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Revised

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> "The bell of the Gion Temple tolls into every man's heart to warn him that all is vanity and evanescence. The faded flowers of the sala trees by the Buddha's death–bed bear witness to the truth that all who flourish are destined to decay."
>
> from the Tale of the Heike

1. Introduction

World history seems replete with tales of overtaking – of success followed by failure for individuals, firms, and nations. At the individual level certain attributes often attend a rise to fame or fortune that turns sour – laziness, corruption, inflexibility, and a tendency to cling on to the forms of behavior which seemed to accompany success. So also firms may cease to pay sufficient attention to changing market conditions or major alterations in technological possibilities. Newcomers, challengers, and those who presently lag behind often claim, as in the Avis advertisement, that "we try harder." And such efforts frequently pay off – the leading firm may find its advantage eroded in the face of challenges from others. As well, whole nations seem to go into relative eclipse – The Roman Empire, China ten to five centuries ago, Great Britain at the end of the 19th century, not to mention, as some would claim, the United States at the end of the 20th.

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Much attention has recently been paid by economists to the central importance of technological progress in the phenomenon of growth. If such progress can be endogenously explained and justified as an on–going phenomenon, theory holds open the possibility of smooth, long–run sustained improvements in per–capita incomes. Such a vision, however, does little justice to the possibility of persistent epicycles wherein individuals, firms or nations are constantly in the process of changing places in the ranking among leaders and laggards. Is there a basic economic rationale in the dynamics of change to suggest that, as in the Tale of the Heike, such overtaking or "leap–frogging" represents a natural outcome of forces working on rational agents? In this paper we put forth an affirmative answer which reflects a basic concept in the field of international economics: comparative advantage.

The doctrine of comparative advantage provides the cornerstone for the theory of international trade. As long as a country contains factors or resources which are immobile behind national boundaries, it can engage in a mutually profitable exchange of commodities with other countries even if these factors would suffer absolutely in any head–to–head productivity comparison with comparable factors abroad. It is a comparison of relative productivities that matters. This paper argues that this basic concept has an even wider range of applicability: A new technology may be embraced by one firm and eschewed by another even if the former firm's resources are absolutely less adept at exploiting the new technology. Such an outcome depends upon a comparison of old and new productivities. Thus it may emerge that a firm surrenders a current position of leadership in an industry and is overtaken by a currently laggard firm because the leader's absolute superiority in an existing technology grants the laggard a comparative advantage in a new technology. And such a phenomenon of "overtaking" or "leap–frogging" need not imply any myopia or irrational behavior on the part of either firm. Thus the concept of comparative advantage may be of primary relevance in explaining the oft–observed phenomenon whereby the growth process is accompanied by epicyclical behavior in which firms and perhaps countries trade places as new products and technologies are developed.

The plan of the paper is to discuss the basic concept of comparative advantage and overtaking in technology in a core model in Section 2. Section 3 allows a less severe switch between technologies and shows why, if both firms start adopting a new technology, the laggard invests in it more heavily. Section 4 relates these ideas to existing literature on patent races and especially to a recent model of leapfrogging in an international trade context. The possibility that market prices respond to the technological choice, and that firms are aware of this sensitivity of price when making decisions, is considered in Section 5, although details are left to the Appendix. In Section 6 the role of principle–agent issues in influencing the outcome is considered, and Section 7 offers some concluding remarks.

2. The Core Model

The relevance of the concept of comparative advantage to the phenomenon of overtaking can most easily be illustrated in a core model with two firms in a given industry. Further to simplify, we start by assuming away the international ramifications of having the two firms in different countries, with the attendant likelihood that wages and other input prices may differ to a degree which affects relative industry success. Instead, these two firms are part of a large national industry. The two firms are asymmetrically placed: one firm has established over time a technological leadership, the other firm lags behind and forms part of a competitive fringe. Further simplification follows if we suppose that the price of the commodity which both produce is set on world markets. The question dealt with here is that of choice of technology for price–taking firms which are thus freed up from concerns which a firm may have as to the repercussions of technology decisions on market prices or, indeed, on the type of market which will emerge.

The advantages of having a head start and the concept of learning–by–doing provide the key explanations for the technological superiority of the leading firm in the initial setting. This firm started earlier, and its production and research team has developed techniques which lead to quasi–rents or profits compared with the rival lagging firm. Firms are nonetheless assumed to be of the same size so as to put aside notions of scale economies, which are not dependent upon the learning experience. Each firm has associated with it the skilled labor which has the acquired knowledge, and this labor is not mobile.

The economy supports many different types of economic activities, and this is an important feature of the model. Although final outputs produced may differ substantially in form or use from industry to industry, technologies developed for some industries may prove to be applicable, perhaps in modified form, to others. That is, there are technological spillovers possible which may prove of use in the industry with which we are concerned. In the initial setting all such possible profitable externalities have been incorporated into the techniques used by the "leading" firm as well as, perhaps to a lesser extent, by the "laggard." But this is a situation which can change in the future. The research team in the leading firm presumably has developed a superior set of skills that allows it better to incorporate technological developments as they emerge in other areas of the economy as long as these developments are in some sense "close" to previously developed technology. However, spill–overs may also prove applicable from technologies that are quite foreign to those currently employed by either the leading or laggard firm, and any advantage the leading firm has from its previous learning experience do not extend, at least to as great an extent, to these new techniques.

These ideas can be captured in the following simple core setting. There are two time periods – current and future. There is an existing technology, whose net productivity in the current period is denoted by θ_1 for the leading firm and θ_1^* for the laggard.

(Although at this stage we assume both firms are located in the same country, we adopt the notation used in trade theory and will think of the leading firm as the "home" firm and the laggard as the "foreign" firm). Technological superiority of the leading firm implies that θ_1 is greater than θ_1^*. Looking towards the future, the θ–technology will yield to improvements by a learning process in production for each of these firms, by the development efforts of its research labs, and by an assimilation of knowledge stemming as technological spill–overs from other industries whose methods of production contain elements which are "near" to those used by these firms. Thus future net productivities, θ_2 and θ_2^*, are respectively higher than θ_1 and θ_1^*. Nonetheless, as long as the θ–technology forms the primary source for productive techniques, the leading firm maintains its acquired technological dominance and θ_i exceeds θ_i^* for i = 1, 2. These θ's represent productivities net of costs of labor or other inputs acquired on open markets.

The current value to the firm of its resource base, V_θ or V_θ^*, depends on the factor by which future productivity is discounted. Denote such a discount factor by δ and δ^* for the two firms, although in most of what follows these two firms are assumed to discount the future at the same rate, leading to the same discount factor, δ. Thus

$$V_\theta = \theta_1 + \delta\theta_2$$
$$V_\theta^* = \theta_1^* + \delta^*\theta_2^*$$

Unless these discount factors differ markedly between firms, and we assume they do not, the leading firm's technological superiority in both periods guarantees that V_θ exceeds V_θ^*.

The presumed rich variety of productive activity throughout the economy eventuates in a set of technological breakthroughs in a number of areas. Some of these are close to the θ–technology, and get absorbed by these two firms, with the leading firm doing a better job of assimilation. Other improvements represent greater departures which nonetheless may have relevance in the production of the commodity in which these two firms are involved. (We abstract in this description from an extremely important feature of actual change – the product itself may improve in quality or, indeed, be superceded by a new product which satisfies many of the needs of the demanders of the old). Let β denote one such new technology that emerges from the activities of firms in other industries. Some new possibilities would unquestionably be attractive to the laggard, e.g. if future net productivity, β_2^*, exceeds future expected θ_2^* *and,* as well, current productivity of the new technology, β_1^*, exceeds θ_1^*. Given the distance separating the current technology of the two firms, such a new possibility could nonetheless be dominated by the old for the leading firm, both in current and future productivities. In such a case the laggard would switch to the new β^*–technology but would succeed only in narrowing the gap between firms, rather than in overtaking the leading firm, which would stick with the old.

