Leapfrogging in International Competition: A Theory of Cycles in National Technological Leadership

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Endogenous-growth theory suggests that technological change tends to reinforce the position of the leading nations. Yet sometimes this leadership role shifts. We suggest a mechanism that explains this pattern of "leapfrogging" as a response to occasional major changes in technology. When such a change occurs, the new technology does not initially seem to be an improvement for leading nations, given their extensive experience with older technologies. Lagging nations have less experience; the new technique allows them to use their lower wages to enter the market. If the new technique proves more productive than the old, leapfrogging of leadership occurs. (*JEL* F12, F43)

In recent years the "new growth theory," which emphasizes the role of nonconvexities and external economies in the growth process, has increasingly focused on the interrelationship between trade and growth—and in particular on the possibility of economic divergence between nations. The mechanism emphasized by such authors as Robert Lucas (1988), Alwyn Young (1991), Paul Romer (1990), and Gene Grossman and Elhanan Helpman (1991) is essentially an updated version of the traditional idea of uneven development. Suppose that some sectors generate more endogenous technological progress than others, say through learning-by-doing. Then a country that has acquired a comparative advantage in such technologically progressive sectors for whatever reason, will tend to reinforce that advantage over time and thus to establish a growing lead over less lucky rivals.

In spite of recent claims that the process of international growth is typically marked by convergence rather than divergence, (see e.g., Robert Barro and Xavier Sala-i-Martin, 1991) it is easy to think of historical episodes in which a cumulative process of divergence does seem to have been at work; one need only think of England's growing industrial leadership in the early phases of the Industrial Revolution, or America's widening lead in the first half of the 20th century. Yet while individual countries have established long periods of economic and technological leadership, such periods of dominance are not forever. The early modern preeminence of the Dutch was ended by the rise of England; England's preeminence was ended by the rise of America and Germany; and we may be seeing the United States overtaken by Japan (see Table 1).

Such economic and technological "leapfrogging" could be essentially random: lagging countries may simply get lucky, and leading countries get unlucky. Historians have often suggested, however, that a more systematic process is at work, in which the very success of the leading country at one stage of economic development prevents it from taking the lead in the next.

Why should success breed failure? One might appeal to sociological factors; or one might, like Mancur Olson (1982), suggest that a successful nation is bound to accumulate institutional rigidities that eventually cripple its economic performance. In this paper, we want to suggest a more narrowly

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TABLE 1—GDP PER CAPITA AT 1970 U.S. PRICES

Year	Netherlands	United Kingdom	United States	Japan
1700	440	288		
1820	400	454	372	251
1870	831	972	764	251
1950	1,773	2,094	3,211	585
1979	4,396	3,981	6,055	4,419

Source: Angus M. Maddison (1982 p. 8).

economic explanation, based on a hypothesis about the nature of technological change.

We suggest that technological change is of two kinds. Most of the time technology proceeds incrementally, by gradual improvement of methods within a well-understood framework. This "normal" technical change is likely to proceed largely through learning-by-doing and will tend to occur most rapidly in those countries with established advantages in technologically progressive sectors. At intervals, however, there are major breakthroughs that change the nature of technology fundamentally. Such major breakthroughs require that nations start fresh.

When a new technology becomes available, however, it may not seem much better initially than the old one—and to a nation that has established a commanding lead in the old technology, it may well seem worse. Thus 18th-century Holland, with its established lead in shipping, banking, and trading, was not attracted by the prospects for cotton spinning; it was the somewhat poorer English who moved into the new area and exploited its eventually far greater potential.

