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Technological Change and Factor Mix over the Product Cycle: A Model of Dynamic Comparative Advantage

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ECONOMIC GROWTH CENTER

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Center Discussion Paper No. 186

TECHNOLOGICAL CHANGE AND FACTOR MIX OVER THE PRODUCT

CYCLE: A MODEL OF DYNAMIC COMPARATIVE ADVANTAGE

by

Richard R. Nelson

and

Victor D. Norman

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TECHNOLOGICAL CHANGE AND FACTOR MIX OVER THE PRODUCT

CYCLE: A MODEL OF DYNAMIC COMPARATIVE ADVANTAGE

Richard R. Nelson

Victor D. Norman

Introduction

Over the past decades, international trade economists have attempted to disentangle theoretical and empirical issues related to the celebrated Leontief paradox. By now, much of the paradox has been stripped from Leontief's empirical findings. We have begun to realize that the problem was in the way we looked at comparative advantage, having both a too static and a too gross perspective. We are now far more comfortable about interpreting phenomena at any moment as temporary points generated by a moving dynamic system, thus seeing that U.S. export patterns often reflect a transient comparative advantage in new technologies. At the same time, we can see more clearly the great diversity underneath conventional factor aggregates, thereby realizing that many U.S. exports are "education" intensive. Of course, the two explanations of the now not so paradoxical facts are not independent--it is well recognized that highly educated manpower and technological advance are associated.

At the same time that international trade economists have been establishing these correlations, studies of technological change have improved our understanding of the processes involved. We now know, for example, that technological advance often occurs in the form of periodic major advances followed by a stream of product and process improvements--

usually at a diminishing rate--again followed by a major new innovation. It is this "cyclical" pattern of technological change that appears to lead to product cycles in trade. It is therefore illuminating to consider what is going on technologically over such a cycle.

Part of what is going on is product design evolution. As Miller and Sawers tell the story, the original DC 3--the result of the confluence of a number of R & D strands--represented a radically new civil aircraft package: All metal skin, low wing, streamlining including engine configuration, more powerful engines. Over the subsequent decade, the basic design was improved in a variety of models, designed by other manufacturers as well as by Douglas. The successive generations of planes were faster, had longer range, and were more comfortable. The original basic design was stretched to achieve additional performance, and differentiated to meet a variety of different demands and conditions. The DC 4 represented the start of a series of four engine versions. By the mid 1950's, the potentialities of this design concept appear to have been largely exploited. The advent of the 707 and DC 8 represented the start of another technological product cycle within the civil aircraft industry. John Enos has reported on a similar pattern in petroleum refining technology: Again, technical change was marked by periodic introduction of major new technologies (the batch thermol process in 1931, catalytic cracking in 1936, etc.) followed by a wave of improvements. The flow of follow-on improvements in petroleum refining appears to have been even more important than in aviation. Enos reports that in many cases the first versions of the new technology tended to be only marginal superior to the most recent versions of the older

technology, and sometimes not superior at all. The advantages of the new were achieved largely through the wave of improvements that were possible on the new design, compared with the harder sledding to find further major improvements in the old one.

As the product evolves, so do the processes of production. Hirsch, in one of the earliest but still among the most illuminating of the studies of "learning curves", pointed out three different kinds of mechanisms at work: Workers are learning to do their jobs better, management is learning how to organize more effectively, and engineers are redesigning the product to make the job easier and to replace labour where it is possible and economic to do. Hirsch (in his study of machinery) and Asher (for aircraft) have noted that different kinds of costs are affected differently over the learning process. In particular, unit labour costs tend to be reduced dramatically, unit materials costs are reduced to a lesser degree, and unit capital costs may rise. This corresponds closely to what Enos observed as happening during the design improvement process for petroleum refining equipment. We might also remark here that the detailed studies of the "learning process" do not treat learning as somehow an inevitable and un-influencible consequence of doing. Rather, learning is viewed more actively, and it is apparent that resources can be applied to learning.

The key role of well educated manpower is apparent in the early stages of the product cycle. There are scientists and engineers involved in the R & D processes which lead to the major innovations which generate the cycle. Highly trained technical personnel continue to be involved in R & D in the successive rounds of design improvements, in process redesign, and in equipment design--and then not just in R & D, but on the production

line in the early stages of a new product or process. At the outset of a new technology technically trained people may be needed simply to produce the product to minimal quality standards: Because experience is so limited, there is no known and easily taught set of procedures for coping with events that can not be fully foreseen. For the same reason operations cannot be mechanized. For example, in the early days of transistor production no one knew exactly what conditions were necessary or sufficient to produce satisfactory crystals. However, a well trained chemist or physicist could--by examining the last batch and the difficulties involved there--make a shrewd guess as to what changes should be made.

It is also apparent that the relative importance of highly educated labour tends to decline as the technology advances. In the absence of a breakthrough into a new technological regime, the returns to design improvement R & D tend to diminish. Process improvements became harder to achieve, and returns to further R & D fall there too as the technology is better understood. Gradually, procedures can be developed, articulated, and built into training manuals and machines.

The above characterization enables us to understand some of the "why's" behind the correlations observed by international trade economists. However, while the description of what is going on is rich, it is discursive. It would seem worthwhile to try to abstract somewhat from the richness, build some simple models, and see what can be learned from them. There obviously are a variety of different kinds of models which can be built. It is apparent, however, that if the description above is basically accepted, the models must depart from traditional ones in certain respects. In particular, the models must be explicitly dynamic, and oriented around certain kinds of learning phenomena which are related to the educational

composition of the labour force.

In the remainder of this paper we develop such a model and put it through its paces. While unorthodox in the sense mentioned above, the model does preserve such orthodox notions as profit maximization, competitive equilibrium, and a common choice set available to all producers in all countries (who, however, do face different sets of factor prices). In the final section of the paper, we discuss whether this half way house is sufficient, or whether perhaps more radical departures in theorizing are required to deal with "Schumpeterian" competition on an international scale. The appendix develops formal proofs of some of the propositions developed in the paper.

Technical change and skill requirements over the product cycle

In this section we shall consider a simple model of what happens to productivity and factor mix over the course of a product cycle, assuming a given and constant set of factor prices facing all firms. In effect we are treating the process as it occurs within a particular single country. In the following section we shall look across countries possessing different sets of factor prices.

We conceive of a product cycle as a sequence of product and process innovations following on the advent of a major innovation which establishes a basic new product line. Examples of products experiencing such a cycle include DC3-like aircraft, subsonic jet passenger aircraft, equipment for catalytic cracking of petroleum, black and white TV, major new kinds of transistor or other electronic devices, new pharmaceuticals, etc. We make a number of assumptions about the nature of a stylized product cycle, some to capture salient aspect of the empirical reality discussed above, some

for analytic convenience.

The first major assumption is that technical change proceeds at a declining rate over the product cycle, as the product is perfected and the processes worked out and simplified. The declining rate here can be interpreted either as decreasing frequency of innovations of a given importance, or decreasing importance of innovations of constant frequency, or some combination of these. What interpretation is chosen is irrelevant for the analysis. A commitment must, however, be made to the meaning of "importance": For analytic convenience we shall assume that all innovations are process innovations. This permits us to measure the magnitude of an innovation in terms of its cost saving. Sometimes one can treat a product innovation as equivalent to a cost saving process innovation --a necessary condition being that the improved product and the old one are perfect substitutes. This, in effect, enables one to translate a new product into "more" of an old product, or into less cost per given "effective" unit of the product. In the absence of this kind of an assumption, the old version of the product and the new version can coexist (in different relative quantities) over a range of relative prices, and the concept of a single product dissolves. Thus, something like the assumption that all innovations are equivalent to more product per unit cost seems necessary if one is to build a model with only a single product market.

