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A SIMPLE DYNAMIC MODEL OF UNEVEN DEVELOPMENT AND OVERTAKING

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Abstract

This paper extends the Brezis, Krugman and Tsiddon (1993) Ricardian leapfrogging model, allowing for a wider variety of development patterns. In a two-region two-sector economy localized learning-by-doing causes specialization and uneven development. Technological change *reverses* the existing development pattern if the new technology locates in the low-wage region. However, in contrast to Brezis *et al.*, the development pattern may also get *reinforced* if spillovers between the old and the new technology make the leading region a more attractive location. The results are not affected by including capital and extending the model to a two-factor Heckscher-Ohlin framework.

Keywords: Trade and growth, regional growth, uneven development, localized externalities, structural change

JEL Classification: F1, F43, R11.

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1 Introduction

At the end of the 18th century the Dutch enjoyed the highest consumption per capita on the European continent, quite different from the meager subsistence income of Belgium's impoverished peasantry. However, during the industrial revolution many new technologies located in Belgium, attracted by its low wages (Mokyr, 1976). By 1850 Belgium had become the most industrialized nation on the continent, leaving the Netherlands far behind. This is not to say that technological change always favors lagging regions or countries. The concentration of internet firms in Silicon Valley, for instance, has hardly been driven by low wages, but by the availability of specific skills. This paper proposes a two-region model of uneven development, in which the nature of technological change determines whether the advanced or the backward region benefits from the new technology.

Since Marshall (1890) first introduced the notion of external economies, it has been widely used to explain why countries or regions which are similar in terms of preferences, access to technologies, and endowments may develop differently. Although most of the literature has focused on closed economies,[1] uneven development may also arise because of trade. In Krugman (1981) localized technological externalities drive specialization and lead to diverging growth.[2] Taking this model one step further, the life-cycle of industries may then explain the rise and decline of regions. This is the approach taken by Brezis, Krugman and Tsiddon (1993). In a two-region[3] two-sector Ricardian trade model the initial pattern of uneven development is reversed by the exogenous introduction of a new technology. Since neither of the regions has any experience with the new technology, it gets adopted by the low-wage, backward region. As

[1]See, e.g., Young (1928), Rosenstein-Rodan (1943), Murphy, Schleifer and Vishny (1989), Azariadis and Drazen (1990), Matsuyama (1991), Stokey (1991), Rodríguez Clare (1993), Ciccone and Matsuyama (1993).

[2]Similar results - - uneven development due to specialization - - are also obtained in the more recent economic geography literature. See, for instance, Krugman (1991), Krugman and Venables (1995), Puga and Venables (1997).

[3]In reality, Brezis *et al.* focus on "countries", rather than "regions". We will later on be more precise about what we mean by "regions".

the productivity of this new technology increases through learning-by-doing, the lagging region eventually overtakes the leading region.

In spite of its intuitive appeal, the model of Brezis *et al.* is unsatisfactory on at least three accounts. First, the introduction of a new technology always benefits the poorer region. As mentioned before, Silicon Valley is but one counter-example. Denmark is another interesting case in point; its knowledge of fermentation techniques, stemming from a long tradition in beer brewing, gave it an advantage in the biotechnology sector (Porter, 1990). This suggests that not only the wage level, but also the expertise of the labor force determines which region adopts the new technology. Our model formalizes this argument by allowing for learning spillovers between a region's expertise and the new technology; if spillovers in the advanced region are sufficiently strong, the new industry may be attracted to the high-wage region, in which case the development pattern gets reinforced. This idea has been explored in earlier work by Desmet (1998). However, our approach here is simpler, allowing for a more direct critique of Brezis *et al.* and making the model easily extendable to a two-factor Heckscher-Ohlin framework.

Second, Brezis *et al.* sidestep the question of what happens when the new technology proves attractive to both regions. As will be shown, in their framework this leads to a trivial outcome, where comparative advantage disappears and the two regions become identical. Their result is not surprising; in the absence of spillovers, the productivity of the new technology is identical in both regions. In our model, this outcome will be the exception, rather than the rule; since spillovers depend on a region's accumulated experience, they will generally differ across regions, leading to a productivity wedge in the new technology.

Third, the Ricardian approach in Brezis *et al.* leaves capital completely out of the picture. Given the central role of capital in growth and development, it is important to analyze how our results are affected by including capital as a second factor of production. In doing so, we find that the main conclusions go through.

