative to T curves.

drop below those of T, the tables begin to turn. T* becomes the more profitable operation. Consequently, T* is likely to begin rapid capacity expansion, which leads to more rapid output accumulation and more rapid cost decreases. The net effect is apt to increase supply and to drive prices from P to P*. As prices cross T's unit cost, T will begin loosing money and will eventually be forced out of business as T* expands into its markets.

VARIATIONS OF CURVE FORM

The extent to which learning costs impede technological substitution probably depends on the magnitude of the costs in relation to the magnitude of the expected gain. In the above model we can note that learning costs vary greatly with the shape, slope and end points of T and T*'s progress functions. Some of the patterns of this variation can be seen by comparing Figures 4a, 4b and 4c. In each case T* is assumed to enter the market with zero cumulate output while T has a cumulative output of T_o. T is assumed to have progressed to a cumulative output T_n (point N on its progress function) when T* reaches that value of cumulative output, T_n*, which is required for it to equal T*'s efficiency.

Figure 4a shows that a strongly S-shaped curve greatly adds to the new technology's learning cost. Figure 4b shows that if T* is initially close to T's efficiency it may be profitable quite early in its development and face minimal learning costs. Figure 4c shows three things. First, if the old technology sells its product at very near cost (i.e., operates on a highly competitive market) the new technology's losses are greatly increased. This suggests that price cutting can be an effective strategy for an established technology faced with competition by a new technology, or, conversely, that high price margins (as in monopoly conditions) may encourage innovation. Second it shows that if T*'s efficiency potential is not substantially greater than T's, T* learning costs are greatly increased. Third it shows that competing with a technology that has yet significant opportunity for technological advance is a great deal more expensive than competing with a technologically stagnant one.

We also note that all functions involved have high uncertainty. T may make unexpected progress when faced with competition. T*'s growth may flood markets and depress prices below cost or T may drop prices as a competitive strategy. T* itself may progress either more slowly or more rapidly than anticipated. The assumptions of perfect knowledge static price margins and continuous progress function implicit in Figure 2, therefore can be relaxed to lead to a construct such as Figure 5a, in which efficiencies and prices are shown as upper and lower bounds. Here the regions of price uncertainty, which carry over to set the learning cost, are shaded. Figure 5b--the learning cost mapping of Figure 5b--shows the potential variation of learning costs resulting from extreme cases. Examination of the figure reveals that delayed start and lesser efficiency gain coulg greatly increase T*'s learning costs, while unanticipated large efficiency gains and severe price cutting by T have the potential to prolong T*'s region of learning costs indefinitely.

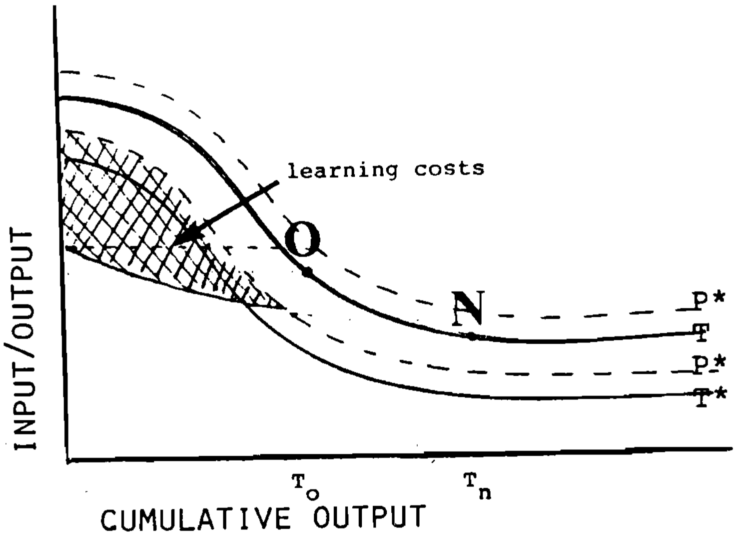

Figure 4a.