All new innovations are assumed to be embodied in particular capital goods. In order to produce an improved product, or employ an improved process, we must replace the old machine with a new machine designed for that particular improvement. Undoubtedly, the full blown embodiment assumption here is unduly strong (not admitting that often old machines can

be modified relatively simply to take the new product or new process), but it is useful in generating some plausible conclusions. We further shall assume, also for analytical convenience, that all innovations are neutral in the sense of Hicks.

For any particular vintage of the product or process, we shall assume that there are ex ante possibilities for substitution among the three factors of production that we shall consider--machinery, unskilled labour, and skilled labour--but fixed proportions once a machine has been installed. Thus, we assume a putty-clay technology of the Salter Johansen-Solow type. We shall begin by assuming fixed proportions between capital and unskilled labour, even ex ante, so that the analysis initially can be undertaken in terms of only two factors of production. Later that assumption will be relaxed.

The heart of the model is its treatment of the role of educated and skilled labour. Our formulation is meant to capture two aspects. We assume that both the R & D undertaken by a firm, and the level of skills employed in production, operate in the form of ex-ante learning, learning that can substitute for actual operating experience with a particular technology. We assume that when a new machine--incorporating a product or process improvement--is put into place, the details of efficient operation are not fully known, but must be learned over time. However, high skills employed by the firm, either in the form of R & D scientists, engineers on the production line, or skilled workers generally, enable operation initially at a higher level of efficiency than if the firm did not employ these skills. As experience with a vintage accumulates, the initial advantage of skilled labour dissolves.

With these assumptions we can write the production function as follows:

$$(1) \quad Q(t,v) = A(v)F [k(v), N(v),S(v),t]$$

where

$Q(t,v)$ - rate of output from machines of vintage v after t years of experience with those machines

$K(v)$ - machines of vintage v

$N(v)$ - unskilled labour used with machines of vintage v

$S(v)$ - skilled labour involved either in R & D or operation with machines of vintage v

Let $n(v)$ and $s(v)$ denote the unskilled and skilled labour/capital ratios, and $q(t,v)$ the rate of output per unit of capital. Then, under assumptions of constant returns, the production function can be restated as

$$(2) \quad q(t,v) = A(v)f[s(v),n(v),t]$$

The key characteristic of the present analysis which differentiates it from more conventional production function formulations is, of course, the treatment of $S(v)$. Skills are assumed to have their effect through bringing to the job ex ante learning which reduces the gap between actual and potential productivity at the early stages of a new production process. This is shown in figure 1: Productivity on a particular vintage increases both with skill level and experience. However, the advantage of high skill levels over low decreases with experience. More formally:

$$(3) \quad \begin{array}{ll} \frac{\partial f(s,n,t)}{\partial s} > 0 & \frac{\partial^2 f}{\partial s^2} < 0 \\ \frac{\partial f(s,n,t)}{\partial t} > 0 & \frac{\partial^2 f}{\partial t^2} < 0 \\ & \frac{\partial^2 f}{\partial s \partial t} < 0 \end{array}$$

Other aspects of the production function are conventional.

With $n(v)$ initially assumed to be technologically fixed (later that assumption will be opened) the decision variables for a producer, assuming he wants to run a vintage at all, are the skill level $s(v)$, and the length of time technology v will be used, call this $t^\#$. (Given our constant returns to scale and "competition" assumptions the overall level of use is indeterminate for the firm but not the industry). With this model, the product cycle is characterized by a decline rate of technical progress. Letting $\lambda(v)$ denote the rate of technical progress, we have

$$(4) \quad \lambda(v) = [A'(v)/A(v)] \quad \text{with } \lambda'(v) < 0$$

the central question under analysis is--how does optimal skill mix and vintage length vary over the product cycle?

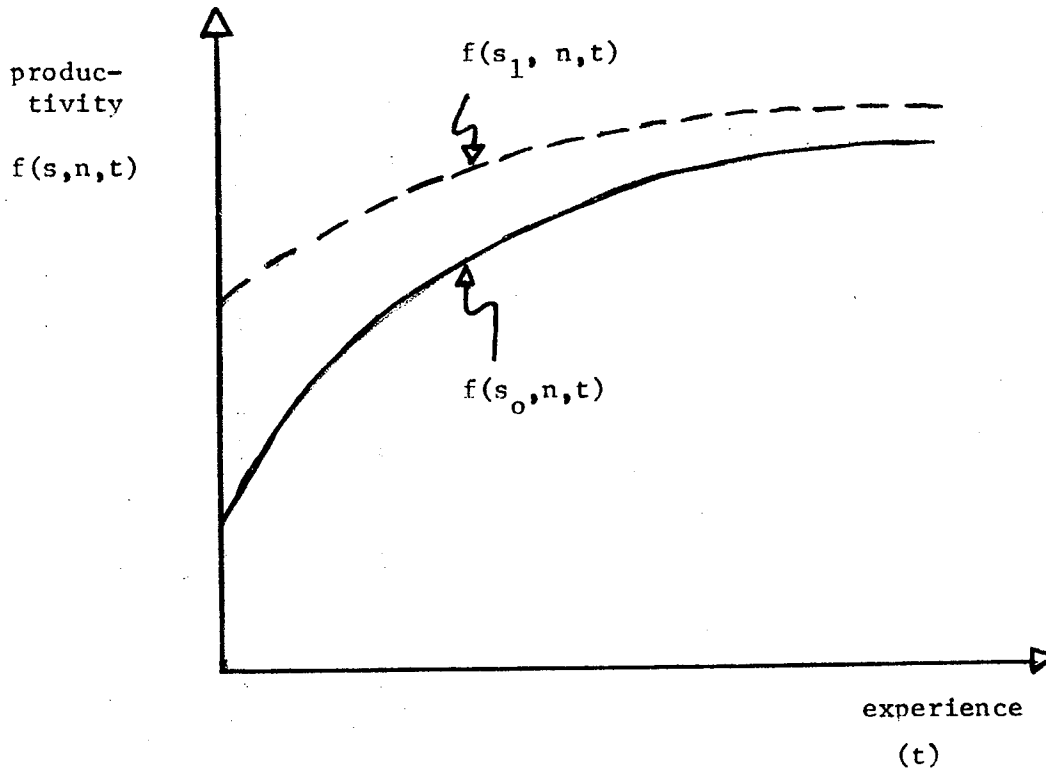
In this section we are considering firms in a competitive industry in a single country, postponing the discussion of an international equilibrium to the next section. We therefore assume that factor prices are the same for all firms in the industry, and take it that all firms are quasi rent maximizing price takers. Factor prices are determined outside the model, while product prices are determined within the model.

Quasi-rents are defined as the value of production less variable costs. At time $T = v+t$:

$$(5) \quad \pi(t,v) = P(T)q(t,v) - us(v) - wn$$

where $\pi(t,v)$ stands for quasi-rents from operating a machine of vintage v after t periods of use, $P(T)$ is the product price at time $T=v+t$, and u and w are the prices of skilled and unskilled labour.