Before introducing the model, we should be more explicit about our definition of "region".

Since localized externalities are at the basis of specialization in our model, the size of what we call a "region" should be related to the spatial extent of those externalities. At the same time, uneven development is only sustainable in equilibrium if labor is immobile between regions. In other words, regions should be small enough to benefit from localized externalities, and large enough to limit the mobility of labor between them.

We can get a rough idea of the geographical reach of externalities by looking at the size of localized industrial clusters. Marshall (1890) goes back in time, citing examples from medieval England: scarlet was produced in Lincoln, cord in Warwick, soap in Coventry, and needles in Wilton.[4] In the early 20th century Akron (Ohio) was specialized in rubber, New York in garments, Providence (Rhode Island) in jewelry, Detroit in auto assembly.[5] More recently, geographical concentration has been epitomized by the high-tech industry, with Silicon Valley, Boston's Route 128 and North Carolina's Research Triangle being prime examples. In addition to this anecdotal evidence, more careful econometric work by Jaffe, Trajtenberg and Henderson (1993) and Audretsch and Feldman (1996) has found evidence of geographical externalities at both the state and the SMSA level. All of this suggests that countries are not the appropriate unit to study the geographical clustering of specialized activities; instead, smaller units such as U.S. states or city-regions may be more adequate.[6]

However, the size of regions also needs to satisfy the assumption of limited labor mobility. In this respect a lot depends on the part of the world we are considering. In the U.S., for instance, adverse shocks at the state level are resolved nearly exclusively through migration (Blanchard and Katz, 1992). In Europe, however, mobility between regions of roughly the same population size as the U.S. states is extremely low (Decressin and Fatás, 1996). Our model of the dynamics of regional growth may therefore be a more accurate description of European regions than of

[4]Marshall (1890), *op.cit.*, IV.x.3.

[5]See Krugman (1991).

[6]Authors that have emphasized the importance of cities or city-regions include, among others, Jacobs (1969, 1984), Henderson (1974, 1988), and Glaeser, Kallal, Scheinkman and Schleifer (1991).

U.S. states.

The remainder of this paper is organized in the following way. *Section 2* describes the set-up of the model and illustrates the process of uneven development; *Section 3* introduces technological change, and shows how the development pattern gets reinforced or reversed; *Section 4* extends the model to include capital; and *Section 5* concludes.

2 Uneven Development

The basic structure of the model follows closely Brezis *et al.* Consider two regions, East and West. For notational convenience, variables referring to the West will be starred ("*"). Labor is the only factor of production, and is present in identical amounts in both regions:[7]

$$L = L^* = 1 \tag{1}$$

As mentioned in the introduction, labor is geographically immobile. If this were not the case, income would equalize across regions. There are two sectors, food and manufacturing. The unit labor requirement in food production is one, so that:

$$Q_F = L_F \tag{2}$$

$$Q_F^* = L_F^* \tag{3}$$

In each region there are dynamic gains to manufacturing productivity due to localized learning-by-doing:[8]

$$A(E(t)) = \bar{A} - (\bar{A} - \underline{A})(1 + E(t))^{-\lambda} \tag{4}$$

$$A(E^*(t)) = \bar{A} - (\bar{A} - \underline{A})(1 + E^*(t))^{-\lambda} \tag{5}$$

[7]This assumption neutralizes any effects that might be due to different sizes of the labor force. The standard learning-by-doing assumption, for instance, has the undesirable feature that bigger economies learn faster. See Matsuyama (1992) and Lucas (1993) for a further discussion.

[8]The effect of localized learning-by-doing on comparative advantage and growth has been studied, amongst others, by Bardhan (1970), Ethier (1982), Krugman (1987), Lucas (1988) and Young (1991).

where learning depends on both direct experience producing manufactures and on spillovers from other technologies:[9,10]

$$E(t) = \int_0^t L_M(s)ds + S(t) \tag{6}$$

$$E^*(t) = \int_0^t L_M^*(s)ds + S^*(t) \tag{7}$$

Without any direct experience or spillovers, productivity is $\underline{A}$; as a region learns how to use the technology, A rises; eventually, learning peters out and productivity tends asymptotically to $\bar{A}$. Aggregate output of manufactured goods at time t is:

$$Q_M(t) = A(E(t))L_M \tag{8}$$

$$Q_M^*(t) = A(E^*(t))L_M^* \tag{9}$$

Consumers' preferences are Cobb-Douglas; they spend a fraction μ of their income on manufactures and the rest on food, where $\mu > 1/2$.[11] After normalizing the food price to 1, the inverse demand function of manufactures relative to food can be defined as:

$$p_M = \frac{\mu}{1-\mu}\frac{C_F}{C_M} \tag{10}$$

where C_F and C_M are the consumption of, respectively, food and manufactures.