To highlight the phenomenon of overtaking when the new technology is potentially attractive for both firms, but would require a current sacrifice in order to obtain future productivity enhancement, assume that β_1 and β_1^*, the current productivities for the new technology, fall short even of θ_1^*, but learning–by–doing with the new technology holds out the promise of sufficient productivity enhancement in the future that both β_2 and β_2^* actually exceed the leading firm's expected value of θ_2.[1]

Each firm appraises the new β–technology in terms that encompass both present and future net productivities. Thus the laggard firm switches to the new technology if $V_\beta^* > V_\theta^*$ or:

$$\beta_1^* + \delta^* \beta_2^* > \theta_1^* + \delta^* \theta_2^*$$

However, the leading firm would retain its old technology if

$$\beta_1 + \delta\beta_2 < \theta_1 + \delta\theta_2.$$

[1]This is a stronger assumption than needed; β_1 need not be smaller than θ_1^*. See our later comments on the paper by Brezis, Krugman and Tsiddon (1991).

Alternatively phrased, the current lagging firm overtakes the leader in commandeering the new technology if

$$\delta^* > \frac{\theta_1^* - \beta_1^*}{\beta_2^* - \theta_2^*}$$

and

$$\delta < \frac{\theta_1 - \beta_1}{\beta_2 - \theta_2}$$

The numerators express the current losses or opportunity costs of switching to the new technology, whereas the denominators capture the excesses in future period 2 of the productivity in the new over the old technology. Both numerator and denominator are assumed to be positive, so that the inequality for the lagging firm requires a sufficiently high value for δ^*. (Higher interest rates at which the future is discounted lead to lower values for δ^*. If there were no discounting of future benefits, δ^* would rise to a maximum value of unity. Of course since real rates of interest often are negative, δ could exceed unity, but this possibility is ignored). Similarly, the leader finds the new technology less attractive than the old if it discounts future benefits at too high a rate. Suppose both firms share the same discount factor, δ. A necessary condition for the β–technology to be adopted by the lagging firm but not by the leader is that

$$\frac{\theta_1 - \beta_1}{\beta_2 - \theta_2} > \frac{\theta_1^* - \beta_1^*}{\beta_2^* - \theta_2^*}$$

This is a statement of the *comparative advantage* which the leading firm possesses in the old technology, which implies a *comparative disadvantage* in the new.

Figure 1 illustrates how such an overtaking (or leapfrogging) in technology may take place even if the current leading firm's skills impart to it an *absolute advantage* in the new technology. The vertical axis represents the *current* net productivity of the new

β–technology, but points θ_1 and θ_1^* are also depicted, showing comparable firm values for the older θ–technology. The horizontal axis shows *future* possibilities for the new β–technology, along with expected values for θ_2 and θ_2^*. Thus points θ and θ^* represent current and future net productivities for the two firms if they stick with the old θ–productivities but by learning develop them further in period 2. The fact that both θ and θ^* lie to the right of a 45° ray expresses such learning. θ and θ^* have been drawn so that they both lie on the same ray from the origin. This is a neutral assumption, suggesting that the learning curve for the θ–technology is linear. The alternative assumption that there are diminishing marginal returns to the learning process would serve to position point θ on a steeper ray from the origin than θ^*, although dominating it.

As for the new β–technology, we have assumed that it is potentially of relevance to both firms. In more detail, we restrict attention to a possible β–technology that lies in the cone CDE, ensuring that

(i) In the current period both β_1 and β_1^* reflect diminished net productivity even relative to low θ_1^*. These values of β_1 and β_1^* are assumed to be positive in Figure 1, although high learning costs could make them negative;

(ii) In the future period both β_2 and β_2^* reflect superior technology even compared with the leading firm's θ_2;

(iii) The β–technology would be adopted by both firms if the (assumed common) discount factor, δ, is sufficiently large. (That is, consider a value of δ equal to unity. Line DC has slope –1 so that $(\beta_1 + \beta_2)$ and $(\beta_1^* + \beta_2^*)$ both exceed $(\theta_1 + \theta_2)$).[2]

[2]This leaves out of account possible β–technologies such as point ω. For such a technology, the laggard firm would switch and the leading firm would obviously not. Thus the phenomenon of overtaking is not constrained to the shaded area.

In addition, we assume that the leading firm would have a higher net productivity than the laggard with the new technology in each period of time. That is, β dominates β^*. This latter assumption is made in order to emphasize that the current laggard may in some cases surpass the current leader by being the only firm to switch to the new technology even if the current leader should possess an absolute advantage in the new technology.

The negatively sloped lines drawn through θ and θ^* have slope $-\delta$, implying a common positive interest rate and vertical intercepts equal to V_θ and V_θ^*. The shaded region indicates the set of possible β–technologies (of those restricted to cone CDE satisfying these specified properties) that lead to a switch to the new technology by the current lagging firm and an adherence to the old technology by the current leading firm. (Discounting β_2 and β_2^* leads to a value of V_β less than V_θ and of V_β^* greater than V_θ^*). Line segment $\theta\beta$, not drawn, would be steeper than $\theta^*\beta^*$. The absolute value of the slope of the former is $(\theta_1 - \beta_1)/(\beta_2 - \theta_2)$, and of the latter is $(\theta_1^* - \beta_1^*)/(\beta_2^* - \theta_2^*)$. Overtaking reflects a relatively low opportunity cost in the present period of adopting the new technology for the laggard, and a relatively large increase in future productivity. The leading firm's absolute superiority in the old technology encourages such comparisons. Actual overtaking requires both that the laggard firm has a comparative advantage in the new technology (despite the leading firm's absolute advantage in each technology) and that the common rate at which future benefits are discounted leads to an increase in profitability for the laggard firm but not for the leader.

Also shown in cone CDE are two other possible triangular regions for β and β^*. In the lower of these the ratios of future benefits to present costs are so low that neither firm would switch; in the upper triangle these ratios are sufficiently high that both firms abandon the θ–technology in favor of the new β–technology. The shaded area lies in between. Thus the laggard's comparative advantage in the new technology, derived primarily from the laggard firm's absolute disadvantage in the old technology, is a necessary, but by no means sufficient, condition for overtaking. The leading firm would protect its lead if both firms adopt the new technology despite the leading firm's comparative advantage in the old.

3. Choice in Resource Allocation

The preceding analysis has a stark all–or–nothing flavor in contrasting the choice between the old–θ and new–β technologies. Firms are frequently more cautious. It is not typical for firms abruptly to abandon old technologies and wholeheartedly to embrace new. Instead, they may go through a period in which the new is tried, absorbing some of the firm's resources, but still leaving in place productive activity using the old technology. If the new technology is initially inferior, as assumed, such a strategy helps to maintain current levels of productivity. However, it also entails a cost in that the fewer resources currently devoted to learning by using the new technology, the smaller will be the future benefits flowing from its adoption. Here we provide a simple model designed to highlight the optimal allocation of the firm's resources between the two technologies. We start with the analysis for the leading firm. By comparing this with the position of the lagging firm we are able to establish that if both firms should channel some resources into the new technology, the lagging firm, with a comparative advantage in new techniques, always devotes a greater fraction of its resources in the current period to the new technology. This leads to overtaking in the following period.