Such a failure to take advantage of new technologies may seem in retrospect like shortsightedness. In fact, however, it may have been a fully rational decision from the point of view of individual entrepreneurs. A country with an established lead will be a high-wage nation;[1] new technologies or industries that are *initially* less productive than the old are therefore not profitable. It is only in a lagging nation, where the old technology is less well developed and hence wages are lower, that the new, relatively untried techniques seem attractive.[2]

This relationship between high wages in leading countries and the failure to switch to sectors with higher productivity was mentioned by Angus Maddison (1982 p. 33). On the turning point between the Netherlands and the United Kingdom, he notes that "there seems little doubt that a contributory factor to Dutch decline in the 18th century was that the currency was overvalued"; similarly, in describing the switch from Britain to the United States, he underlines that "At the time it was overtaken by the USA, there were strong signs that the UK was growing at less than its potential because its currency was over-valued."[3]

In this paper we develop a simple formalization of these ideas, using a minimalist two-country model of trade and growth. The

[1]The Netherlands remained a distinctly richer and higher-wage nation than England as late as the time of *The Wealth of the Nations*, in which Adam Smith (1776 p. 91) remarked in passing that "The province of Holland, on the other hand, in proportion to the extent of its territory and the number of its people, is a richer country than England.... The wages of labour are said to be higher in Holland than in England."

[2]There is an industrial-organization literature on "leapfrogging" among firms; the key concern of this literature is with the possibility that established monopolists may systematically have less incentive to innovate than potential rivals and thus may in effect eventually cede technological leadership. Among the key papers in this genre are Richard J. Gilbert and David M. G. Newbery (1982), Drew Fudenberg et al. (1983), Jennifer F. Reinganum (1983), and Fudenberg and Jean Tirole (1985). Our leapfrogging mechanism is, however, quite different; we briefly analyze the differences in Section V.

[3]For our purpose, an overvaluation of the exchange rate is equivalent to overvalued real wages.

paper is in six parts. In the first part we set out the basic assumptions of the model. In the second we describe the conditions of equilibrium at a point in time. In the third part we describe the model's dynamics during a period of "routine" technological progress, where productivity rises only because of learning within the bounds of a well-established technology, and show how such learning tends to "lock in" the role of the leading nation. In the fourth section we show how introducing a new technology, for which experience with the old is not very helpful, can lead to endogenous leapfrogging, in which the leader is passed by the erstwhile follower. The fifth part discusses the relationship between our model and the industrial-organization literature on leapfrogging among firms. A final section suggests some conclusions and possible extensions.

I. The Basic Model

We consider a world of two countries, Britain and the United States. There are two kinds of goods: a technically stagnant good (food) and a set of technically progressive manufactured goods. Labor is the only factor of production, and we assume that the two countries have equal labor forces L.

In the food sector we suppose that there are constant returns to scale, with the productivity of labor the same in both countries. Without loss of generality, we set the productivity of labor in food production equal to 1. Thus the outputs of food in Britain and America, respectively, are:

$$Q_{\mathrm{F}} = L_{\mathrm{F}} \tag{1}$$

$$Q_{\mathrm{F}}^{*} = L_{\mathrm{F}}^{*} \tag{2}$$

where L_{F} and L_{F}^{*} represent the employment in food production in the two countries.

Manufactures consists of a series of increasingly sophisticated generations of goods, which for simplicity we assume to be perfect substitutes. Production within each generation of the sequence is subject to external learning effects, which are specific to each country. This assumption of country-specificity of learning is crucial to the model and therefore needs some justification.

The essential argument for national specificity of learning is that much knowledge—and especially the kind of knowledge that arises from experience within a particular technological universe—is hard to codify and is transmitted largely through personal contact. One can hardly improve on Alfred Marshall's (1890 p. 271) description of the reasons why improvements in industry tend to occur best when those industries are geographically localized: "When an industry has thus chosen a locality for itself, it is likely to stay there long: so great are the advantages which people following the same skilled trade get from near neighborhood to one another. The mysteries of the trade become no mystery; but are as it were in the air.... Good work is rightly appreciated, inventions and improvements in machinery, in processes and the general organization of the business have their merits promptly discussed: if one man starts a new idea, it is taken up by others and combined with suggestions of their own; and thus it becomes the source of further new ideas."

Modern geographers, such as Allen J. Scott (1988) and Michael Storper (1992), have provided considerable evidence that innovative industries tend to thrive in geographically concentrated districts within which personal, face-to-face contact is routine. This is a theme that is central to the influential recent work of Michael E. Porter (1990).

