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Endogenous Learning and Economic Growth

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The basic conception that motivates the analysis presented in this entry is that the development of knowledge and training of the labor force are crucial determinants of productivity growth. This idea is in keeping with the widely held view that education, broadly defined, is closely linked with an economy's productivity (see *Education and Economic Growth* and Easterlin 1981). But what precisely is the nature of that link and how does it generate changes in productivity in different economies over time? The specification of that link is a key element and distinctive feature of this analysis.

The traditional production function approach identifies the main sources of productivity increase as external to the production process: in increases in human capital, physical capital, and exogenous technological change (see *Education and Economic Growth*). However, this entry will take an alternative approach. The emphasis is placed on productivity increase as a self-generating process depending on specific activities geared to the production of new knowledge. Also emphasized is the embodied learning associated with production in the form of both learning-by-doing and learning-by-using. Productivity increase occurs when the production process itself generates new knowledge (education and training) and when education and training are incorporated as new knowledge in the production process. Thus, this approach keeps education and training as a central focus, but situated within the production process itself rather than as external inputs.

With this approach, a specific set of analytical questions is addressed. These questions arise from the empirical record of productivity growth among different world economies, both regional and national.

1. Convergence in Productivity Levels

Among a selected sample of advanced capitalist economies, a notable feature of the postwar experience of productivity growth is a tendency to convergence in productivity levels. This tendency has been identified and discussed by a number of observers (Abramovitz 1986, Baumol 1988, Maddison 1982, 1987, Matthews et al. 1982). However, the strength and generality of this tendency are a matter of dispute (Baumol et al. 1988, De long and Bradford 1988, Romer 1989, Dowrick and Nguyen 1989, Baumol et al. 1989). Even if it is accepted for a specific subsample of countries, it remains evident that there is great diversity in the actual pattern of experience of a wider class of countries, including developing countries, observed over the same period. Among this wider class, the coexistence of both convergence and divergence can be found with no clear and unambiguous case for either tendency to prevail across the whole set of countries.

Owing to the absence of comprehensive productivity data for developing countries, per capita income figures which admittedly provide only a rough guide to productivity levels have to be relied on. The available data (World Bank 1992) show that, for much of the postwar period, the group of "middle income economies" have narrowed the gap relative to the top group of "industrial market economies." The most dramatic examples of this tendency are the countries constituting the so-called "Asian Miracle" (World Bank 1993). On the other hand, for the "low income economies" as a group, the gap has actually been increasing relative to the top. As to the actual magnitude of the gaps involved, in 1990 the ratio between the top and the bottom stood at 56:1 and between the top and the middle it was 6:1.

This record of experience in productivity growth poses deep problems for economic analysis. The overall picture is evidently much more diverse and complex than either a simple convergence thesis, or its opposite, a divergence and polarization thesis, would suggest. (For a penetrating discussion of some of the complex issues involved in analyzing the historical record of differential productivity growth among countries, see Abramovitz 1986 and Nelson 1981.)

As mentioned before, this entry addresses a specific set of analytical questions that this picture raises. The focus is on the nature of the so-called "convergence process" as such and, in particular, on the following questions. Under what circumstances does the process of productivity growth tend to converge or diverge? What are the factors that determine such convergence or divergence? If a productivity gap persists, what determines its ultimate size?

In order to provide an answer to this set of questions, "a model of a productivity race" will be developed in this entry, a model in which there are specified relationships governing the rate of productivity growth among different production units viewed as countries or regions. From these relationships it is possible to find certain characteristic conditions, related to the parameters of the productivity-increasing process. These conditions allow a direct inference concerning factors that determine the possibility of convergence/divergence among different units and the size of the gap, if any, that remains between them.

2. A Heuristic Model

This is a model of pure productivity growth. It ab-

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stracts essential features of productivity growth as an endogenous process, putting aside other factors that are usually considered to affect growth of output, such as saving/investment rates, aggregate demand, supply of labor, and natural resources.

The concept of productivity used here is the simple and well-defined concept of labor productivity; that is, average product per unit of labor. This bears comparison with the neoclassical concept of total factor productivity, measured as the ratio of output to a weighted index of (augmented) capital and labor inputs. All the well-known capital-theoretic problems implicit in the aggregate production function underlying that concept are avoided here by focusing on labor productivity. Actually, in this model it is assumed that labor is the only input in production, although there is an augmentation effect on the side of labor arising from experience. Correspondingly, factors related to "capital deepening" that have traditionally been used to account for productivity growth, whether one thinks of capital deepening either as increasing mechanization or as variation of the length of life of different vintages of capital, are left out of consideration. Other factors such as investment in human capital (formal education) are also ignored.