In order to make the optimal decision as to factor intensity and length of use of vintage v technology, the vintage. We assume constant



(Figure 1)

factor prices, in which case the product price must decline over the cycle. If the conditions of competitive equilibrium, with free entry, are met, the rate of price decline will be approximately equal to the rate of technical progress. (We shall qualify this assumption later.) For vintage lives that are short relative to the overall product cycle, technical progress can be taken to be approximately constant over the life of a particular innovation within the longer product cycle.

The present value of quasi-rents of a machine of vintage v run until $T = vt'$ will then be

$$(6) \quad V = \int_0^{t'} [P(v)e^{-\lambda t} A(v)f(s(v), n, t) - us(v) - wn]e^{-rt} dt$$

The profit-maximizing firm will choose the scrapping age of machinery (t') and the skill intensity (s) so as to maximize this expression.

Repressing the vintage notation, the first-order conditions for a maximum are

$$(7) \quad \frac{\partial V}{\partial t'} = [Pe^{-\lambda t'} A f(s, n, t') - us - wn] = 0$$

$$(8) \quad \frac{\partial V}{\partial s} = \int_0^{t'} [Pe^{-\lambda t} A \frac{\partial f(s, n, t)}{\partial s} - u]e^{-rt} dt = 0$$

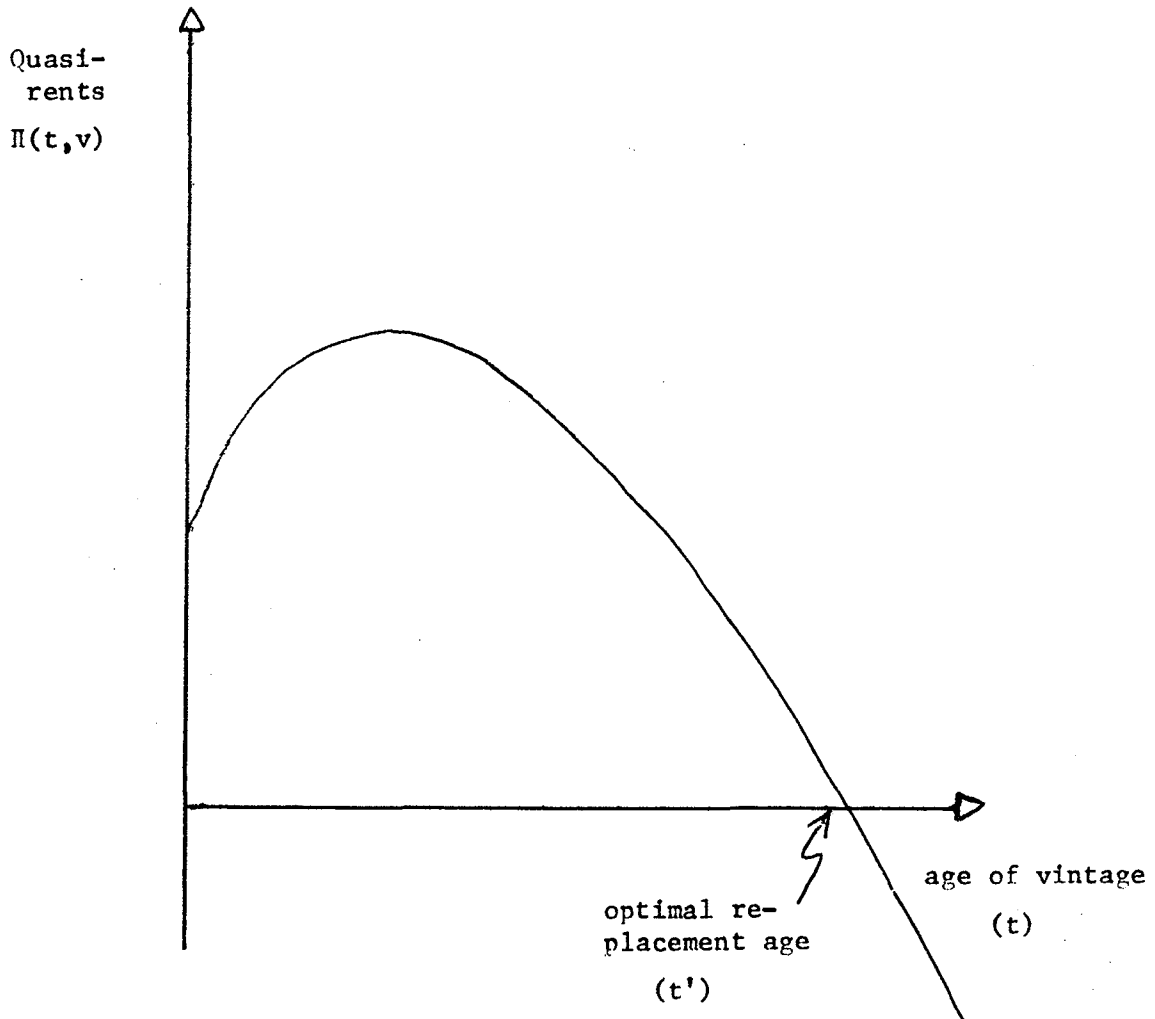
If the industry is in a competitive equilibrium, then (with free entry and constant returns) there must be equality between the maximal value of discounted quasi-rents and the cost of capital. Thus,

$$(9) \quad \hat{V} = c$$

where \hat{V} is the maximal value of V , and c is the unit cost of capital goods. The competitive equilibrium condition (9), together with the optimality conditions (7) and (8), enable us to study how the skill intensity and economic life of innovations change over the product cycle.

To see this, let us consider the economic meaning of the first-order conditions and the competitive equilibrium condition. Condition (7) says that, for a given skill intensity (or more generally, for given factor inputs), a machine should be retained until its quasi-rents vanish. Observe that as a machine grows older, its quasi-rents decline at the rate of technical progress, minus the rate of learning. The time profile of quasi-rents, for any given set of factor inputs, will therefore look as shown in figure 2 (where it has been assumed that the initial rate of learning exceeds the rate of technical progress). For profit maximization, the machine should be retained until time $T' = v + t'$ when the flow of quasi-rents drops to zero.

Next, consider the optimal skill level equation (8). An increase in the skill intensity will increase gross revenue over the period of machine life. However, since skill-intensive operations substitute ex ante learning for on the job learning, the increase will be greater early in the life of a machine than later, so an increase in skill intensity will shift the gross revenue profile as shown in figure 3. Condition (8) says that, for a given economic life of machines, skill intensity should be increased until the average (discounted) increase in gross revenue over the life of the machine from the hiring of an extra skilled worker equals the wage rate of skilled workers.



(Figure 2.)