Indeed, such is the localization of technological innovation that we should arguably offer a model of regional or even urban rather than national leapfrogging. We intend to pursue this line in future work. In this paper, however, we treat countries as if they were natural untis, both for labor mobility and for information diffusion.

Returning to the model: we let $Q_i(t)$ be Britain's rate of output of the manufactured good of generation i at time t; then for the current output we have

$$Q_i(T) = A_i(K_i(T))L_i \tag{3}$$

where

$$(4) \qquad K_i(T) = \int_{-\infty}^{T} Q_i(t)\,dt.$$

Similarly, for the United States we have

$$(5) \qquad Q_i^*(T) = A_i(K_i^*(T))L_i^*$$

where

$$(6) \qquad K_i^*(T) = \int_{-\infty}^{T} Q_i^*(t)\,dt.$$

We assume $A' > 0$, $A'' < 0$. That is, there are positive learning effects; but learning is subject to diminishing returns as each technological generation matures. The significance of this assumption will become apparent shortly.

We choose units so as to make quantities of successive generations of manufactured goods comparable. Given this choice of units, each successive technological generation is *better* than the previous one; that is, $A_{i+1}(Z) > A_i(Z)$ for any given Z. The new technology is only better, however, given sufficiently equal experience. A nation with extensive experience in an old technology may be more productive using that technology than it would be in the early stages of a new one.

We assume demand to be identically Cobb-Douglas in the two countries.

$$(7) \qquad U = D_{\rm M}^{\mu} D_{\rm F}^{1-\mu}$$

where $D_{\rm M}$ is consumption of the manufactures aggregate and $D_{\rm F}$ is consumption of food. We assume, for reasons that will be clear shortly, that the share μ of manufactures exceeds 0.5.

II. Short-Run Equilibrium

Except for occasional moments when one of the countries in our model is just in the process of passing the other, one of the two countries will have higher productivity in manufactures, while they have the same productivity in food. We will consider an initial situation in which Britain is the high-productivity nation, that is, where $A_1 > A_1^*$; but with a few changes the same equations apply when the countries' roles are reversed.

At any given point in time this model is simply a conventional two-good Ricardian model. In general, such models have three kinds of equilibrium: one in which both countries produce food and therefore receive equal wages; one in which both countries are specialized, and relative wages are determined by demand; and one in which both countries produce manufactures, with relative wages determined by relative productivity in manufactures. Our assumptions that $\mu > 0.5$ and that the two countries have the same labor force rule out the first kind of equilibrium and ensure that one country will always be specialized in manufactures.[4] To determine whether the other country also produces manufactures, we first ask what the relative wage rate would be if both countries were specialized. In that case $L_{\rm M} = L = L_{\rm F}^*$. Let E be world expenditure. Of this world expenditure, a share μ falls on manufactured goods, and a share $1-\mu$ falls on food. Thus we must have

$$(8) \qquad wL = \mu E$$

$$(9) \qquad w^*L = (1-\mu)E$$

implying

$$(10) \qquad \frac{w}{w^*} = \frac{\mu}{1-\mu}$$

where w and w^* are the nominal wages in Britain and America, respectively. Is this situation, which we will refer to as "full

[4]Suppose that both countries produced food. Then the nominal wage rates in both countries, w and w^*, would necessarily equal 1, and whichever country had the higher productivity in manufacturing would therefore produce all manufactured goods. Total world expenditure on manufactured goods would be $2\mu L$, implying since $w=1$, that $L_M = 2\mu L$; but with $\mu > 0.5$, this implies $L_M > L$—which is impossible. Thus, only one country produces food, with the other completely specialized in manufactures.