It is assumed that productivity increase is a "self-generating process." This self-generating feature derives from two conditions that are crucial to the model. First, it derives from the operation of what might be termed the "knowledge industry." This industry consists of the congeries of activities taking place within universities and research institutes, within the Research and Development (R&D) divisions of firms, in industrial laboratories, and in the activities of people tinkering in the basement. It therefore includes what is commonly referred to as "Research and Development" activity, but much else besides. Operationally, the output of this industry is embodied in technical blueprints, patents, professional and trade journals, books, videos, computer software, and the like. These outputs are linked to production, and hence to productivity, in many complex ways that defy detailed specification. Nevertheless, the link is clear and well-established. Conceptually, what this analysis seeks to capture is the crucial role of these activities as a determinant of overall productivity growth.

Freeman (1982) provides the most forceful statement of the argument supporting this view of the role of the knowledge industry as a key feature of the development of modern economies in the twentieth century. Freeman conceives what he calls "the Research and Development System" as "the heart of the whole complex." Even so, there are still considerable empirical difficulties in identifying exactly what constitutes this "system", as shown in National Science Foundation (1987). Machlup (1962) gives a much wider definition of the "knowledge industries" and estimates that 30 percent of the labor force in the United States economy is included in his definition. Porat (1977) defines a similar category of "information occupations" to include about 50 percent of total occupations. (For relevant empirical evidence on the contribution of Research and Development to productivity growth, see Griliches 1986 and Mansfield 1980.) From the standpoint of ascribing causality, the relationships involved are considerably complex, as is argued forcefully by Nelson (1981).

Second, the self-generating feature of productivity growth derives from an intrinsic characteristic of the production process, namely that experience counts in some meaningful sense. In particular, it counts here towards further increase in productivity. In this respect, there exists a "learning effect", which is modeled here as both a learning-by-doing effect and a learning-by-using effect. This feature of the model also conforms well to ideas that have been demonstrated and documented in the literature (Arrow 1962b, Rosenberg 1982.)

This particular way of approaching the problem of productivity growth has the significant implication that every producing unit (country or region) has the capacity to generate its own productivity growth from its own activity of knowledge production and learning. This capacity is subject to a critical threshold effect that, as shown below, may operate to inhibit some units from starting up the process. Still, every producing unit has the capacity to pull itself up by its own bootstraps, so to speak, provided that the required minimum condition is met. Therefore, observed differentials in performance among units, instead of being reduced simply to arbitrary external factors, barriers, or limits, must be accounted for by factors that are internal to the productivity increasing process. Furthermore, once these factors are known, the conditions under which the process will tend to converge or to diverge can be identified, as well as what determines the asymptotic state of that process as regards the magnitude of the productivity gap. This is essentially the thrust of the analysis presented here.

For the purpose of this analysis, the following assumptions about knowledge as a commodity are made. First, it is permanent and indestructible and therefore does not depreciate over time. Second, it is a produced commodity, made by its own production process in the knowledge industry. Third, it is a high-powered commodity in that it has the capacity to increase the productivity of all industries including its own. Fourth, it generates significant externalities in the course of its production and use, in the strict sense that any producer can benefit from access to and use of a given total quantity of knowledge without diminishing the amount available to others. This externality feature of knowledge as a commodity implies that there are intrinsic problems of establishing property rights and hence of appropriation of income from its use. Thus, the idea of inferring a unique market-determined price of knowledge or an immediate connection with income of its owners is highly problematical. For this reason, it is worth emphasizing that no significance is assigned here to the pricing and income distribution side of the production of knowledge. (Some relevant issues concerning the conception of knowledge as a commodity with its own peculiar attributes are considered by Arrow 1962a and Nelson 1959.)

3. *The Model*

In constructing the relations of the model, a critical variable x, the stock of knowledge, which is the sum of all the flows of knowledge generated in the past is defined. Thus,

$$x = \int_0^{\tau} \dot{x}\, dt \qquad (1)$$

It would be straightforward to extend this formulation to allow for depreciation of the stock of knowledge, but this complication is not considered here. The essential point is that x is assumed to be a scalar. This notion of an aggregate of knowledge is used here for heuristic purposes only. A simple way of giving it a concrete representation is, for instance, as a number of blueprints or a number of patents. There are, of course, important theoretical and practical problems involved in constructing such an aggregate (as with many other aggregates commonly used in economic analysis) in a real-world context of heterogeneous knowledge commodities, but these problems are not considered here, and neither are they strictly relevant for present purposes.