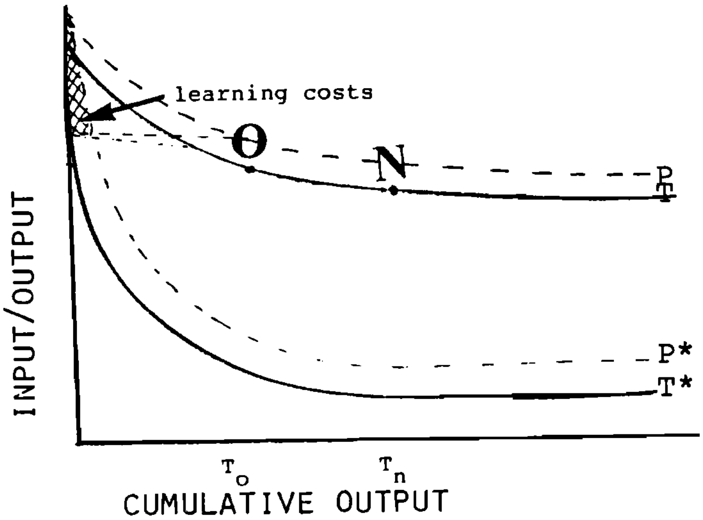

Figure 4b.

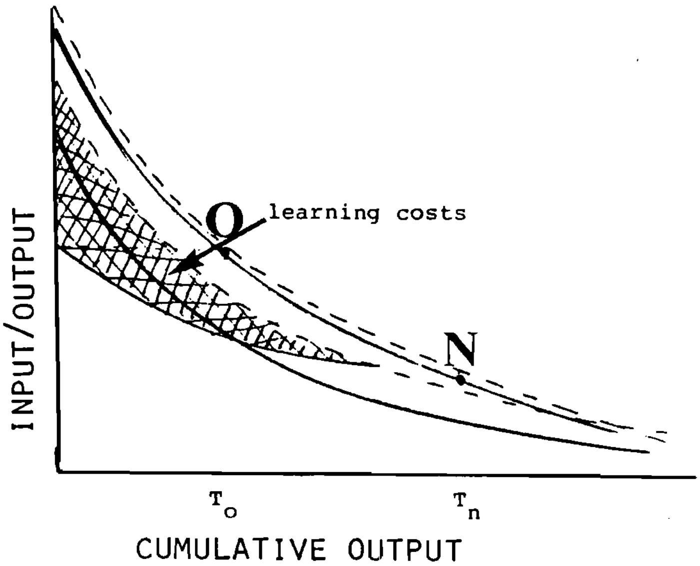

Figure 4c.

Figures 4a, 4b and 4c. Variations in relative progress functions greatly incluence learning costs.

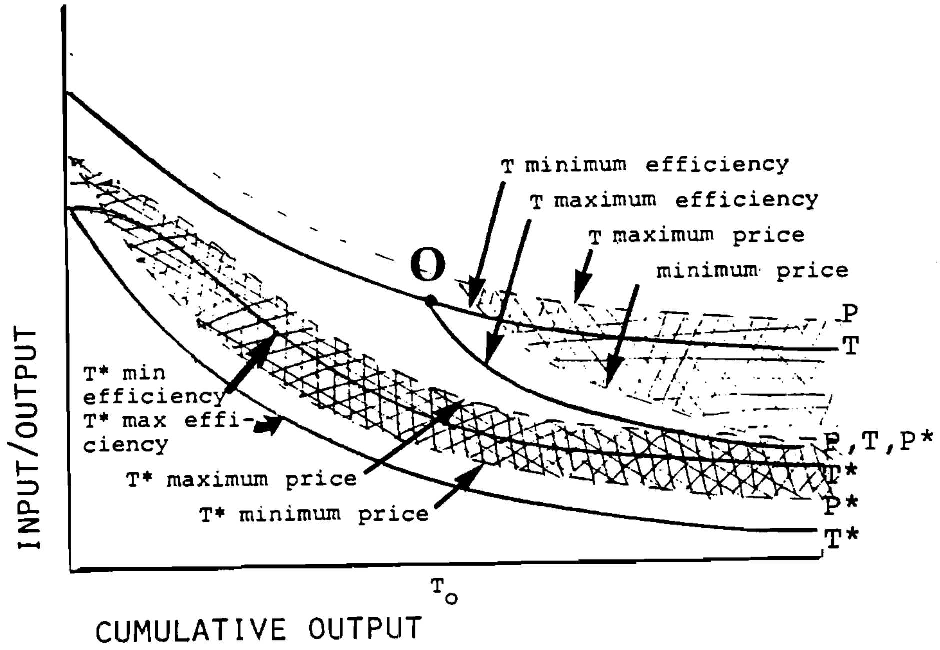

Figure 5a. Uncertainties in progress functions and price.