specialization," an equilibrium? Only if this relative wage rate does not exceed A_i/A_i^*. If this criterion is not met, America must also produce some manufactures, and the relative wage rate will be

$$(11) \qquad \frac{w}{w^*} = \frac{A_i}{A_i^*}.$$

In such an equilibrium, which we will refer to as "partial specialization," we can immediately determine the allocation of American labor between food and manufactures. Let food (and hence American labor) be the numeraire. Then world income is

$$(12) \qquad Y = \left(\frac{w}{w^*} + 1\right)L$$

and world spending on food, which equals American employment in food production, is simply

$$(13) \qquad L_F^* = (1-\mu)L\left(\frac{A_i}{A_i^*} + 1\right).$$

As we will see, in general the model will predict alternation between full and partial specialization. Thus we note for future reference several features of the two kinds of equilibria. First consider full specialization. In this case, as noted, the relative wage is $\mu/(1-\mu)$. The price of manufactures in terms of food is

$$(14) \qquad P_M/P_F = \frac{\mu}{(1-\mu)A_i}.$$

The real wage rates of the two countries are:[5]

$$(15) \qquad \omega = \gamma A_i^{\mu}\left(\frac{\mu}{1-\mu}\right)^{1-\mu}$$

$$(16) \qquad \omega^* = \gamma\left(\frac{(1-\mu)A_i}{\mu}\right)^{\mu}$$

[5]The price index is $(P_m/\mu)^{\mu}[P_f/(1-\mu)]^{1-\mu}$.

where $\gamma = \mu^{\mu}(1-\mu)^{1-\mu}$. In the case of partial specialization, the relative wage is A_i/A_i^*. The price of manufactures in terms of food is

$$(17) \qquad P_M/P_F = \frac{1}{A_i^*}$$

and the real wage rates of the two countries are

$$(18) \qquad \omega = \gamma A_i (A_i^*)^{-(1-\mu)}$$

$$(19) \qquad \omega^* = \gamma (A_i^*)^{\mu}.$$

We will assume that Britain initially has a productivity advantage in manufacturing that exceeds $\mu/(1-\mu)$. Thus the initial equilibrium is one of full specialization, in which Britain is specialized in manufactures, while America specializes in food.

III. Dynamics within a Technological Generation

Given the assumed initial pattern of specialization, Britain will steadily widen its productivity advantage over the United States. This will simply ratify, indeed lock in, that pattern of specialization. Since the entire British labor force L is devoted to manufactures production, we have

$$(20) \qquad \frac{\dot{A}_1}{A_1} = A_1' L.$$

Thus British productivity will rise over time, while American productivity will remain constant. Given the assumed shape of $A(\cdot)$, however, the rate of British productivity growth will decline over time.

Throughout this period, relative wages will be governed by (10); thus they will remain unchanged in spite of Britain's growing productivity advantage in manufactures. The growing productivity will instead be reflected in a corresponding decline in the relative price of manufactures.

If this were the only form of technological change, this would be the full story. To get leapfrogging, we must add a second kind of change.

IV. Leapfrogging

We now suppose that a new technology, which we designate as technology 2, is introduced. As assumed above, the new technology is better than the old in the sense that, given the same amount of experience, it yields higher productivity. We assume, however, that for the British, who have extensive experience in the old technology but none in the new, the new technology is initially inferior. That is, at T_2, the date at which the new technology is introduced,

$$A_2(0) < A_1(K_1(T_2)). \tag{21}$$

The result is that individual producers in Britain have no incentive to adopt the new technology.[6]

American producers are in a different situation, because they pay lower wages and lack experience in the old technology. The new technology will be profitable to introduce in America provided that

$$\frac{A_2(0)}{A_1(K(T_2))} > \frac{1-\mu}{\mu}. \tag{22}$$

We assume this to be the case. The assumptions about the new and old technologies are illustrated in Figure 1.

The introduction of the new technology has an immediate impact on the pattern of specialization, shifting it from full to partial specialization. Britain's relative wage rate (w/w^*) falls from $\mu/(1-\mu)$ to A_1/A_2^*, and America begins to produce manufactured goods.