Let $0 \leq \lambda \leq 1$ denote the fraction of the firm's resources devoted to production using the new technology, with productivity in the present period given by β_1 (a constant assumed smaller than θ_1 or θ_1^*). If we assume the two technologies do not interfere with each other, the actual net productivity this period will be a weighted average of the new (β_1) and the old (θ_1):

$$\lambda\beta_1 + (1 - \lambda)\,\theta_1$$

The net productivity of the new technology in future period 2 depends upon λ:

$$\beta_2 = \beta_2(\lambda), \qquad \text{where} \qquad \beta_2(0) = \beta_1, \beta_2' > 0, \beta_2'' < 0$$

That is, the future productivity of the new technology depends upon the extent to which current resources are engaged in its use, but there are diminishing returns to this allocation. The older θ–technology will also improve as more resources, $(1 - \lambda)$ of the total, are devoted to it in the present period. Of special relevance, however, is the value of θ_2 (or $\overset{*}{\theta}_2$) if $\lambda = 0$, that is if the firm maximizes its profits by sticking with the old technology. If the firm chooses to put current resources into the new technology, it must be the case that $\beta_2(\lambda)$ will exceed this maximum value of θ_2.

If the leading firm engages at all in the new technology, it wishes to maximize

$$\{\lambda\beta_1 + (1 - \lambda)\ \theta_1\} + \delta\beta_2(\lambda)$$

with respect to λ. The optimal value for λ, λ°, satisfies the first–order conditions for optimization:

$$\delta\beta_2'(\lambda^\circ) = (\theta_1 - \beta_1).$$

It may turn out, however, that the leading firm wishes to stay with the old technology. This reluctance to invest in the new will prove a superior policy if

$$\{\lambda^\circ\beta_1 + (1 - \lambda^\circ)\ \theta_1\} + \delta\beta_2(\lambda^\circ) < (\theta_1 + \delta\theta_2),$$

where θ_2 is the benefit in period 2 if the firm devotes all its current resources to improving the θ–technology.

Figure 2 illustrates the possibilities for the leading firm. The ray from the origin, $(\theta_1 - \beta_1)\ \lambda$, shows the opportunity costs in this current period of allocating resources to production using the new technology, in the form of foregone rents earned using old techniques. The rising curve shows the discounted value ($\delta < 1$, assumed the same for both firms) of the excess of future benefits with the β–technology over the benefits with the

θ–technology if the maximum value, θ_2, is attained in the future period. As drawn, it is assumed that future productivity of the new techniques, $\beta_2(\lambda)$, would actually fall short of the future productivity of the old, θ_2, if insufficient resources are currently devoted to learning the new. Indeed the vertical intercept is the negative value, $(\beta_1 - \theta_2)\ \delta$. Furthermore, Figure 2 illustrates the case in which the allocation of resources, λ°, that is optimal if the new techniques are to some extent employed indeed proves to be a superior strategy to maintaining the old since $\delta[\beta_2(\lambda^\circ) - \theta_2]$, the present discounted value of the relative superiority of the new technology in the future, exceeds the current opportunity costs, $(\theta_1 - \beta_1)\ \lambda^\circ$. This comparison favoring some use of the new technology, however, does not warrant a complete switch in the present period away from the old (contrast the relative values at $\lambda = 1$).

Of special interest is the comparison that can be made with the situation of the laggard firm. For this purpose we now suppose that the superior knowledge acquired by the leading firm by virtue of its greater familiarity with the θ–type technology does not carry over any benefits with the new β–type technology. Instead, let β_1^* equal β_1, and let the $\beta_2(\lambda)$ function be identical for both firms. In Figure 2 the present discounted value of the excess of future benefits, $\delta[\beta_2(\lambda^*) - \theta_2^*]$, is shown by a curve that is everywhere higher than that for the leading firm by the amount $\delta(\theta_2 - \theta_2^*)$. Therefore the slopes are equal for comparable values of the fraction of resources devoted to the new technology. By contrast, the ray showing the current opportunity costs of the switch to the new is flatter than for the leading firm since θ_1^* falls short of θ_1. Two consequences are immediately apparent:

(i) If the leading firm finds it profitable to begin exploiting the new technology, the laggard must also find it profitable to devote some resources to the new. However, the converse need not be the case. The leading firm may find its optimal strategy is to adhere to the old technology while the laggard channels some resources to the new.

(ii) If both firms devote some resources to the new technology, the fraction of resources thus devoted is higher for the laggard firm.

It is still possible to get the kind of overtaking result illustrated in the previous section whereby the laggard firm ends up in the future period using the superior technology (but perhaps low on the learning curve, depending upon its optimal value of λ^*), and the current leading firm sticks completely to the old technology. (In Figure 2 the $\delta[\beta_2(\lambda) - \theta_2]$ curve would lie strictly below the $(\theta_1 - \beta_1)\ \lambda$ ray). But even if both firms are attracted to the new β–technology, optimal resource allocation finds the current lagging firm leap–frogging into technological leadership in the future. It is important to note the asymmetric role played by the absolute advantage of the leading firm in both periods in the old technology. Its advantage in period 2, $\theta_2 > \theta_2^*$, affects the position of the future excess benefits curve (discounted) but not its shape. Thus its advantage may dissuade the leading firm from switching at all, but if both firms do decide to invest in the new technology, the *marginal* gain to each from choosing a higher λ is the same. By contrast, the leading firm's advantage with the old technology in the current period, $\theta_1 > \theta_1^*$, implies a higher opportunity cost for the leading firm to make the switch, and this cost discrepancy gets higher the greater the fraction of resources devoted to the new. It is for this reason that, should both invest in the new, the current lagging firm will emerge in the future as the technological leader.

4. Relationships to Other Models

In the decade after World War II much was made of the possibility that countries such as Germany and Japan were perhaps presented with a blessing in disguise when much of their capital equipment was destroyed during the war.[3] The disadvantage faced by countries such as England or the United States, so it was argued, would arise from the

[3]See Ames and Rosenberg (1963) for a brief critique of views such as this.

possession and use of old or obsolete capital equipment. Late–comers would have an advantage, a "fresh start", whereas the leader may become "locked–in" to an older technology and capital equipment. Views such as these were expounded (Frankel, 1955) and criticized (Gordon, 1956) four decades ago. As Gordon emphasized, ownership of old capital equipment represents sunk costs and should not impose a relative disability. Any firm is free to acquire capital equipment embodying the latest technology.

The scenario in which our core model is placed shifts attention from physical capital to put heavy emphasis on the human element as expressed in Arrow's (1962a) concept of learning–by–doing. Technical progress is the reward for accumulated investment or output. Increased familiarity with technical processes serves to heighten productivity. Machines do not learn, people do. But such acquired human capital tends to be especially vested in certain techniques, and possession of such knowledge imparts a comparative advantage in exploiting the familiar technology relative to a freshly–available new technology which ultimately may prove superior. The time–profile of learning for the "old" θ–technology (as illustrated by points θ or θ^* in Figure 1) may be less slanted towards future benefits than the "new" β–technology. This could lead to rational outcomes different from those associated with "obsolete" physical capital in the earlier literature.

The possibility of costless "diffusion" of technology from the leader to the laggard is absent in our setting, although it assumes an important role in other models. The existence of such effortless diffusion serves as an attraction to waiting – to be a free rider on another firm's innovative activity. As Benhabib and Rustichini (1993) stress, a firm or country may have a lead based on devoting resources to production instead of to research and development if this latter activity can be left to others. In the words of Katz and Shapiro (1987), a sufficiently high rate of diffusion can turn a technology race into a waiting game. By contrast, in the present setting gains in technology are only acquired by effort, although external spill–overs from activity elsewhere in the economy can provide new technological profiles. But to get experience with this new technology requires productive input and a re–allocation of resources from the old technology. As well, learning may involve making mistakes or false starts. In our core model history is condemned to repeat itself – others learn only from their own mistakes.