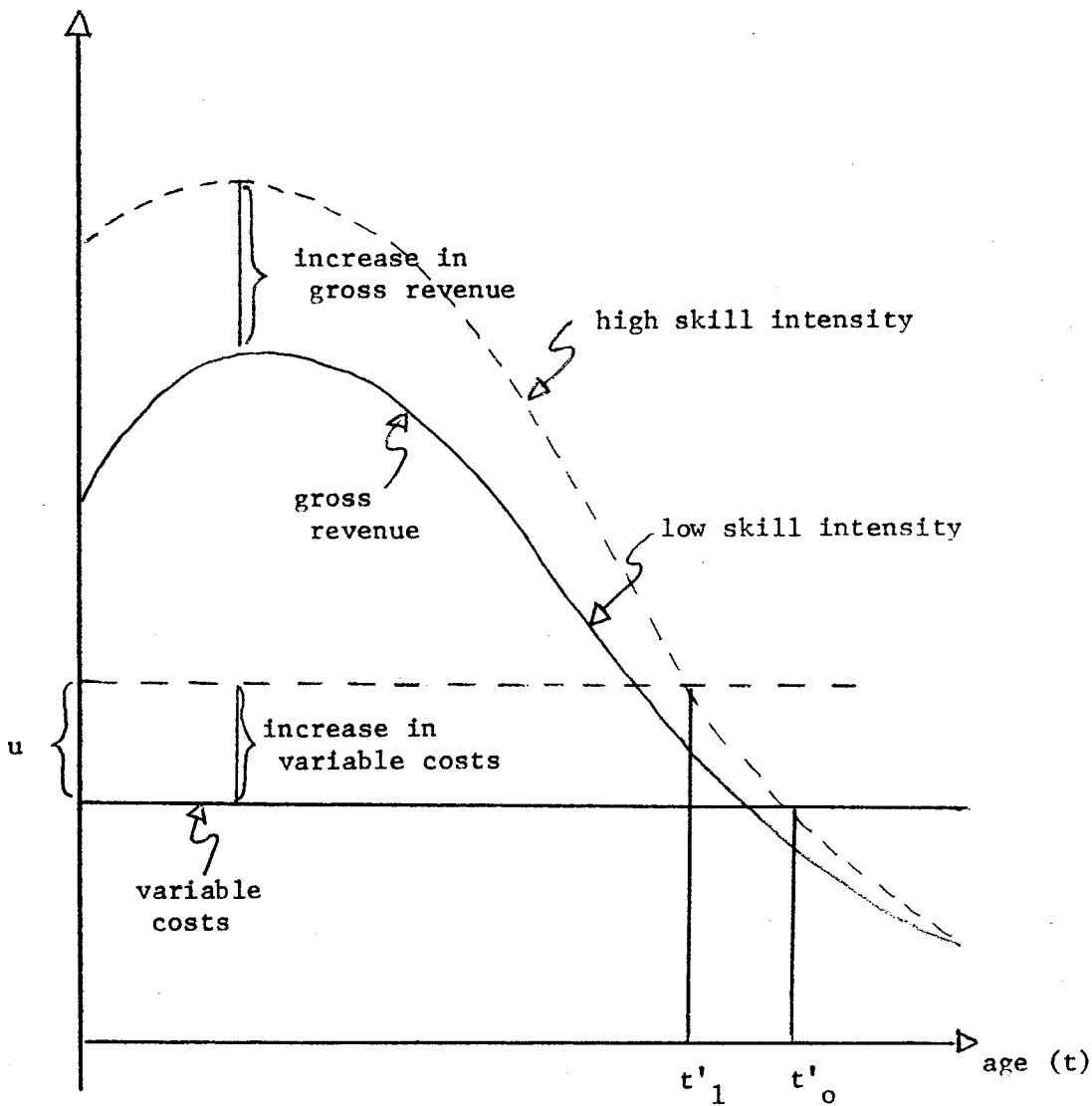


Figure 3: Impact of skill-intensity on the optimal scrapping age

Simultaneously, these equations determine the optimal skill intensity and scrapping age of machines. As shown in figure 3, near the optimum, an increase in skill intensity will reduce quasi-rents for high machine age (and increase them for low machine age), and thus reduce the optimal scrapping age of machines. Thus, the optimal scrapping condition (7) defines a negative relationship between skill intensity and economic life (in the neighbourhood of the optimum). The condition for optimal skill intensity also defines a negative relationship between skill intensity and economic life of innovations: Suppose we found the optimal skill intensity for an arbitrary economic life of machinery. Now consider a somewhat greater scrapping age. The average (over the life of the machine) marginal value product of skilled workers will then be smaller, calling for a reduction in skill intensity.

Thus, the two conditions define relationships between skill intensity and economic life of machinery as indicated by the curves $a-a'$ and $b-b'$ in figure 4. (The second-order condition for a regular maximum assures that the slope of the $a-a'$ curve is smaller than the slope of the $b-b'$ curve.) The overall optimum requires the simultaneous solution of both equations, and is thus given by the intersection of the two curves. The competitive equilibrium condition then requires a time path of prices such that, at optimal input combinations, the net present value of quasi-rents will equal the unit cost of capital goods. Thus the optimization conditions and the competitive equilibrium condition determine the factor ratio, vintage life, and price history over the product cycle. The product demand curve then determines the time path of output (and total inputs).

The key question in which we are interested is what happens to skill intensity and economic life of machinery over the product cycle. As the cycle is characterized by a falling rate of new innovations, this is equivalent to asking what happens if (when) the rate of technical progress declines.

To answer this question, let us first suppose the skill intensity is fixed, and see what happens to the scrapping age (to the a-a' curve in figure 4). The ceteris paribus effect of a lower rate of technical progress will be a shift in the quasi-rent profile: For a given initial price level, P , when the new equipment is first adopted, a more slowly falling price means that the quasi-rent profile will shift upwards, from $c_0 - c'_0$ to $c_0 - c'_1$ in figure 5. However, with a constant cost of capital, this would mean that quasi-rents would exceed capital costs. By our assumption about the competitive structure of the industry (reflected in equation (9)) this would induce more investment, and output, and lower price. This lower initial price must be just sufficient to make the net present value of quasi-rents equal to the cost of capital goods. Thus, a slower pace of technical progress means that the quasi-rent profile will take on the shape $c_2 - c'_2$ as compared with the shape $c_0 - c'_0$ at a faster rate of technical progress. (The reader may note that the implication is that - if the rate of technical change is declining - the rate of price decline will be greater than the rate of technical change). The two time profiles must have the same discounted present value. It is then obvious that the effect of a shift from $c_0 - c'_0$ to $c_2 - c'_2$ will be to increase the optimal economic life of machines for a given skill intensity. Thus a decrease in the rate of technical progress will shift the a-a' curve upwards.