The production characteristics of the knowledge industry are specified as follows:

$$\dot{x} = f(x,L) = \phi(x) \cdot L \qquad (2)$$

Here, the flow output of knowledge $\dot{x}$ is a function of the stock of knowledge x and the labor input L. The stock of knowledge represents an index of productive experience, which has a positive effect on production through a process of "learning by doing." The learning function is further specified to be a function $\phi(x)$ which is a multiplicative factor applied to the labor input. This formulation says simply that the track record of experience in producing knowledge, as measured by the cumulated stock of knowledge already produced, governs the productivity of labor in producing knowledge.

It is assumed that the average product of experience is greater than the marginal product and that the marginal product is positive:

$$\frac{\phi(x)}{x} > \phi' > 0 \qquad (3)$$

Thus, there is a kind of "diminishing returns" to experience. This assumption is intended to capture an idea that recurs in the literature, taking different forms. In its most common form it is the idea of running up against a frontier of technological knowledge, which essentially implies that beyond a certain point the yield of incremental efforts in Research and Development activity rapidly falls off (to zero in the extreme). It is sometimes tied to Wolff's Law referring to a general tendency to "retardation of progress" (Freeman 1982). It could also be derived from the idea of a "lock-in effect" arising from cumulative experience along a given trajectory of technological development (Dosi 1984, 1988). Or, it could be that there is a kind of "dead weight" of past experience connected with the social and institutional structures that it generates, such as "the accumulation of special interest groups" (Olson 1982). Whatever form it takes, this idea evidently entails the existence of some condition within the knowledge-producing industry that acts cumulatively to retard the process of increase in productivity. That condition may itself be considered to be of an essentially transitory nature if, over time, "major breakthroughs" in knowledge occur so as to expand the scope for productivity increases at any level of experience. Nevertheless, while recognizing its "short run" character in this sense, the analytical implications of this idea are worth exploring here.

The logic of this idea does not necessarily rule out the existence of an initial phase of increasing returns, but for simplicity this analysis focuses on the case of diminishing returns as an "ultimate" phase of the process. Also, it must be emphasized that, as presented here, there is nothing inherent in the idea of "diminishing returns to experience" that makes it a purely technological condition. Rather, it is considered to be an analytic expression for a wide range of social and institutional factors that are themselves the product of historical development.

It is further assumed that, in order to start up the knowledge industry, it is strictly necessary to have some positive amount of labour input to begin with:

$$L \geq L^* \qquad (4)$$

Thus there is a critical mass, or minimum threshold, of engineers, physicists, economists, and the like, that have to be assembled in order to run an effective knowledge-producing process. This assumption also captures an idea that is commonly found in the literature on research and development. It has the significant implication that any unit (country or region) which is unable, for whatever reason, to mount the required minimum scale of the activity is unable to gain the full advantages of the productivity-increasing process.

Assume that there is a second productive sector, the y-sector, that produces a consumption commodity. Output of this commodity, y, is produced by labor L_y. The labor employed in this sector is able to enhance its productivity by drawing on the total stock of knowledge accumulated from production in the x-

sector without diminishing the amount of it available to that sector. The same total stock of knowledge therefore enters into the production equation of both the x- and y-sector. In the x-sector, however, it represents a "learning-by-doing effect." whereas, in the y-sector, it incorporates a "learning-by-using effect." This learning-by-using effect is specified to be a multiplicative factor applied to the labor input, as follows:

$$y = h\,(x, L_y) = \psi(x) \cdot L_y \qquad (5)$$

Hence, there exists a two-sector economy, with a knowledge-producing and knowledge-using (consumption–good producing) sector. There is a degree of circularity in production insofar as the knowledge output reenters the productive process as the stock of experience, giving rise to learning effects in both sectors. There is an externality feature of knowledge associated with the fact that both sectors draw on the same total stock of knowledge to boost their productivity. Output of the consumption commodity, though forming part of the aggregate national income, drops out of the picture viewed from the standpoint of the total reproductive process. In the subsequent analysis, no attention is given either to consumption behavior or to movements of the aggregate national income: the focus is entirely on the production side, specifically on productivity growth which is uniquely connected with growth in the stock of knowledge.