The question of overtaking or leapfrogging of one firm by another is closely related to that of comparing the amount of inventive or innovative activity which would be undertaken by firms in different market situations. Thus Arrow (1962b) contrasted the benefit to an inventor who can extract royalties in a competitive market with that possible for a monopolist with the same invention. The latter is making profits in both situations, and benefits only by the difference in the two profit rates whereas in the competitive situation there is no offsetting subtraction. In Arrow's words, "The pre–invention monopoly power acts as a strong disincentive to further production" (p. 177 in Rosenberg, 1971). This distinction between the position of a monopolist and an inventor dealing in a competitive market has bred an analogous distinction between an "incumbent" and a "challenger" in the more recent industrial organizational literature, and this in turn can be related to our "leader" and "laggard" with reference to current superiority along the learning curve for a given technology.

Gilbert and Newbery (1982) argue that a monopolist has an incentive to engage in inventive activity leading to a patent which serves to preempt effective competition from potential challengers. The setting chosen for their model is one in which both the monopolist (or incumbent) and the challenger enter bids representing the maximum the firm is willing to spend on research and development. The Gilbert and Newbery result, wherein the monopolist wins in such an auction market, appears to rest on a basic assumed asymmetry: If the monopolist wins, it retains monopoly control, whereas if the incumbent wins, the market is shared, and in a non–cooperative arrangement total rents are dissipated. That is, letting R^m denotes rents for the monopolist if it retains its monopoly power, and R^e and R^i denote, respectively, the non–cooperative rents for the entrant (e) and incumbent monopolist (i) if the incumbent loses the auction and both share, the dissipation of rents associated with the change in market structure implies that:

$$R^m - R^i > R^e$$

The monopolist has more to lose ("opportunity losses") than the entrant has to gain.[4] This leads to a conclusion that the monopolist would outbid the entrant in an auction market, which contradicts the Arrow result that the monopolist invests less.

In countering the Gilbert and Newbery argument, Reinganum (1983) considers the case of "drastic" innovations, those in which the winner of a race to develop new technology captures (or retains) a monopoly position. Reinganum stresses that her model is stochastic instead of deterministic, and that this feature of uncertainty supports the difference in her conclusions: the challenger invests more than the incumbent. With the stochastic racing model the incumbent has an (uncertain) period of time in which it receives a profit stream using the old technology. Should the incumbent succeed in achieving the innovation before the challenger, it wins, but "merely 'replaces himself'" (Reinganum, 1983, p. 741). This is an asymmetry which tilts the balance towards the challenger, especially since (unlike Gilbert and Newbery) the challenger, if successful, does not have to share the market.

The asymmetry which is introduced by these two assumptions – uncertainty and a similar (monopolistic) outcome regardless of who first gets the innovation – makes her model more similar to our core model. The incumbent ("leader") has less to gain than the challenger ("laggard"). In our core model this asymmetry reflects a head–start in

[4]Details of the argument are discussed as well in Reinganum (1989), p. 869.

learning–by–doing with an existing technology, which imparts a comparative advantage in a *new* technology to the "laggard" (challenger).

The recent paper by Brezis, Krugman and Tsiddon (1991) aims explicitly at providing an economic explanation of the phenomenon of leapfrogging. It differs from our model in several key respects. It embodies the question in a simple general equilibrium format in which the two firms are located in two different countries, America and England. England is initially the leader in that it has progressed further along the learning curve for a kind of technology used by firms in both countries. Indeed, in the context of the Ricardian setting which they use, the industry subject to learning–by–doing, manufacturing, is not the only potential employer of labor. As well, there is a food sector, in which technology is static and at the same level in both countries. Demand conditions are of the Cobb–Douglas variety, identical in the two countries, with the common expenditure share on manufactures exceeding 0.5. This, coupled with the assumption that the two countries are of comparable size, guarantees that at least one of the countries is specialized to manufacturing. Initially this is England, and America may produce some manufactured goods as well as food, in which case relative wages reflect directly the productivity differential along the learning curve in manufacturing. Alternatively America may specialize in food, if demand conditions lead to relative wages at which America would prove uncompetitive in the manufacturing sector.

Given this scenario, the terms of trade and relative wage rates can change if America is specialized in food since British learning in manufacturing tends to improve America's terms of trade. Thus wage rates may tend to converge. Leapfrogging, however, depends on the appearance of a new technology, one in which previous learning experience imparts no advantage to the leading British firm. In our model this new technology represents an external spill–over as a consequence of progress in other industries in which outputs can be radically different although techniques may prove adaptable between industries. Brezis, Krugman and Tsiddon assume, furthermore, that this new technology is subject to improvement with experience, but that initially it represents an advance in productivity for the American (lagging) firm (or potential firm if America is specialized in food) but not for the British firm, which is at an advanced state using the old technology. In terms of our setting, the new technology currently yields a productivity, β_1 (equal to β_1^*), that lies intermediate between θ_1 (the leader's old productivity) and θ_1^* (the American current productivity in their model). They argue that leading Britain therefore eschews the new technology, which is adopted by laggard America.

Such an asymmetric response need not lead to leapfrogging. Much depends on the shape of the learning curve for the new technology as America improves its productivity in the future compared with the British move along its learning curve with the old technology. Brezis, Krugman and Tsiddon assume that American productivity expands more rapidly and eventually surpasses that of Britain. In such a case America takes the productivity lead, specializing in manufactures, and drives Britain into food production.

Figure 1 helps to connect this development scenario to our model. Consider points ω', ω'' and ω'''. All three show a new technology which initially represents a productivity advantage to the lagging firm ($\beta_1 > \theta_1^*$) but not to the leader ($\beta_1 < \theta_1$). Even without discounting future benefits from the learning process, technology ω' is clearly of no advantage to the leading firm, although it dominates for the lagging firm. Thus the appearance of such a technology leads to overtaking in the sense that in the future period the current laggard would have superior technology. ω'' represents a technology which would in our model still be ignored by the leading firm even though a fall in interest rates (a rise in δ) could alter that decision. If future benefits are even greater, say at ω''', in our case both firms would switch to the new technology. In the Brezis, Krugman and Tsiddon scenario, in the ω''' case Britain would be guilty of myopia if, as they conclude, it sticks with the old technology. Note that since all three ω_i lie east of a ray (not drawn) through θ and θ^*, they all satisfy the condition that the potential for improving technology by learning from production is greater in the new technology than in the old. But in comparing ω'' and ω''', discounting makes all the difference in evaluating the conclusion reached by Brezis, Krugman and Tsiddon that the leading firm decides to retain the old technology.

The concept of comparative advantage is, of course, ever present in their Ricardian setting. But it does not represent the same kind of comparison which we highlighted earlier. In their model, the leader started with a comparative advantage in manufacturing relative to food. Given their assumption of static and identical productivities in the food sector, such a comparative ranking also reflects positions of absolute advantage in manufacturing. By contrast, we focused on the comparative advantage one firm possessed in the old technology relative to the new, a ranking which, in Figure 1, held despite the leading firm's absolute advantage in the new technology ($\beta > \beta^*$). And this comparison of technologies between firms involved sweeping together present and future along the learning curve to derive present discounted values. Our principal contention is that a firm which has, through more experience with the old techniques, established an absolute advantage using those techniques, finds itself therefore at a *comparative disadvantage* with respect to potential technological spillovers from other sectors (or from new research and development). In this sense current superiority sets the stage for future reversals of leadership. And these reversals need not imply myopic behavior on the part of the current technological leaders who, in the Brezis, Krugman and Tsiddon case, give a "pass" to the option of linking onto the learning curve of a new and eventually superior technology.