Assume that the West has a comparative advantage in manufacturing. Since this is a Ricardian trade model, the economy exhibits either full or partial specialization. In the case of full specialization, the West produces exclusively manufactures, whereas the East only produces food. Plugging the production in both sectors into (10) allows us to derive the equilibrium

[9] For algebraic tractability, direct learning is chosen to be a function of labor employed in manufacturing, rather than of production of manufactures.

[10] Learning spillovers will be given a more precise definition subsequently.

[11] The assumption that $\mu > 1/2$ ensures that one of the two regions is completely specialized in manufactures. If this were not the case, both regions would produce food; since food productivity is equal across regions, wages would also equalize.

manufacturing price under full specialization:

$$p_M = \frac{\mu}{1-\mu}\frac{1}{A(E^*)} \tag{11}$$

In order for full specialization to be an equilibrium, nobody in the East (West) should have an incentive to produce manufactures (food). This implies that the price expression in (11) should satisfy the following condition:

$$\frac{1}{A(E^*)} \leq \frac{\mu}{1-\mu}\frac{1}{A(E^*)} \leq \frac{1}{A(E)} \tag{12}$$

Since $\mu > 1/2$, the inequality to the left in (12) holds by definition, so that the West is always fully specialized in manufactures. If the inequality to the right is satisfied, the East only produces food; if it is not satisfied, the East also produces some manufactures, so that the economy is only partially specialized.

Introducing dynamics in the model allows us to study how specialization and growth patterns evolve over time. Assume that at time $t = 0$ productivity in the East is at its lower bound, whereas in the West it is slightly higher:

$$A(E(0)) = \underline{A} \tag{13}$$

$$A(E^*(0)) = \underline{A} + \epsilon \tag{14}$$

If the difference in manufacturing productivity is small enough, i.e., if $\frac{\underline{A}+\epsilon}{\underline{A}} < \frac{\mu}{1-\mu}$, the economy is initially in the case of partial specialization. Since therefore both regions produce manufactured goods, the income per capita of the West relative to the East is equal to the relative productivity of their respective manufacturing sectors:

$$\frac{Y^*(0)}{Y(0)} = \frac{A(E^*(0))}{A(E(0))} = \frac{\underline{A}+\epsilon}{\underline{A}} \tag{15}$$

Both regions are therefore at comparable levels of development. Over time manufacturing productivity increases in both regions. However, since the West's entire labor force is employed in manufacturing and only a fraction of the East's, the West moves up its productivity curve faster than the East. As the productivity gap widens,[12] the East becomes more and more specialized in food. The economy gets into a process of uneven development, since relative income per capita follows relative manufacturing productivity as long as the East continues to produce some manufactures. Eventually the East is completely driven out of manufacturing if the following condition holds (proof in the Appendix):

Condition 1 (sufficiency)

$$\text{Max}_t[\frac{\bar{A}-(\bar{A}-\underline{A})(1+t)^{-\lambda}}{\bar{A}-(\bar{A}-\underline{A})(1+t(2\mu-1))^{-\lambda}}] \geq \frac{\mu}{1-\mu}$$

In other words, if μ is not too great, and the difference between $\underline{A}$ and $\bar{A}$ is not too small, the manufacturing productivity gap between the West and the East becomes sufficiently large to ensure full specialization. The relative manufacturing price is then given by (11), so that the relative income per capita is:

$$\frac{Y^*}{Y}=\frac{\mu}{1-\mu} \tag{16}$$

The dynamic path of relative income per capita therefore follows relative manufacturing productivity until it reaches (16), at which point the East stops producing manufactured goods. Once full specialization is reached, productivity growth in the West does not further widen the income gap. Cobb-Douglas preferences are such that the gain in productivity is exactly offset by the decline in the terms of trade. It has thus been shown how regions that start off in fairly similar conditions may end up at very different levels of development.