Now, assume that there are two countries (or regions), A and B. Both have an established and viable knowledge-producing industry and a consumption-good industry. Issues involved in determining the pattern of trade and specialization in the countries are left out of this analysis, inasmuch as the pricing side of the picture (on which an account of comparative advantage must be based) is being ignored. Still, it is not unreasonable to suppose that both countries produce some of the same commodities, unless it should turn out that specialization according to comparative advantage yields a corner solution, which would be a very special case.

The assumption that production conditions are the same in both countries could be usefully dropped and the model extended to allow for differences in production conditions across countries. Country A is the leader in the strict sense that it has a greater stock of knowledge than country B, so that $x_A > x_B$. Correspondingly, A also has all-round higher levels of labor productivity. In addition, country A allocates relatively more labor to the knowledge industry than country B, so that $L_A > L_B$. Insofar as ther exists a gap in the stock of knowledge between country A and B, there is room for a one-way process of diffusion of knowledge from A to B. Assume that diffusion itself is costless in terms of labor and that the amount of knowledge transmitted to B at any moment is proportional to the size of the gap by a factor of proportionality equal to δ.

Accordingly, one has the following equations of production of knowledge in both countries:

$$\dot{x}_A = \phi\,(x_A)\,L_A\,,\ x_A > x_B \qquad (6)$$
$$L_A \geq L_B$$

$$\dot{x} = \phi\,(x_B)\,L_B + \delta\,(x_A - x_B)\,,\ 0 < \delta < 1 \qquad (7)$$

A convenient interpretation of the diffusion term in Eqn. (7) is that it represents a direct transfer from A to B that is costless to both A and B. It amounts, therefore, to a kind of "spillover effect" or pure externality. The parameter δ could then be taken as a measure of absorptive capacity in B, hence dependent on internal conditions within country B (such as range and depth of social infrastructure, size of the market, language skills, and policies of the national state). Or, δ could be a reflection of regulative measures and other institutional barriers in A to the export of knowledge. An alternative interpretation is that the diffusion term represents a flow of foreign investment from A to B; but this interpretation would raise further complications that cannot be pursued here. Whatever the case, it is supposed that this transfer has a direct impact on the current flow output of knowledge in B equivalent to the size of the transfer. The impact is assumed to be positive; but the possibility that it is negative could be introduced because of the existence of retarding effects from the transfer process. The latter case is an implication of the argument that relations between advanced and developing economies are characterized by a "structure of dependence" (Dos Santos 1970).

In practice, of course, there are likely to be significant resource costs of adoption of imported knowledge and of adaptation to local conditions. Insofar as these are accountable to labor costs, they can conveniently be absorbed into L^* for the importing country. A more complex treatment, consistent with the spirit of this model, and as a possible extension to it, would be to make diffusion itself a labor-using activity, subject to its own learning process.

The analytical problem that is posed now is the following: if both countries operate in accordance with the conditions specified in this model, what would be the associated pattern of productivity growth over time and what is the outcome of the process in the long run, as regards the size of the gap in productivity levels? Since productivity levels in both countries are uniquely related to the prevailing stock of knowledge, the analysis focuses on movements in this variable.

4. *Dynamics of the Productivity Gap*

Eqn. (6) and (7) constitute the key dynamic relationships indicating how the two countries evolve over time, starting from given initial conditions. To simpify the analysis and sharpen the results, let the learning function in both countries conform to the following linear relationship:

$$\phi(x_i) = a + bx_i,\ i = A, B;\ a > 0,\ b > 0 \tag{8}$$

Then, by transforming Eqns. (6) and (7) to proportional rates of growth and subtracting one gets:

$$g_A - g_B = \frac{aL_B}{x_A}\left(\frac{L_A}{L_B} - \frac{x_A}{x_B}\right) + b\,(L_A - L_B) - \delta\left(\frac{x_A}{x_B} - 1\right) \tag{9}$$

$$g_i = \dot{x}_i/x_i\ ,\ i = A, B$$

For clarifying the properties of the underlying process, one can distinguish the following cases:

(a) $\delta = 0,\ L_A = L_B,\ x_A > x_B$

Here, A is the leader in the stock of knowledge, but the two countries are equal in every other respect, and there is no diffusion. In this case, Eqn. (9) simplifies to

$$g_A - g_B = \frac{aL_A}{x_A}\left(1 - \frac{x_A}{x_B}\right) < 0 \tag{10}$$

Since $g_A < g_B$, the ratio x_A/x_B falls. There is a process of convergence to a steady state. However, the stocks of knowledge are never equalized; they diverge in absolute terms. The speed of convergence is determined by aL_A/x_A which reflects the role of diminishing returns to experience in A. In particular, a/x_A is the difference between the average and the marginal product of experience and it diminishes as experience grows. This result indicates that what dominates the process of convergence is diminishing returns to experience in the leading region. Thus, it appears that the leader leads not only in experience; it also leads the process of convergence by its slowing down from "aging" or "maturing" of experienc e.