The Brezis, Krugman and Tsiddon model conveys an explicit international flavor in that competing manufacturing firms are in different countries and therefore (may) face different wage rates. In our core model firms were assumed to face the same wage rate since they were in the same country. The θ–technology and β–technology there discussed revealed productivities of these two techniques *net* of payments to labor or other non–specific factors in the market. Therefore the comparison more directly reflects *technology* than would be the case in comparing firms in countries with different wage rates.

A country's internal factor prices depend upon technology in all the industries actively pursued, so that one country may be a high–wage country because of superior technology in industries other than the one under consideration. (This is not the case with the Brezis, Krugman and Tsiddon paper since technological conditions in the single other industry, food, are assumed identical in the two countries.) Such a higher wage would lower its θ or β technology profile relative to that of a firm in the low–wage country. Under the Brezis, Krugman and Tsiddon conditions, any wage differentials directly reflect the productivity differentials in the industry being compared, whereas more generally a firm may be a "leader" in the sense we have used because asymmetry in technology in *other* sectors of the economy relative to the foreign country results in lower wage rates or returns to other key factors. Positions of leadership depend on relative costs and these are influenced by comparative advantages among different industries and not merely by technology comparisons among firms in the same industry. The phenomenon of the "Dutch Disease" is ubiquitous. One country's firms may have technical superiority in a certain industry (e.g. cotton textiles in Britain) compared with firms abroad, but may switch from being leaders to laggards because improvements elsewhere in the economy drive up factor prices and these cost increases may more than offset any advantage in absolute technology. Our basic modeling strategy has been to focus on the possibility that a firm that initially lags behind can overtake a leader not because the leader is suffering increases in factor prices but because the leader's superiority in a currently used type of technology gives the laggard a comparative advantage in a newly–arrived technology.

In the international setting with firms located in different countries, it becomes less defensible to assume that discount factors are the same. If δ differs from δ^*, it is clear which way the comparison must run in order to enhance the possibility of overtaking. A common new β–technology has been assumed to offer future benefits (from learning) at the expense of current sacrifice (before learning the new can progress). The present leader would face a bigger current sacrifice in exchange for a smaller increase in future net benefits. If these future returns are more severely discounted by the leading firm, future overtaking becomes more likely. Such discounting could also take the form of a shorter time horizon.[5] For example, the investment strategy of Japanese firms is often favorably compared with those of American firms in that a longer time horizon is allowed for future returns. If Japanese firms originally lagged in technology, such a difference would encourage technological overtaking.

5. Imperfect Markets: A Sketch

The core model envisaged price–taking firms contemplating a new β–technology, and considering whether the initial relative cost of switching away from an older θ–technology would more than be made worthwhile in discounted future earnings. In this section we sketch out a different scenario – one in which market prices respond to choice of techniques by either firm. Details of the proofs required for our final propositions are banished to the Appendix.

Two firms share a market, and the equilibrium price depends on market demand, cost conditions for the firm and the nature of the duopolistic competition. The home firm under the original θ–technology has a productivity advantage, and this is captured by an assumed constant marginal cost that is lower than that of the lagging firm. If both firms

[5]The potential importance of different time horizons in evaluating the Brezis, Krugman and Tsiddon paper has been stressed by Jeddy (1993).

were to stick with the θ–technology, cost vectors for the two periods would be denoted by $c(\theta)$ and $c^*(\theta^*)$. The home firm's head–start advantage with this technology implies that

$$c_i(\theta) < c_i^*(\theta^*) \quad , i = 1, 2.$$

Similarly, learning–by–doing, if not exhausted in the θ–technology, suggests that

$$c_2(\theta) \leq c_1(\theta); \qquad c_2^*(\theta^*) \leq c_1^*(\theta^*).$$

Suppose that new β–technology becomes available. If used in the first period (by the home firm), costs rise to a constant $c_1(\beta)$ level, but with learning–by–doing in the second period $c_2(\beta)$ has fallen to a level lower than $c_2(\theta)$. Similarly there is a cost vector for the foreign firm with the β–technology, $c^*(\beta^*)$, which, following the core model, we assume is not lower in either period than home $c(\beta)$ costs. Although the cost figures for either firm depend only upon that firm's decisions, the net profitability of either firm's technology depends on market prices and reflects the technology choices of *both* firms.

A two–stage game is suggested: First each firm decides on a technology, and then prices in the two periods are determined so that markets clear (with a given market demand curve). Thus each firm's net profit in each period depends upon the selection of technologies by both firms. If θ^* is the foreign selection made, the home firm's pay–off vector is $\theta(\theta^*)$ if it selects the old technology, or $\beta(\theta^*)$ if the home firm opts for the β–technology. Similarly the vectors $\theta(\beta^*)$ and $\beta(\beta^*)$ denote home profits in each technology if the foreign firm selects the new β–technology. The pay–off functions for the foreign firm, $\theta^*(\theta)$, $\theta^*(\beta)$, $\beta^*(\theta)$, $\beta^*(\beta)$ are defined in like fashion.

The possibility we stressed in Figure 1's depiction of the core model was that the home firm chooses to stick with the θ–technology while the foreign, lagging, firm leapfrogs by selecting the β^*–technology. This requires that V_θ exceed V_β while V_β^* is greater than V_θ^*. In the present more inter–dependent scenario, we examine the *dominant solution* whereby the foreign firm adopts the new technology regardless of the choice made by the home firm and the home firm sticks to the old θ–technology regardless of the foreign choice.[6] Such overtaking requires

$$V_\theta(\theta^*) > V_\beta(\theta^*)$$
$$V_\theta(\beta^*) > V_\beta(\beta^*)$$

for the home firm and

$$V^*_\beta(\theta) > V^*_\theta(\theta)$$
$$V^*_\beta(\beta) > V^*_\theta(\beta)$$

for the foreign firm. With reference to Figure 1, there would be two sets of points $\{\theta, \theta^*, \beta, \beta^*\}$. Consider the pair $\theta(\beta^*)$ and $\theta(\theta^*)$ relevant if the home firm uses the old technology. The former point would lie northwest of the latter since if the foreign firm switches from the old to the new technology, its higher costs in the first period lead to increased profits in that period for the home firm: $\theta_1(\beta^*) > \theta_1(\theta^*)$; but in the following period home profits suffer: $\theta_2(\beta^*) < \theta_2(\theta^*)$. Connect points $\theta(\beta^*)$ and $\beta(\beta^*)$ on the one hand and $\theta(\theta^*)$ and $\beta(\theta^*)$ on the other. The dominant outcome leading to overtaking has both these lines steeper than a line with slope δ. The opposite would hold for the foreign firm. If this result holds, it must be that the home firm unambiguously has a comparative advantage in the old technology and the discount factor lies between the ratio of present costs to future benefits of the two firms. Overtaking is the outcome.

The Appendix works out the details in the case of a linear demand curve. There it is shown that of the two forementioned lines for the home firm, $\theta(\theta^*) - \beta(\theta^*)$ and $\theta(\beta^*) - \beta(\beta^*)$, the former is the flatter. That is, the opportunity costs in the current period of the home technology switch relative to the net gains in the future period are smaller if the foreign country sticks with the old technology. Similarly the steeper of the two curves for

[6]If the solution is a Nash equilibrium but not a dominant solution, some of our conclusions are altered. The appendix refers more explicitly to this result.

the foreign firm corresponds to the home firm using the new technology. The discount line (δ) in Figure 1 must have an intermediate slope for the overtaking result in the dominant case. Furthermore, if we assume there is little learning left for the old technology, then if an index of conjectural variation is used to indicate the degree of competition in the duopoly market, less competitive settings result in a wider range of common discount factors, δ, that lie between the flatter home line and steeper foreign line. That is, overtaking becomes a more likely possibility given a set of cost curves for each technology for the two firms. This is a result that corresponds to that found in Vickers (1986) for patent races determined by the outcome of auction markets.