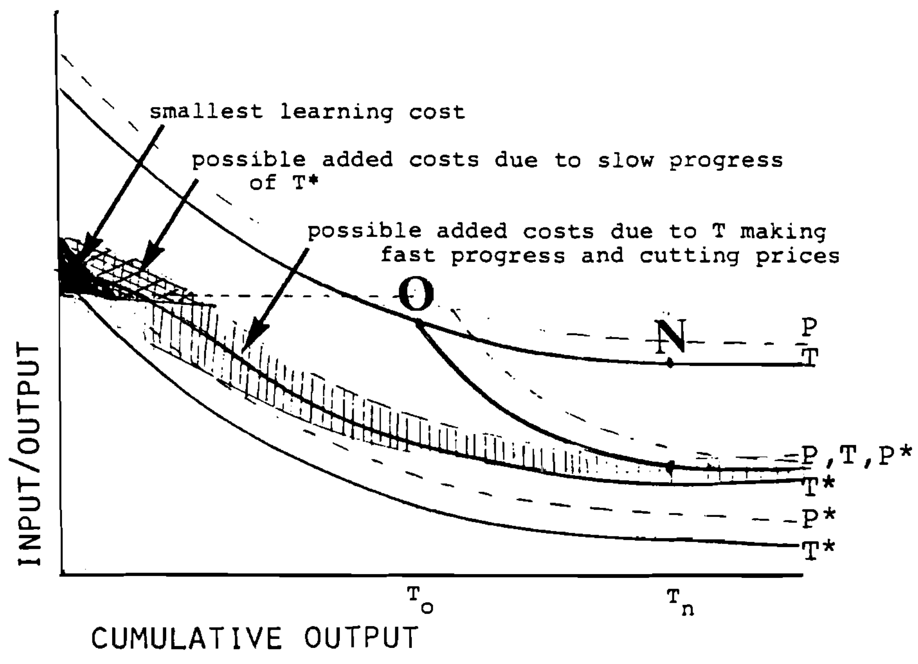

Figure 5b. Uncertainties in learning costs.

PROGRESS WITH PRODUCT MARKETABILITY

Pure efficiency competition is relatively uncommon. For the most part process innovation is accompanied by product innovation. This results, typically, in T*'s output selling at a different price than T's output. In times of rising income market conditions often support innovations with higher production costs that sell at higher market prices. For example, color television will probably always face higher production costs than black and white. Because consumers are willing to pay for the increase in product quality, prices for color TV are not forced down to the level of those for black and white, and black and white prices cannot increase to the level of color.

Attractiveness factors, in that they introduce the possibility of different prices for T and T*--greatly complicate the model. Let us start with the case shown in Figure 6 in which T* always faces higher costs than T (and therefore has a progress function that is at all points higher than T) but is consistently preferred by customers. The price at which T*'s product sells is in all cases higher than T's price, and (barring an extremely efficient monopoly) will not in the long term be more than a reasonable margin above T*'s costs. However, if T* cannot expand supply to keep up with demand--as may be the case of a technology with high entry costs and/or long construction times--it may maintain prices at an immoderate margin above costs for at least a few years. In this case the price at which T* sells its product may exceed P* and may for any value of T*'s cumulative output be anywhere within the bounds of the shaded region above that cumulative output. For example, when T* has a cumulative output of Q it may sell at a price anywhere between P^*_Q max and P^*_Q min.

The location of price within this region will depend on the dynamics of supply and demand for T*'s output as described previously.