(b) $1 > \delta > 0,\ L_A = L_B,\ x_A > x_B$

This case allows for diffusion from A to B. Eqn. (9) now becomes:

$$g_A - g_B = \frac{aL_A}{x_A}\left(1 - \frac{x_A}{x_B}\right) - \delta\left(\frac{x_A}{x_B} - 1\right) < 0 \tag{11}$$

Here again, $g_A < g_B$, the ratio x_A/x_B falls, and there is convergence in growth rates but not in abolute levels. The speed of convergence is augmented in this case by the existence of diffusion from A to B. Contrariwise, if $\delta < 0$, implying negative spillovers, it is easy to see that there is no convergence; x_A/x_B rises without limit.

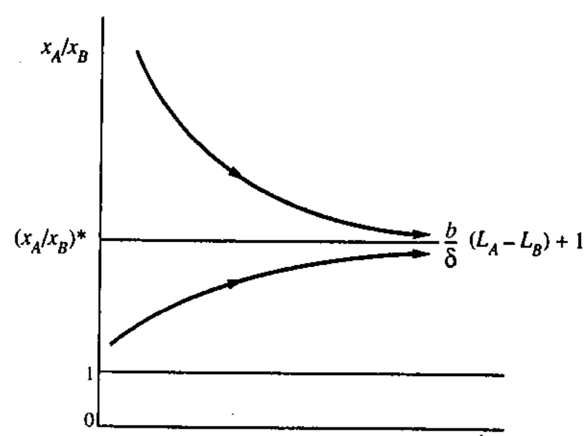
(c) $1 > \delta > 0,\ L_A > L_B,\ x_A > x_B$

This is the general case encompassing full differentiation among countries and diffusion of knowledge between them. The basic story which can be told in this case is as follows. For L_A/L_B sufficiently large in relation to x_A/x_B, country A has an advantage deriving from its larger allocation of labor to the knowledge industry. This advantage allows it to grow faster than B, so that x_A/x_B increases and, correspondingly, the productivity gap increases. However, part of this advantage, as represented by the first term on the right-hand side of Eqn. (9), is diminished by growing experience (due to diminishing returns to experience) as x_A rises both absolutely and relatively to x_B. It is converted to a disadvantage as x_A/x_B comes to exceed L_A/L_B. This advantage is also diminished by the increasing contribution (represented by the third term on the right-hand side of Eqn. (9)) that the growing gap in the stock of knowledge makes to growth in B due to diffusion of knowledge from A to B. Both these factors contribute to reducing the difference in growth rates between A and B. Consequently, the magnitude of the gap in the stock of knowledge, while continuing to grow, approaches an upper boundary given by the critical ratio:

$$(x_A/x_B)^* = \frac{b}{\delta}\,(L_A - L_B) + 1 \tag{12}$$

However, what if x_A/x_B is large enough to begin with, in particular, x_A/x_B exceeds this critical ratio? The logic of Eqn. (9) entails that, with such initial values of x_A/x_B, the growth advantage that A has from its larger allocation of labor to the knowledge industry is overpowered by the diffusion effect and the diminishing returns effect. The advantage in growth then shifts from A to B and this results in reducing the size of the gap between A and B in the stock of knowledge and, correspondingly, in productivity levels. In this case, the gap asymptotically converges from above to the critical ratio x_A/x_B^*.

Thus, no matter how small or large the initial gap in the stock of knowledge between leader and follower, this process operates to bring about convergence in terms of growth rates of the stock of knowledge. But, as to the size of the gap itself, there is a sharp asymmetry, as shown in Fig. 1. For small initial gaps, the size of the gap widens, up to some upper limit. For gaps that are large enough to begin with, that is, gaps larger than the critical ratio, there is a reduction in the size of the gap. However, whatever the initial size of the gap, there always remains a gap and it is positive. This result follows from the fact that the critical ratio is necessarily greater than 1, given that $L_A > L_B$, $b > 0$, $\delta > 0$. The magnitude of this permanent gap



is uniquely determined by the difference in the allocation of labor to the knowledge industry, $L_A - L_B$, by the marginal product of experience, b, and by the diffusion parameter, δ.