6. Principal–Agent Issues

In our core model rents or profits are earned by the competing firms, such flows accruing not only because of a possible limit on entry but because of the knowledge acquired in the production process and from any research and development activities. This knowledge, however, is specific to the kind of technology that is being utilized – although there may be external spillovers applicable to other industries just as these firms may benefit from a new β–technology that is not an outcome of their own productive or research efforts. Implicit in our treatment is the view that the net returns over and above payments to mobile factors available in the market all accrue to the owner of the firm. If, instead, the owner is separate from a group of skilled laborers who acquire the knowledge specific to a particular technology and are in a position to make decisions as to which technology is exploited, non–optimal decisions from the firm's point of view may be made.

Previous argument suggests that the leading firm has a vested interest in pursuing production with the old θ–technology, in which it has acquired a comparative advantage. However, should the new technology eventually offer benefits which, when discounted, more than offset the lower current productivity flows involved in making the switch, V_β

would exceed V_θ, and the firm would abandon the old θ–technology (as would the laggard). And such a comparison suggests that skilled agents working for the firm could as well increase the present value of their income stream by investing in knowledge of the new technology. However, we now argue that even if $V_\beta > V_\theta$, skilled agents working for the firm may have a vested interested in sending a false signal to owners of the firm, to suggest that V_θ actually is larger than V_β so that a switch in technology is not advisable.

There is an attribute of human capital in addition to its growth possibility through learning by doing via production or research. Human life is finite, and there is a terminal date for employment and utilization of skilled personnel. Although mortality is a characteristic shared by owners of firms, they generally are assumed to care about the present value of the firm that will be passed on to their heirs, whereas skilled employees of the firm may not. The two–period structure of the core model does not lend itself well to a consideration of this asymmetry. But it is not difficult to imagine a multi–period model in which future learning takes place over a number of periods. The returns to individual skilled agents, however, would be represented by a finite stream, and such a stream more heavily weights current and near–future productivities in a new β–technology by ignoring potentially higher periods of productivity beyond the terminal date. Thus the skilled agents may find it in their own interests to block the switch to a new technology even in those cases in which V_β exceeds V_θ.

Academic life provides a setting in which such behavior may be quite visible. It is often remarked that an individual's best research is done in earlier stages of his or her career, especially in the sciences and social sciences. There are exceptions, of course, but the general idea is that researchers develop a comparative advantage in pursuing or extending their original lines of research, and insist on continuing to work along certain lines even after the focus of interest in the profession has passed to new areas. This is evident in teaching performance as well. The content of, say, a graduate course in theory may not be as heavily weighted towards new material if taught by a senior professor with more limited time left to justify heavy investment in mastering the new, especially as the professor puts heavy emphasis on the value of older material with which he or she is familiar.

These remarks suggest that a firm may have an alternative to keeping a senior research and production team at work, or at least relying heavily on their advice as to the best technology to exploit. New technology does not fall from heaven – it often comes from being tried elsewhere in the economy. Thus the firm might hire from other sectors in which skilled labor has no vested interest in (or comparative advantage in) the old technology. Such mobility lessens the ability of skilled agents with a vested interest in preserving the old to block the switch to new, and eventually more productive, technology.

The asymmetry discussed here, between the owner of the firm with a long horizon and hired agents who can influence the choice of technology but with shorter horizons, suggests that firms with younger agents will be in a better position to switch to a new technology which will prove attractive, but only after the passage of some time. Thus comparative advantage in a new technology may in part be a reflection of a younger skilled work–force. This asymmetry fits into that of the core model to suggest that firms with a head–start on an older technology may more likely be overtaken by a newer firm when a new technology appears: The older firm not only has hired agents who have comparative advantage in the old technology, but also the average age of such agents could be higher with a consequent shorter horizon for productive employment.

7. Concluding Remarks

An extremely important type of over–taking has not received explicit attention in our discussion: One firm may introduce a type of product which differs in a quality dimension from existing brands. Every year firms introduce new automobiles, higher–powered computers, new forms of sporting equipment utilizing newly–developed materials. More significant is the introduction of radically different goods which prove to be good substitutes for the old. A classic case would be the development of steamships in the 19th century. This led to a decades–long competition with sail during which some parts of the market (shorter hauls in earlier days) were served by the new steam vessels whereas others (lumber and other bulk cargoes, where speed was less essential), stuck with sail until early in the 20th century. (Harley, 1971). Transportation provides other famous examples – rail vs. canals; cars, buses, and trucks vs. horse–drawn conveyances; air vs. ships. The field of communication as well is in a current state of transition as computers are utilized to provide cheaper and speedier transmissions than ordinary postal methods.

The type of competition explicitly considered in this paper is more prosaic: Firms may utilize different technologies in their competition to produce a product of standard quality. The concept of learning–by–doing provides the connective tissue whereby asymmetric past experience carries on to affect current and future costs and productivities. But one firm's advantage in the utilization of a standard technology, making it a current leader in its industry, lends a presumption as to its comparative disadvantage in adapting to a new technique where experience and learning are required in order to improve productivity. The doctrine of comparative advantage, of such profound significance in explaining trade patterns among countries, sheds light as well on the phenomenon whereby a current industry laggard may be first off the mark in gaining experience with a new technology, precisely because the leader's absolute advantage in mastering the old technology implies a comparative disadvantage in the new. Such overtaking or leapfrogging may take time since new technologies may not be forthcoming that frequently or, when they do appear, may be adopted by leaders as well as laggards on the one hand or neglected by both on the other. But comparative advantage nonetheless provides an opening in which the discounting of net productivity benefits in the future with the opportunity costs of currently switching away from a more established technology may encourage the lagging firm rationally to opt for the new whereas optimizing behavior on the part of the leader entails a pursuit of the older technology.

If the industry has a global basis, the overtaking firm may be located in one country and the present leader in another, with consequent repercussions on the pattern of international trade. However, the phenomenon whereby one country overtakes another depends as well on features of the economy not prominent in our analysis of leapfrogging by firms. Thus the Dutch Disease phenomenon described in Section 4 may adversely affect all firms in one country's industry but not in another country's. Or government industrial policy might be utilized to promote one country's industry at the expense of other industries in that country with mixed chances of success in encouraging overtaking. These possibilities raise an important question – do such policies, even if successful in leading to overtaking, serve as well to raise welfare? In this paper we have not answered this question, focussing instead on the mechanism whereby overtaking may be a natural reflection of comparative advantage.