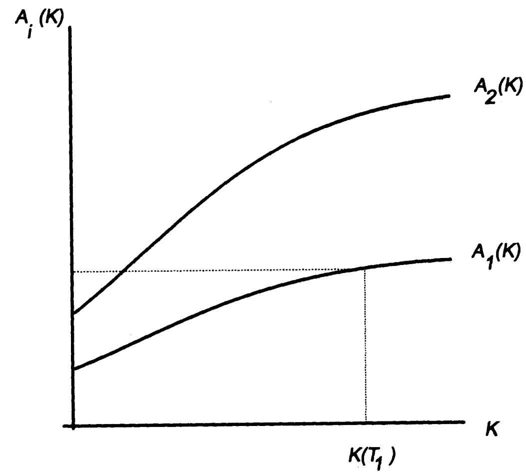

FIGURE 1. ASSUMPTIONS ABOUT THE NEW AND OLD TECHNOLOGIES

What we now assume is that the $A(\cdot)$ function for the new technology is sufficiently steep in its early stages, and the slope of the function for the established technology sufficiently flat (at its current, well-developed stage), that American productivity now begins to rise more rapidly than British productivity does.[7] During this rise in American relative productivity, the equation for American employment in food is

$$L_F^* = (1-\mu)L\left(\frac{A_1}{A_2^*}+1\right). \tag{23}$$

Since A_2^* will be rising relative to A_1, American food employment will steadily fall. As long as A_1/A_2^* remains greater than 1,

[6]One might imagine that firms could have an incentive to adopt an initially higher-cost technology in the knowledge that this technology will eventually prove superior. This is not the case here because of our assumption that learning is wholly external to firms. Suppose that a firm expected all other firms to move to the new technology immediately; would the firm want to do the same? No: it would be more profitable to stay with the old technology as long as it remained lower cost, and then switch. However, since each firm will make the same calculation, nobody will adopt the new technology.

[7]A sufficient (though by no means necessary) condition is that each successive $A(\cdot)$ function approaches an asymptotic level of productivity that is surpassed by the next technological generation; in this case, the country that adopts the new technology is guaranteed eventually to overtake the leader.

however, the pattern will remain one in which Britain remains specialized in manufactures.

During this transition, real wages in America will steadily rise, because rising productivity in manufacturing will lead not only to higher output, but to improving terms of trade:

$$\omega^* = \gamma(A_2^*)^{\mu}. \tag{24}$$

Meanwhile, however, rising relative American productivity will worsen Britain's terms of trade, possibly leading to a declining real wage:

$$\omega = \gamma A_1(A_2^*)^{-(1-\mu)}. \tag{25}$$

At some point, America may overtake British productivity in manufactures. At that point there must be an abrupt reversal of the trade pattern: America now specializes completely in manufactures, while Britain produces some food as well as manufactures.

Why has America now surpassed Britain in productivity? Because America has adopted and gained experience in the ultimately superior technology, while Britain has not. Eventually if the new technology surpasses the old by enough, that is, if

$$\frac{A_2^*}{A_1} > \frac{\mu}{1-\mu} \tag{26}$$

we get full specialization again, and we have reversed the initial position. After this reversal, the British produce only food, while the Americans produce manufactures. At this point, of course, we now have the conditions for a future reversal of fortune, in which lagging Britain once again overtakes America.

A useful way to think about this potential cycle is in terms of relative wages, as illustrated in Figure 2. In periods of full specialization, the leading country has a wage rate $\mu/(1-\mu)$ times that of the lagging nation; when there is a major change in technology, that wage advantage is suddenly reduced, then gradually erodes further, and is eventually reversed. The stage is then set for the next major technological shock to initiate a new round of leapfrogging.

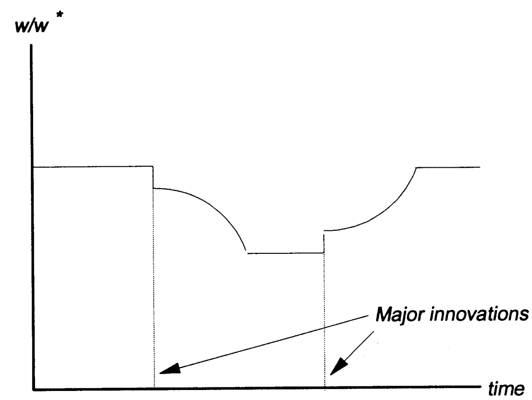

FIGURE 2. RELATIVE WAGES ACROSS THE CYCLE

V. Relationship to the Industrial-Organization Literature

There is an extensive industrial-organization (IO) literature on the conditions under which the technology of dominant firms tends to be overtaken by that of new entrants. This literature evidently bears on similar phenomena to those discussed here. The underlying mechanism is, however, quite different.