(d) $$1 > \delta > 0, L_B < L^* < L_A$$

If country B is unable to achieve the threshold size of allocation of labor to the knowledge industry, then it is unable to participate actively in the productivity race. It remains in a dependent status of receiving whatever spillovers it can get from those already in the race and its productivity level continues to fall further and further behind relative to the rest.

5. Conclusion

So far as the process of convergence/divergence in productivity growth is concerned, the analysis presented here identifies exactly what form that process takes and the conditions which affect the outcome.

The productivity gap is analyzed in terms of the relative size of the stocks of knowledge existing in the leader and follower countries. It is shown that, given some initial gap to begin with (no matter how big or small), the gap asymptotically approaches a definite size from above or below depending on initial conditions. Whether the gap increases or diminishes depends on how big the initial gap is. Thus, it is a matter of the exact degree of "relative backwardness" in a precise sense, specified in relation to the critical ratio $(x_A/x_B)^*$. In particular, only if the initial gap is "large enough" does convergence occur. In this respect, this result serves to give a certain precision to the well-known hypothesis of relative backwardness as a factor determining the tendency to convergence in productivity levels. Abramovitz (1986) provides a discussion of this hypothesis, along with several extensions and qualifications, and reviews some of the historical evidence pertaining to it. The general idea that the "degree of economic backwardness" is a significant factor governing the pace and direction of development was put forward by Gerschenkron (1952).

This result also replicates the diversity of the empirical record, insofar as that record exhibits the coexistence of dual tendencies of convergence and divergence. The coexistence of these two tendencies is shown here to be precisely connected with the cross-country distribution of initial conditions and paramater values around the critical ratio.

The analysis supports the need to maintain a sharp distinction between convergence in growth rates and convergence in terms of levels. In one class of cases depending on initial conditions, even though growth rates converge, levels diverge and the gap correspondingly widens, albeit to an upper limit.

It is evident also that the process of productivity growth, under the conditions specified here, operates to keep the size of the gap within bounds. This is for reasons related, first, to the existence of a "maturity" effect in the leading country associated with diminishing returns to experience. Second, it is related to the advantage that the follower country gains from the operation of a diffusion effect or of "spillovers" from the leader.

If the gap does not explode, it is never eliminated altogether. A certain positive size of the gap is permanently reproduced by this process. That size, given by the critical ratio $(x_A/x_B)^*$, is uniquely determined by specific conditions of the productivity-increasing process, namely; the marginal product of experience, b, the diffusion parameter, δ, and the difference in relative allocations of labor to the knowledge industry, $L_A - L_B$.

A special class of cases consists of those countries that are unable to mount the scale required to start up the productivity-increasing process. In such cases the gap increases without limit. The same result would occur if the diffusion parameter is negative, implying that there are retarding effects or negative spillovers from diffusion.

It is accepted that this analysis does not, nor does it attempt to, tell the whole story concerning the empirical record sketched in the first part of this entry. It does provide a heuristic framework with which to identify various essential elements of the story that need to be explored in greater depth, in seeking to explain the record of productivity growth.

As it stands, the model focuses on the character of the convergence/divergence process that occurs over a period of time appropriate to what one might call "a given technological paradigm," during which it might be said that the frontier of technological knowledge is relatively fixed. It is in that context that it would seem to make sense to talk about "diminishing returns to experience." However, in the long term, the paradigm does change and the frontier shifts out along with it. This introduces the possibility that, by leapfrogging, followers may overtake and surpass leaders, so that the pattern of leadership changes. It would remain to determine who leads and who follows under those conditions, and whether there is any tendency to convergence. This effect is not considered here and is intrinsically more difficult to model. (For an examination of the issues involved in the question of overtaking and of changing leadership, see Ames and Rosenberg 1963.)

Another effect not captured here, which may be considered a significant part of the empirical record of productivity growth, is the intersectoral effect associated, for instance, with a shift from agriculture to manufacturing industry, or from traditional manufacture to services. This aspect of the process is essentially eliminated at the highly aggregative level of this model. For the same reason, it is not possible to capture a significant dimension of the process that is related to the effect of commodity specialization among countries.

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