Consider next what happens over the product cycle to the b-b' schedule

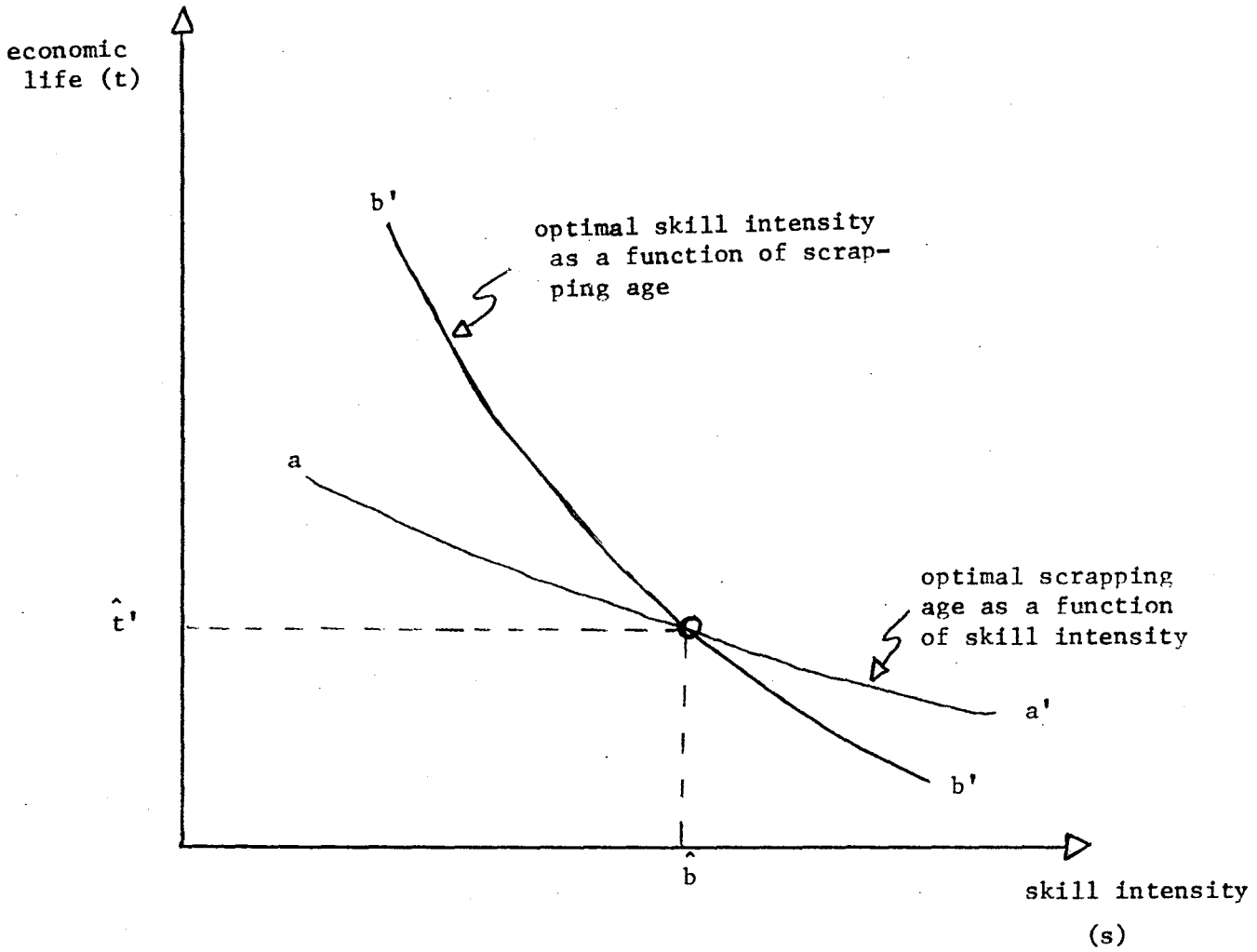


Figure 4: Simultaneous determination of skill intensity and economic life

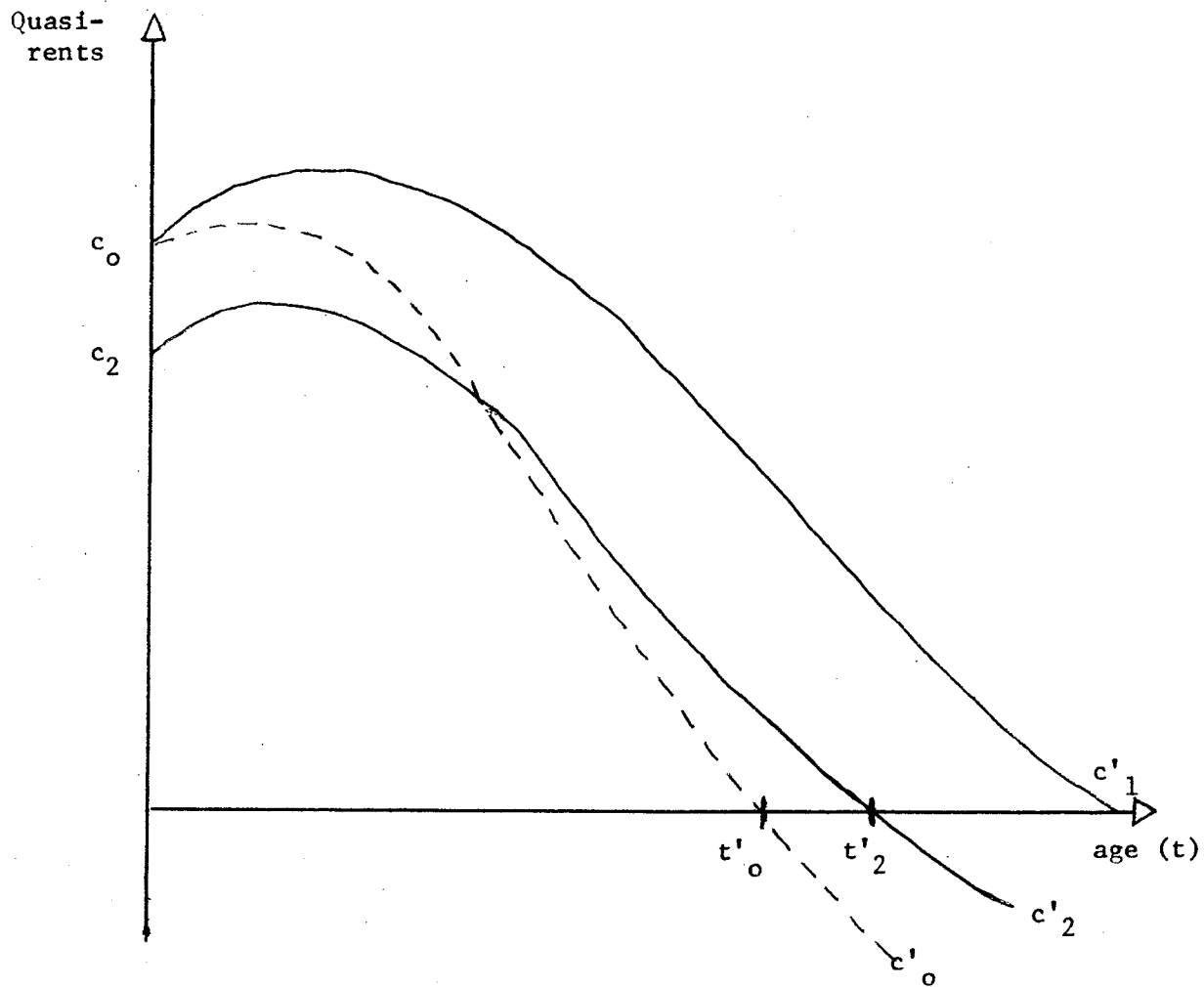


Figure 5

which defines the optimal skill intensity for a given economic life of machinery. Recall that optimal skill intensity is determined by comparing the "average" marginal value product of an extra unit of skilled labour, over the lifetime of machinery, with the skilled worker wage rate. The marginal value product, at any time, is price time marginal productivity. We have seen that the effect of a lower rate of technical progress is to decrease price for low machine ages, and increase it for high machine ages, compared to the equilibrium time profile if the pace of technical progress were faster. But since the marginal physical productivity of higher skills is larger when a machine is still young and low when the machine is old, the average marginal value product of skilled labour must decrease when the rate of technical progress decreases. Thus, for a given economic life of machines, a lower rate of innovation implies a lower optimal skill intensity. Thus the $b-b'$ schedule shifts downwards over the product cycle.