In the IO literature there are usually assumed to be no externalities; firms are assumed to be able to establish full proprietary control over any new technologies they develop. Nonetheless, leapfrogging can still arise because of the so-called "replacement effect" (see Tirole, 1988 pp. 391–2). An established monopolist has a somewhat reduced incentive to innovate because he is earning rents from the old technology. Gilbert and Newberry (1982) showed that, in spite of this effect, an established monopolist in a world of complete certainty would still innovate ahead of potential rivals; but Reinganum (1983) has shown that, in the presence of uncertainty, established monopolists may indeed make less innovative effort than their potential rivals, preferring to cash in on the rents from their established position even though they know that these rents will eventually disappear.[8]

Clearly, our story in this paper is very different. The failure of a country to adopt a new technology is not the result of a rational decision that intertemporal utility is maximized by clinging to an old technology for a while longer, as in the IO approach. Instead, it is the result of decisions by individual firms that may well not be collectively rational, because technological competence is assumed to reside at a national level rather than at the level of the firms. Firms in a leading country fail to adopt a new technology because, *from the point of view of an individual firm*, that technology is initially inferior in a country that has extensive collective experience in older techniques.

There is evidently an incentive in our model for countries to pursue industrial policies; a well-informed government might increase national welfare by providing incentives for firms to adopt a new technology even when it is currently less productive than old methods. The competition between *national* industrial policies would then come to resemble the competition among *firms* in the IO literature. In this paper, however, we choose not to get into such questions.

We may also note that the IO literature is very much focused on partial equilibrium. Our subject forces a general-equilibrium treatment, and indeed general-equilibrium effects on wages and relative prices play central roles in the analysis.

VI. Conclusion

David Landes (1966 p. 563), echoing many other observers, has noted that "Prosperity and success are their own worst enemies." The usual explanation of the dynamic of "shirtsleeves to shirtsleeves in three generations" rests on noneconomic and socioeconomic factors. This paper suggests, however, that there may also be a simple economic explanation. In times of normal, incremental technological change, increasing returns to scale tend to accentuate economic leadership. However, at times of a new invention or a major technological breakthrough, economic leadership, since it also implies high wages, can deter the adoption of new ideas in the most advanced countries. A new technology may well seem initially inferior to older methods to those who have extensive experience with those older methods; yet that initially inferior technology may well have more potential for improvements and adaptation. When technological progress takes this form, economic leadership will tend to be the source of its own downfall.

Of course this need not happen. A number of conditions must hold if introduction of a new technology is to lead to a leapfrogging process:

(i) The difference in wage costs between the leading nation and potential challengers must be large.
(ii) The new technology must, when viewed by experienced producers, appear initially unproductive compared with the old.
(iii) Experience in the old technology must not be too useful in the new technology.
(iv) The new technology must ultimately offer the possibility of substantial productivity improvement over the old.

When these conditions hold, however, there will be a systematic process in which success breeds failure and vice versa.

In conclusion, we might also note that a leapfrogging mechanism of this kind may well apply in other contexts and at shorter time scales than the grand level of national competition described in this paper. In particular, we would argue that leapfrogging stories are highly relevant to regional and urban economies. At this level, high land rents and congestion as well as high wages in the leading region may create the opportunity for the follower to begin its surge. The principle remains the same: those who

[8]Fudenberg et al. (1983), in their model 3, offer yet another leapfrogging story that relies crucially on information lags. Here the point is not so much a systematic tendency for leaders to be overtaken, as a failure of preemption in the face of incomplete information.

have a great deal of experience with an old technology may, for that very reason, fail to take advantage of new opportunities.

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