Appendix to Section 5

Two firms in a duopolistic setting face a market demand curve:

(A.1) $p_i = -ax_i + b$ $\quad a, b > 0$ $\quad i = 1, 2$

In each period, i, market price is linearly related to total market output, x_i, which is the sum of the firms' individual outputs, $(y_i + y_i^*)$. These outputs, in turn, depend upon maximizing behavior. For example, profits for the home firm when it uses technology β but the foreign firm uses technology t^*(equal to θ^* or β^*) are shown by:

(A.2) $\beta_i(t^*) = [p_i - c_i(\beta)]\, y_i$

Each firm maximizes profits in each period by the appropriate choice of output, where we assume a *common* index of conjectural variation, γ, to show how each firm believes the other firm's output will respond to a unit change of its own. Such profit maximization leads to the following pair of first–order conditions:

(A.3)
$$(2 + \gamma)y_i + y_i^* = \frac{[b - c_i(t)]}{a}$$
$$y_i + (2 + \gamma)y_i^* = \frac{[b - c_i^*(t^*)]}{a}$$

The solutions for output levels are illustrated by that for the home firm:

(A.4)
$$y_i = \frac{1}{a\Delta}\{(1 + \gamma)\, b - (2 + \gamma)\, c_i(t) + c_i^*(t^*)\}$$
$$\text{where } \Delta \equiv (1 + \gamma)\,(3 + \gamma)$$

The solution for p_i in period *i* is obtained by substitution in equation (A.1):

(A.5)
$$p_i = \frac{(1+\gamma)}{\Delta}\{(1 + \gamma)\, b + [c_i(t) + c_i^*(t^*)]\}$$

Let π_i and π_i^* represent the profit *margins* for each firm. (e.g. $\pi_i \equiv p_i - c_i(t)$). Thus for the home firm:

(A.6) $$\pi_i = \frac{(1+\gamma)}{\Delta}\{(1+\gamma)\,b - (2+\gamma)\,c_i(t) + c_i^*(t^*)\}$$

Note that outputs are directly related to profit margins:

(A.7) $$y_i = \frac{\pi_i}{a(1+\gamma)},$$

so that total profits for the home firm are shown by:

(A.8)
$$\theta_i(t^*) = \frac{(1+\gamma)}{a\Delta^2}\{(1+\gamma)\,b - (2+\gamma)\,c_i(\theta) + c_i^*(t^*)\}^2$$
$$\beta_i(t^*) = \frac{(1+\gamma)}{a\Delta^2}\{(1+\gamma)\,b - (2+\gamma)\,c_i(\beta) + c_i^*(t^*)\}^2$$

In discussing comparative advantage in old and new technologies, we used Figure 1 to highlight the slope of lines such as $\theta\beta$, revealing the ratio of net loss this period (profits foregone in the switch from the θ to the β technology) to the net future gains. Call these ratios for the home country $\varrho(\theta^*)$ if the foreign country sticks to the old technology and $\varrho(\beta^*)$ if the foreign country adopts the new technology. By definition,

(A.9) $$\varrho(t^*) = \frac{\theta_1(t^*) - \beta_1(t^*)}{\beta_2(t^*) - \theta_2(t^*)},$$

so that substitution from (A.8) yields:

(A.10)
$$\varrho(\theta^*) = \frac{\{2(1+\gamma)b - (2+\gamma)[c_1(\theta) + c_1(\beta)] + 2c_1^*(\theta^*)\}}{\{2(1+\gamma)b - (2+\gamma)[c_2(\theta) + c_2(\beta)] + 2c_2^*(\theta^*)\}} \cdot C$$
$$\varrho(\beta^*) = \frac{\{2(1+\gamma)b - (2+\gamma)[c_1(\theta) + c_1(\beta)] + 2c_1^*(\beta^*)\}}{\{2(1+\gamma)b - (2+\gamma)[c_2(\theta) + c_2(\beta)] + 2c_2^*(\beta^*)\}} \cdot C$$

$$\text{where } C \equiv \frac{[c_1(\beta)-c_1(\theta)]}{[c_2(\theta)-c_2(\beta)]}$$

Note that these two expressions have a common second factor, C, which represents the technological basis for the home country's position of comparative advantage – the increase in average or marginal costs in the first period of switching from the old to the new technology relative to the reduction in costs in the second period. The first factor is different in the two expressions since foreign costs depend upon the technology choice of the foreign firm. Our assumptions about the old and new technologies – in particular that the learning curve is steeper for the new – guarantees that

(A.11) $$\frac{c_1^*(\theta^*)}{c_2^*(\theta^*)} < \frac{c_1^*(\beta^*)}{c_2^*(\beta^*)},$$

which suffices to establish that

(A.12) $$\varrho(\beta^*) > \varrho(\theta^*).$$

This result can be re–interpreted by noticing that the numerators (or denominators) in the first factors in (A.10) are linked to outputs of the home firm in each period, depending upon the choice of technology adopted by the foreign firm. Let $y_i(t, t^*)$ denote output of the home firm in period i if it adopts technology $t(= \theta, \beta)$ and the foreign firm adopts $t^*(= \theta^*, \beta^*)$. Furthermore, let $\bar{y}_i(t^*)$ denote the level of output of the home firm in period i that *averages* its output over the two technologies, assuming the foreign firm adopts technology t^*. Thus:

(A.13) $$\bar{y}_i(t^*) \equiv \frac{y_i(\theta, t^*)+y_i(\beta, t^*)}{2}$$

Therefore the cost/benefit ratios for a technology switch for the home country can be rewritten as (A.10′):

(A.10′)

$$\varrho(\theta^*) = \frac{\overline{y}_1(\theta^*)}{\overline{y}_2(\theta^*)} \cdot C$$

$$\varrho(\beta^*) = \frac{\overline{y}_1(\beta^*)}{\overline{y}_2(\beta^*)} \cdot C$$

As already mentioned, the second factor reflects the cost/benefit ratio that is due to the *technology* difference. The first ratio reflects the altered market situation, which in turn is captured by ratios of average output performances for the home firm. Now divide $\varrho(\theta^*)$ by $\varrho(\beta^*)$ and re–arrange to get:

(A.14)
$$\frac{\varrho(\theta^*)}{\varrho(\beta^*)} = \frac{\left[\dfrac{\overline{y}_1(\theta^*)}{\overline{y}_1(\beta^*)}\right]}{\left[\dfrac{\overline{y}_2(\theta^*)}{\overline{y}_2(\beta^*)}\right]}$$

The average first period output of the home firm if the foreign firm adopts the old technology must fall short of its output if the foreign firm uses the new technology, for in the latter case higher foreign costs ($c_1^*(\beta^*)$) helps support a higher value of p_1. Conversely, in period 2, if the foreign firm adopts the new technology its costs are lower [$c_2(\beta^*) < c_2(\theta^*)$] and therefore a lower value of p_2 (and home output) would ensue. The ratio shown in (A.14) must fall short of unity since the numerator is less than one and the denominator is greater than 1. The inequality in (A.12) is thus supported.

Completely analogous reasoning leads to (A.15):

(A.15) $$\varrho^*(\beta) > \varrho^*(\theta)$$

Overtaking will thus take place in a dominant solution if

(A.16) $$\varrho^*(\beta) < \delta < \varrho(\theta^*).$$

The case of Cournot duopoly is one in which the coefficient of conjectural variation, γ, has value zero. A move towards a more collusive duopoly is reflected in positive values for γ. (An increase in γ raises the market price in any period). Therefore we ask how the range for δ in (A.16) behaves as γ rises. If all learning has been exhausted in the old technology (so that $c_1^*(\theta^*) = c_2^*(\theta^*)$ and $c_1(\theta) = c_2(\theta)$), it is possible to show that an increase in γ raises $\varrho(\theta^*)$ and lowers $\varrho^*(\beta)$. This proves the assertion in the text that the discount factor is more likely to promote overtaking the less competitive is the nature of the market in cases of a dominant solution. However, consider the case of a non–dominant Nash equilibrium in which (A.16′) holds:

(A.16′) $\qquad \varrho^*(\theta) < \delta < \varrho(\beta^*)$.

An increase in δ raises $\varrho^*(\theta)$ and lowers $\varrho(\beta^*)$, and thus reverses this conclusion.