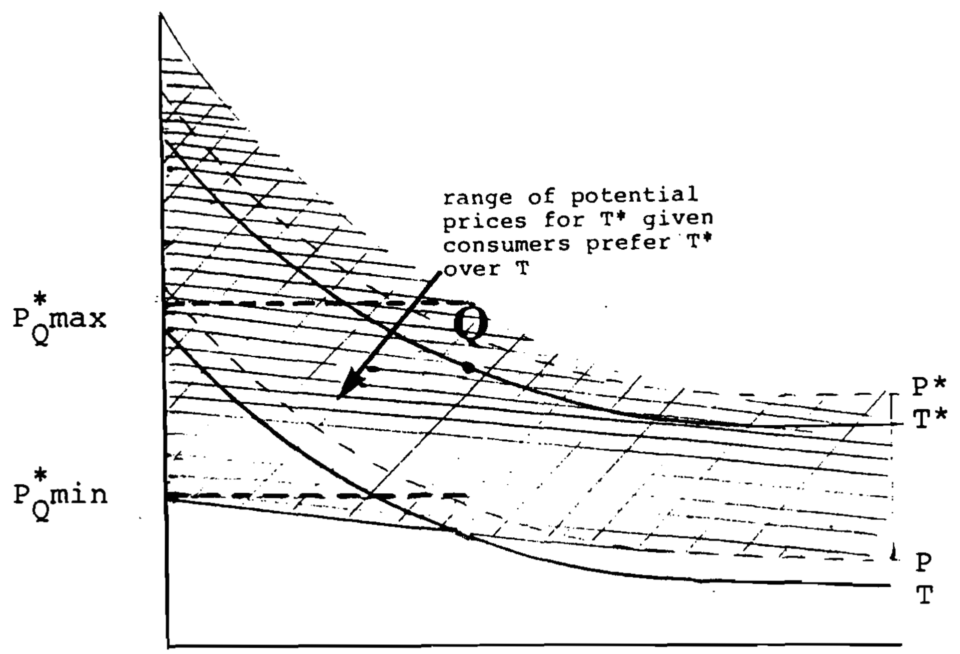

Figure 6. Product innovation where consumers prefer T*.

Marketing Progress

We can postulate that for non-commodities product attractiveness like production efficiency is often subject to a progress function. For example, consumer utility of cars, radios, electricity, television and telephones increased greatly as the product and the support infrastructure for these technologies expanded and improved. Computers are following a similar pattern. Also, in many cases consumers learn to accept a product--even if product quality and infrastructure remain constant there seems to be a tendency for an innovation's appeal to increase as "the word gets around" as values change and prejudices are overcome.

Let us for convenience define increased product attractiveness as an increase in the amount consumders are willing to pay, ceterus paribus, for one unit of product. Under this definition, technological progress will lead to a curve such as A in Figure 7. Superimposed on the production efficiency progress function E, A reveals a new sort of learning cost--which we shall call absolute learning cost (to indicate that we visualize it for a single technology, irrespective of competition).

The magnitude of absolute learning cost signifies the costs imposed on an innovation because it starts out with high costs and weak marketing features. It will vary greatly in size with the shapes of the production efficiency and attractiveness progress functions just as relative learning costs were shown to vary in Figures 4a, 4b and 4c. For some technologies it may be zero.

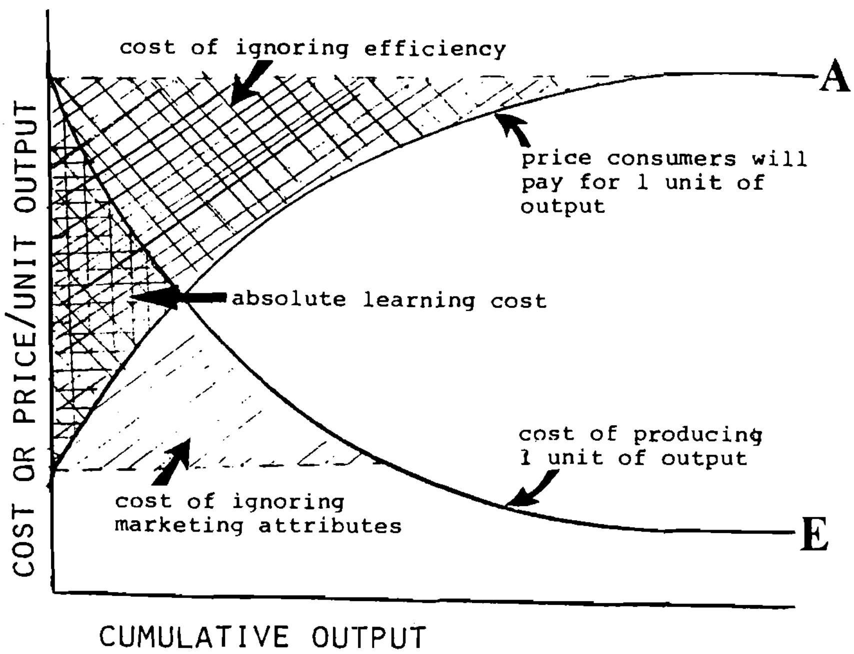

Figure 7. Absolute learning costs as derived from the combination of product and process progress functions.