As is seen from figure 6, the net effect of the decreasing pace of innovation over the product cycle will therefore be to lower the skill intensity and increase the economic life of new machinery. That is, firms will move along the trajectory $d-d'$ over time, from skill-intensive activity and short economic life of machinery (or products) to capital-intensive activities with long economic lives of products and equipment.

Let us now relax the assumption that the unskilled labour to capital ratio is technologically fixed, and admit ex ante substitution possibilities between unskilled labour and capital. Since the basic conclusions are close to obvious, it seems sensible to deduce them in a simple (and heuristically nice) way.

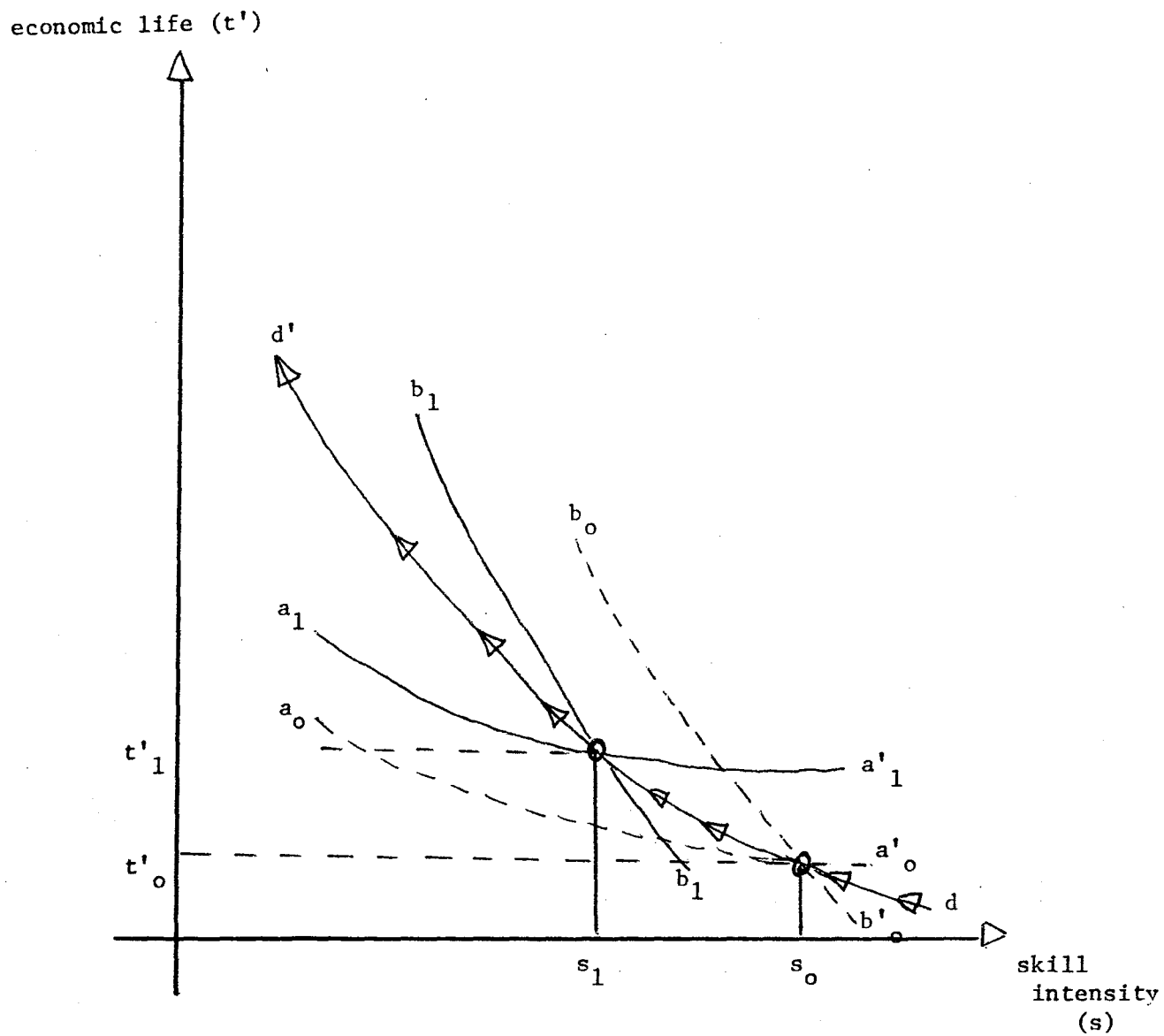


Figure 6: The product cycle

Let us interpret $n(v)$ and $s(v)$ in terms of the kinds of "activities" involved, rather than as the number of heads per machine unit. The former we can interpret as the number of operations that must be performed in parallel per basic machine unit, whereas $s(v)$ can be reinterpreted as activities concerned with reducing and ultimately eliminating waste effort, mistakes, etc. If all operations must be performed by hand, $n(v)$ is the number of men that must man each machine (one per operation), and $s(v)$ is some index of their skill, or of R & D, or supervisory, or problem solving personnel. This is, essentially, the interpretation we have used so far.

However, if we admit the possibility that some of the operations can be mechanized, then $n(v)$ can be performed with a variety of possible combinations of men and equipment ancillary to the basic machine. That is, we can define a traditional isoquant in (ancillary) capital and (unskilled) labour that will map out the alternative ways of accomplishing the number of operations that must be performed per basic machine unit.

Bringing in capital/unskilled labour substitutability in this way, and assuming that ancillary capital equipment, like the basic machinery, is particular product and process design specific, it is almost immediate that capital will be substituted for unskilled labour as the product cycle progresses. If ancillary equipment is purchased when the vintage is introduced, and is junked when the vintage is abandoned, the pre-period price of machinery obviously is (inversely) related to the length of time the vintage is used. The least cost combination of (ancillary) capital and unskilled labour needed to perform $n(v)$ operations, in turn, is related to the price of machines (and the interest rate), the price of unskilled labour, and vintage life.

If we assume that the productivity of $s(v)$ does not depend on the mix of unskilled labour and ancillary capital equipment, and that the trade-offs are not influenced directly by technological progress over the product cycle, the basic analysis can be modified as follows: First, in equations (5), (6), and (7) w_n must be replaced by $w\beta_n$, where β is the fraction of operations that will be performed by unskilled labour if the machine is to be scrapped after t' periods. In general, β will decline with t' . In figure 3, the variable cost curve then will be downward sloping. The $a-a'$ and $b-b'$ curves are derived as before, except that the optimal mix of ancillary capital and unskilled labour for any scrapping age must be pre-calculated. In the analysis of the effect of the decline, over the product cycle, in the pace of technical progress, it must be noted that the competitive equilibrium condition (9) must account for ancillary capital costs, either on the right hand side or the left hand side. The effect of a slower pace of technical progress will be, as argued above, to increase fixed cost relative to variable cost. The effect of this will be to augment the earlier forces to increase vintage life, and therefore reduce skill intensity, over the product cycle.

In the introduction it was suggested that technical progress over the product cycle probably is not neutral, but rather is machinery using and skilled labour saving. The model above has not treated this at all. Rather, we have deduced that rising capital intensity and reduced skill intensity would likely result from decelerating technical progress, even if that technical progress were neutral. The interpretations are, of course, complementary and not conflicting. Non-trivial examination of non-neutral technical progress over the product cycle would, however, appear to require a quite different kind of a model.