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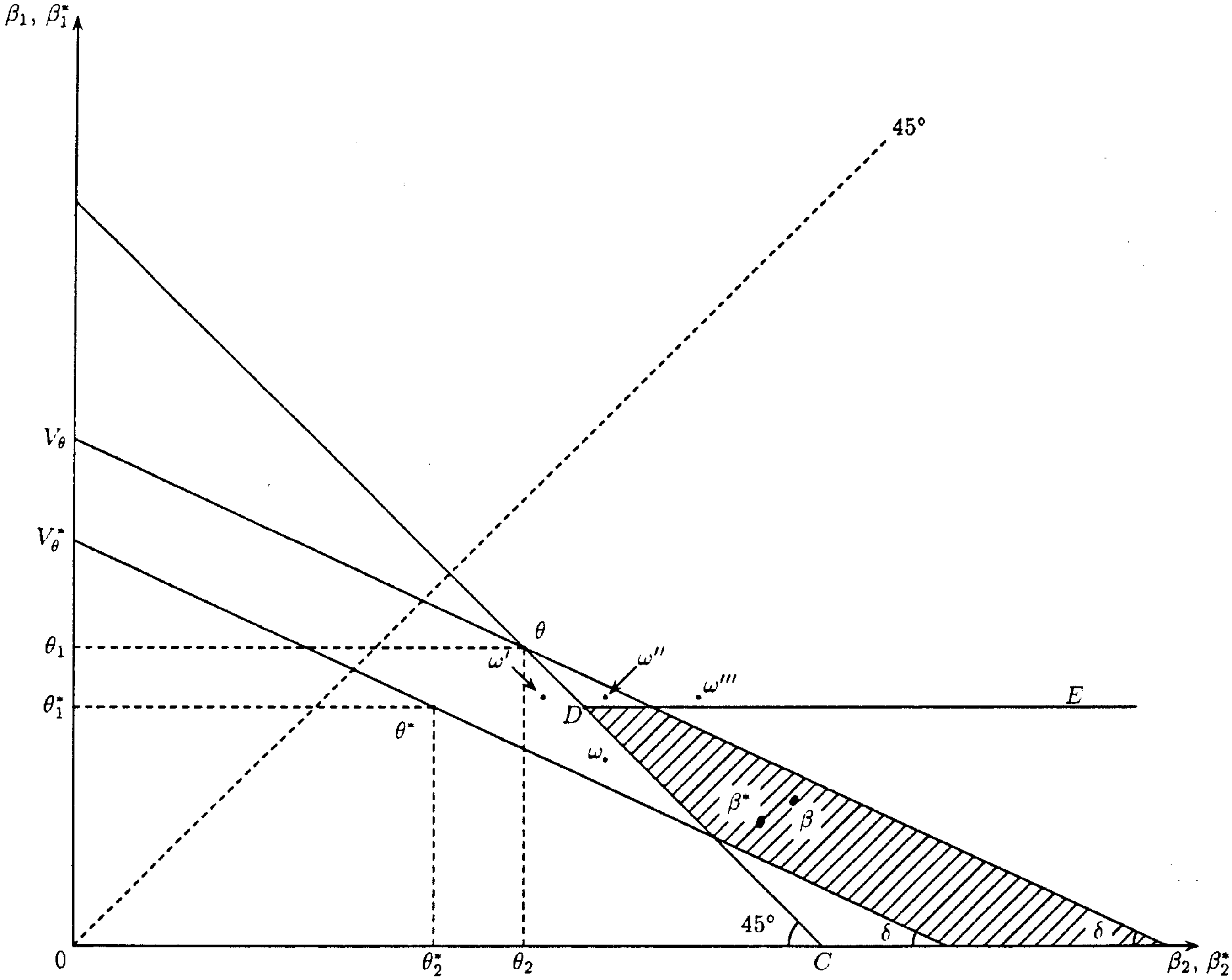
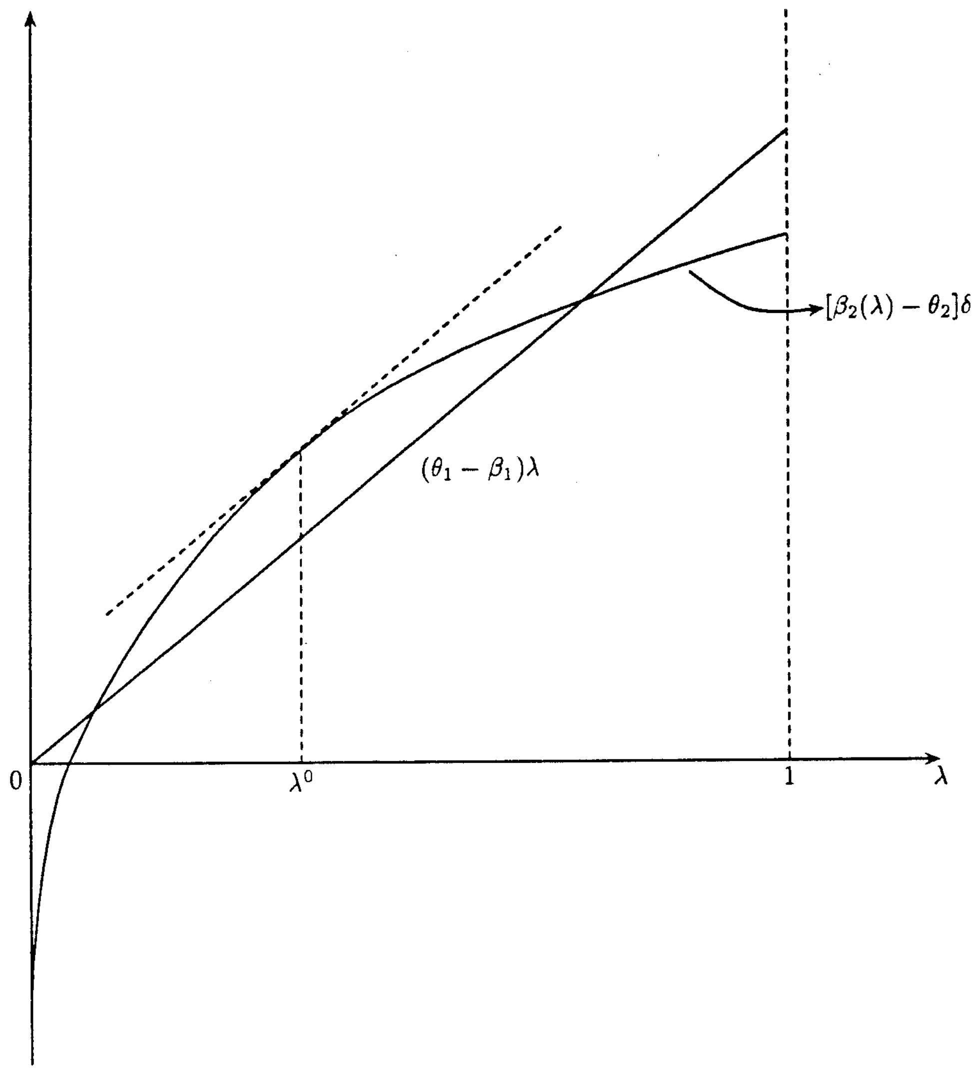


β_1, β_1^*
45°
V_θ
V_θ^*
θ
θ_1
ω'
ω''
ω'''
θ_1^*
D
E
θ^*
ω
β^*
β
45°
δ
δ
0
θ_2^*
θ_2
C
β_2, β_2^*

Figure 1



$[\beta_2(\lambda) - \theta_2]\delta$
$(\theta_1 - \beta_1)\lambda$
0
λ^0
1
λ

Figure 2