It can also be seen from Figure 7 that absolute learning costs are greatly increased if a new technology fails either to increase efficiency or to improve marketing attributes while failure in both dimensions leads to infinite costs. It may be inferred from this diagram that a nation that balances its technical progress between production efficiency improvements and marketing efficiency improvements will have lower learning costs, and thus probably more rapid overall rates of innovation than one that focuses entirely on either production or marketing.

SUMMARY AND CONCLUSIONS

In the preceding text a series of theoretical propositions were set forth and deductions drawn from them. By way of conclusion these propositions and deductions are reviewed and comment made about their potential theoretical and practical contributions.

Initially, it was asserted using graphical representation that learning costs related to production efficiency can be approximated ceterus paribus, from the respective progress functions of an old and a new technology, plus knowledge of the old technology's states of technical progress at the point at which the new technology enters the market and the point at which it equals the old technology's production efficiency. From this assertion it was shown graphically: (1) that learning costs will vary greatly for different relative forms and magnitudes of old and new technology progress functions; and (2) that uncertainty concerning prices and future rates of progress will tend to make learning costs very uncertain.

Later attention turned to market related factors. First it was noted that prices, rates of progress, profitability and capacity accumulation are dynamically linked and that their dynamic interaction can greatly affect learning costs. Second, it was observed: (a) that process innovation and product innovation often occur together and that product innovation often resulted in competing technologies selling at different prices and, (b) that such differentials in marketability could greatly alter learning costs. This led to the proposition that marketability may also be subject to a progress function and to the deduction that products with low initial attractiveness and low initial production efficiency may face absolute learning costs due to their own initial constitutions on top of the relative learning costs imposed on them by competitive necessity.

How are these propositions useful? It is too early to tell. A model's value is best gauged by its power to explain observed facts and to predict and permit control of future events. The model posed above has not been empirically tested. It remains to be seen whether data can be assembled to estimate learning costs for specific technological innovations*. If it can, it remains

*The task of empirical testing will require widespread search through old trade journals, corporate records, engineering texts, and other specialized materials and is not feasible at IIASA.

to be seen whether the costs calculated will be useful in explaining differing rates of technological substitution or will lead insight into how better to manage innovations.

I anticipate that attempts to test will show the following:

1. Data are poor, however the differences between the progress function configurations for various technological substitutions are so great that even crude estimates will be informative.

2. Innovations confronted with extraordinarily high learning costs have succeeded only by virtue of special circumstances such as war (computers, radar), highly specialized markets or the occurrence of a complementary technological substitution that reduced learning costs.

3. The importance of progress in product marketability has generally been underestimated. The initial success of the mechanized textile industry, of steel ground flour, and of many other basic substitutions of the Industrial Revolution was as much a consequence of consumer preference for the new products as of added production efficiency through economies of scale and division of labor.*

I expect that such findings particularly as worked into a dynamic model may have practical and theoretical utility in:

1. Leading to improved understanding of the magnitude and nature of the obstacles confronting various technological substitutions that are going more slowly than society would like, thereby leading to wiser policy decisions on how to expedite technological substitutions.

2. Leading toward an organized and balanced perspective on process (efficiency) innovation and product (marketability) innovation, thus toward improved balancing of research and development activities between product design, production engineering and marketing activities. In the

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*The importance of marketability stands out to adoption of high technology production methods in case studies on choice of technique in flour grinding and block making in Kenya (Stewart 1978). In the flour grinding case, steel ground flour proved non-competitive with water grinding and use of hammer mills--except that the market supported prices for the steel ground product that were 60% above those for the alternative methods, and that market conditions permitted capacity utilization for the steel ground product that was three or more times higher than for the other techniques considered. Field studies on choice of technique may be a good source of material for testing the learning cost concept.

process, the model might upgrade the debate over market pull versus technological push by providing a framework in which to examine how the two interact.

3. Providing insight into pricing strategies for new products in non-market economies.

4. Focusing attention on critical factors, such as initial and potential efficiencies and marketabilities and retardations of progress that greatly increase costs, thereby redirecting data collection and analytical investigation into more fruitful channels.

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