The International Product Cycle

In the preceding section we examined what happened, over the product cycle, to the conditions of production within a given country. Implicitly it was assumed that the country was producing the product throughout the product cycle. The product cycle theory of trade, however, posits that - as the product cycle progresses - comparative advantage shifts from skill rich countries to skill poor countries. And if there is free trade in the product line in question, production will be phased out in the former and established in the latter. In this section we deduce that result from our model.

Before considering the matter relatively rigorously, it is useful to lay out the argument heuristically. Assume that the factor prices prevailing in different countries can be viewed as points along a factor price frontier

$$(10) \quad \phi(w, u, r) = 0$$

Further assume that the rate of return on capital is roughly equalized across the countries. International factor price differences then boil down to differences among countries in the wages of unskilled and skilled workers - these differences being related to the relative abundance of the two labour categories - so the factor price frontier will be a curve like F-F' in Figure 7.

Consider any particular vintage of the product technology discussed in the preceding section, and assume that machines are traded internationally so that machine prices as well as the interest rate are equalized across countries. Maximal profit (present value) per machine will then depend on the wage rates (w and u) alone, so there will be a family of iso-profit

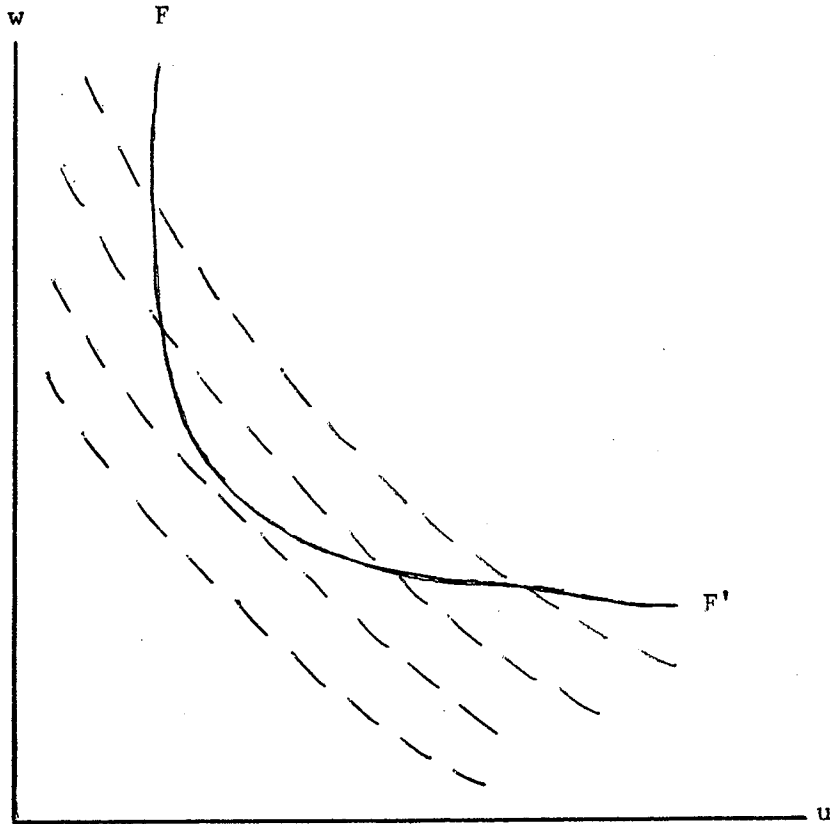


Figure 7

curves of the sort shown by the dashed curves in Figure 7. (Observe that profit increases as we move towards the origin in the figure.) Clearly for any given technology, there will be a point - or a set of points - along the factor price frontier such that the present value is higher there than at any other point along the frontier. Assuming free trade (and perfectly elastic factor supplies to the industry within each country), countries with factor prices associated with these points will produce the output. For all other countries, maximal present value will be less than the cost of capital.

As the product cycle progresses, the shift in optimal factor mix towards a higher ratio of unskilled to skilled workers means that a higher skilled wage rate will penalize profit less, and a higher unskilled wage rate will penalize profit more, than at the factor ratio employed earlier in the product cycle. That is, the iso-profit curves change from a-a to b-b in Figure 8. Obviously, comparative advantage shifts to countries with low unskilled wage rates.

Let us now develop the argument more rigorously: With perfect factor markets and free trade in all goods, the following relationship obtains along the factor price frontier:

$$(11) \quad dw/du = -(S/N)$$

where S/N is the factor ratio associated with the factor price frontier at a particular point. (Recall that it is assumed that all countries have the same rate of return on capital. Thus it is assumed that each country's capital stock adjusts so that this condition holds, given its endowments of unskilled and skilled labour.)

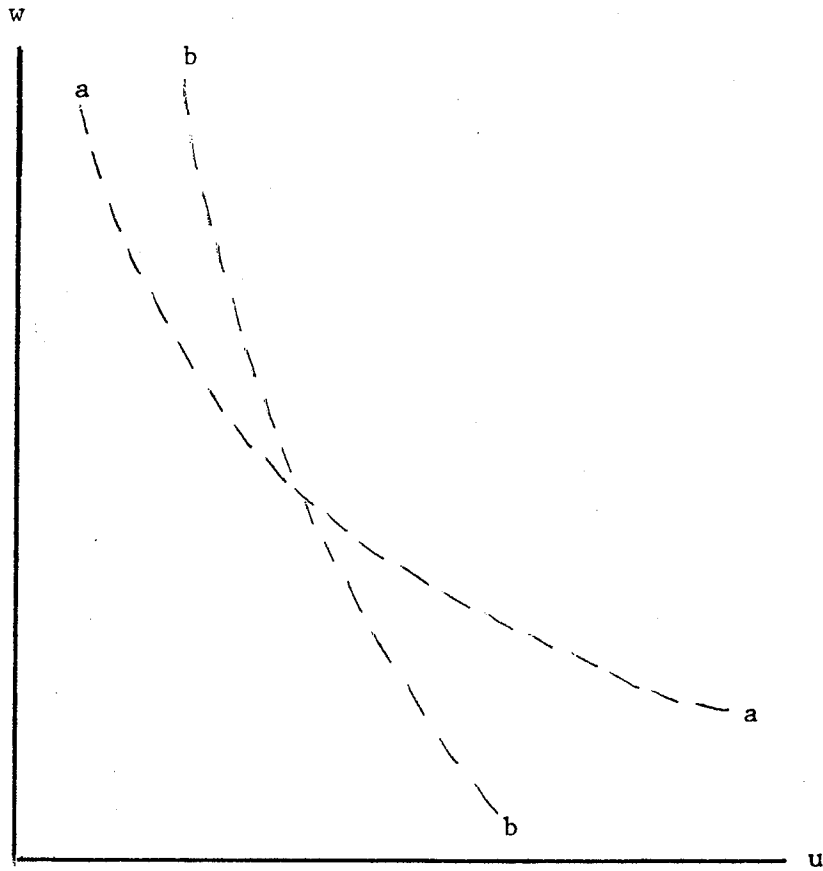


Figure 8.

Let us denote by V_i the maximal present value for an investment in the product in question, at price p , for firms in country "i" facing factor prices w_i and u_i . We must then have

$$(12) \quad V_i = V(p, w_i, u_i) \leq c$$

If firms in country i produce the product, the net present value will equal the unit cost of machinery. Conversely, if they do not produce products of that maturity, the net present value must be lower than the unit cost of capital goods. We also know that equation (12) must hold as an equality for at least one country.

What we shall establish, then, is (I) that the value function contains a maximum point as we move along the factor price frontier; and (II) that this maximum occurs for successively less skill-intensive economies as the product line matures. These two propositions will then establish the character of the international product cycle.

To find the impact of factor prices on the net present value of an innovation, we can differentiate equation (6) with respect to factor prices. We then see that

$$(13) \quad \frac{\partial V}{\partial w} = n \int_0^{t'} e^{-rt} dt$$

$$(14) \quad \frac{\partial V}{\partial u} = -s \int_0^{t'} e^{-rt} dt$$

Thus, if we consider a movement along the factor price frontier:

$$(15) \quad \left. \frac{dv}{du} \right|_{FPF} = -n \left[\frac{s}{n} + \frac{dw}{dq} \right] \left. \int_0^{t'} e^{-rt} dt \right|_{FPF}$$

Substituting in equation (11), we then obtain

$$(16) \quad \left. \frac{dV}{du} \right|_{\text{FPF}} = -n \left[\frac{s}{n} - \frac{S}{N} \right] \int_0^{t'} e^{-rt} dt$$

so a movement along the factor price frontier, towards higher skilled labour wage rates (and lower unskilled labour wage rates) will increase the unit value of an innovation if the skill intensity of the innovation is lower than the skill intensity of the economy at large; and vice versa.

To see how this relates to the product cycle, assume initially that the skill intensity for any level of maturity is fixed (and uniform for all countries), but that this skill intensity declines (exogeneously) with product line maturity. Then equation (16) defines, for a given vintage, a relationship between the profitability of producing the good in question and the overall skill intensities of economies. The value function is maximized for that point on the factor price frontier where the overall skilled/unskilled labour ratio equals the skill intensity of the product under consideration. It is then tautological that the product line will move to successively less skill-intensive economies as it matures, since the skill intensity of the product line is assumed to decline over time.

It is only slightly more complex to prove the same when the technology allows various levels of skill intensity. What we need in addition are two assumptions. The first is that for all sets of factor prices associated with the factor price frontier, optimal (s/n) lies between the smallest and the largest (S/N) associated with the frontier. The second is that the elasticity of substitution between skilled and unskilled labour (holding output constant) be lower within the product line than in the economy at large.

In that case, the change in skilled/unskilled labour ratio induced (through factor prices) by a change in the overall skill intensity of the economy will be less than unity:

$$(17) \quad \frac{d\left(\frac{s(v)}{n}\right)}{d\left(\frac{S}{N}\right)} < 1$$

The first term inside the brackets of equation (16) must now be treated as a function of (S/N) , with (s/n) taking on its optimal value at the factor prices associated with (S/N) . The assumptions above guarantee that one can always find an overall skill intensity $(S/N)^*$ such that

$$(s/n)^* = (S/N)^*$$

in which case $(S/N)^*$ gives a stationary point for the value function.

Consider now

$$(S/N)^0 < (S/N)^*$$

Corresponding to $(S/N)^0$ there is an optimal skill intensity s^0 , with

$$(s/n)^0 \leq (s/n)^*$$

By (17), however,

$$(s/n)^* - (s/n)^0 < (S/N)^* - (S/N)^0$$

so

$$(s/n)^0 - (S/N)^0 > (s/n)^* - (S/N)^* = 0$$

so the value function must be monotonically increasing in the overall skill intensity for skill intensities below (S/N) . Similarly, it must be monotonically decreasing above this value. Thus, for any product line maturity level, there exists a unique point on the factor price frontier maximizing the value function.

Next, consider what happens as the product line matures. If $(S/N)^*$ maximized the value function for $v = v_0$, it cannot maximize it for $v = (v_0 + \Delta)$, since we have shown earlier that for given factor prices, $s'(v) < 0$. If therefore

$$\left(\frac{s(v_0)}{n} \right)^* = \left(\frac{S}{N} \right)^*$$

then

$$\left(\frac{s(v_0 + \Delta)}{n} \right)^* < \left(\frac{S}{N} \right)^*$$

so for maturity $(v_0 + \Delta)$, the value function is decreasing in (S/N) at $(S/N) = (S/N)^*$. Therefore, at maturity $(v_0 + \Delta)$, the overall skill intensity maximizing the value function must be lower than it was at maturity v_0 .

New Wine in Old Bottles

We have written this paper with two purposes. The overt purpose is to call attention to an apparently quite common pattern of technological change - what we have called product cycle - and to explore within a relatively traditional framework how that technological pattern is likely to lead to certain observed phenomena: decreasing skill intensity and increasing capital intensity as the technology matures, a shifting of comparative advantage from skill rich countries to countries with low wage rates. There has been a tendency among international trade theorists either to ignore the product cycle or to treat it in a very mechanical way within traditional theory (by for example simply postulating changes in skill and capital intensity, and deducing their trade consequences). We think the model we have presented probes deeper than that, providing a quite plausible interpretation of some of what is going on.

The second purpose has, up to now, been covert: it is to propose that if dynamic phenomena of the kind examined in this paper are important, perhaps we need to develop a quite different mode of theorizing. As the authors have wrestled intellectually with problems of this kind over the years, several things have become apparent. One is that it certainly is possible to treat dynamic phenomena (like learning, and the interaction of learning with the flow of new technology) within models in the neoclassical spirit. However, in order to do so and deduce results it is usually necessary to pile bothersome assumption upon bothersome assumption, and to sweep certain problems under the rug.

While the mathematical analysis often helps to clarify arguments that were first developed verbally, the intuitive economic arguments seem much more robust and persuasive than the mathematical ones. There is something inherently forced about assuming rigorous and accurate profit maximizing behaviour, or perfect competition, in the regime of rapid technological change which characterizes the early stages of the product cycle. Yet the factor substitution result seems plausible enough. To assume that all countries have access to the technology contradicts an important institutional fact of life with respect to the flow of, and access to, technological information. Yet the shift in comparative advantage seems plausible enough, and for roughly the reasons that the model develops in a highly stylized way.

What is happening here, we would argue, is that we do not really believe the full-blown neoclassical story - but that we do not know how to formalize a better story. We believe that firms go after profits, in a not totally stupid way; and that when ways to cut costs become apparent these will be seized. But this is not the same as saying firms maximize profits. We believe that profitable firms expand and are imitated, unprofitable ones stagnate or contract (with probabilistic exceptions). But this is not the same as saying the sector is in equilibrium, competitive or otherwise. It is our intuitive economic understanding that these forces are sufficient to generate many of the empirical phenomena we observe (or postulate exist). But when we turn to presenting the arguments rigorously, we fall back on assumptions that we intuitively feel we do not need.

While the neoclassical assumptions are unrealistically strong, they are useful for generating some plausible conclusions. In order to handle a number of important phenomena, however, different kinds of models may be needed. In particular, the neoclassical story seems too rigorous and too mechanical to handle important aspects of the product cycle - including Schumpeterian competition, and large portions of the economic development process as we know it.^{*/}

*/ For a discussion of the class of models that might be more appropriate see Nelson and Winter (1973).