3 Technological change

Assume that the economy is fully specialized and that learning in the West has been exhausted, so that its manufacturing productivity is $\bar{A}$.[13] At time t' we exogenously introduce a new

[12]Since A is a concave function, the fact that manufacturing employment is greater in the West than in the East does not suffice to conclude that the productivity gap between both regions increases over time. However, if *Condition 1* holds (see below), then this is a valid claim.

[13]Strictly speaking, $\bar{A}$ is not reached in finite time. However, this assumption enhances tractability since it implies that productivity does not change anymore with time.

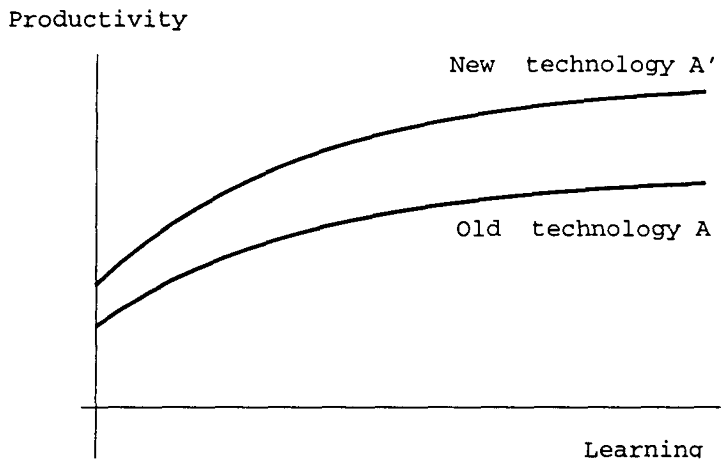

Figure 1: Old and new manufacturing technology: for any given level of accumulated learning (from either direct experience or from learning spillovers) the new technology is more productive than the old one.

technology which produces a perfect substitute for existing manufactures:

$$A'(E'(t)) = \bar{A}' - (\bar{A}' - \underline{A}')(1 + E'(t))^{-\lambda} \tag{17}$$

$$A'(E'^{*}(t)) = \bar{A}' - (\bar{A}' - \underline{A}')(1 + E'^{*}(t))^{-\lambda} \tag{18}$$

As illustrated in *Figure 1*, the new technology A' is superior to the one used previously; since $\underline{A}' > \underline{A}$ and $\bar{A}' > \bar{A}$, it follows from (17) and (18) that $A'(E') > A(E)\ \forall E' = E$. This type of innovation can take on two different forms. On the one hand, it may refer to the production of an identical manufactured good, using a different technology. An example of this would be the introduction of the method of continuous casting in steel production at the end of the 1960s. On the other hand, it could also be a new industry which produces a perfect substitute for the original manufactured good. The rise of composite materials for instance has been replacing steel in many of its applications.[14]

Although low wages tend to attract the new industry to the East, learning spillovers from the original manufacturing technology may give the West an advantage in adopting the

[14] Since perfect substitutes are indistinguishable in the consumer's utility function and there is thus a unique manufacturing price, the two interpretations are interchangeable, and do not make any difference for the theoretical analysis.

new technology.[15] Learning spillovers may differ in degree. If spillovers are complete, having accumulated experience with the old technology is equivalent to having had the same amount of experience with the new technology, so that $A'(S'^*(t')) = \bar{A}'$; if spillovers are non-existent, $A'(S'^*(t')) = \underline{A}'$. In general, $A'(S'^*(t'))$ will be somewhere in between those two extremes.

Given the spillovers between the old and the new technology, the productivity of manufacturing and food in the two regions at time t' is:

	East	**West**
Food	1	1
Manufacturing	$\underline{A}'$	$\max[A'(S'^*(t')), \bar{A}]$

Figure 2: Productivity of food and manufacturing at time t' in the presence of learning spillovers

It is clear that the West initially retains its comparative advantage. Whether or not it adopts the new technology depends on which technology gives its workers a higher productivity; if, for instance, $\bar{A} > A'(S'^*(t')$, the West remains locked into the old technology. The chance of being locked in is limited by the degree of spillovers; the higher the spillovers $S'^*(t')$, the greater the new technology's productivity in the West. As for the East, it may either continue to produce only food or it may become partially specialized in new manufacturing. In order to study the dynamics, three cases can be distinguished:

- **Case 1: Reversal of development pattern** ($A'(S'^*(t')) \leq \bar{A}$ **and** $\frac{\bar{A}}{\underline{A}'} < \frac{\mu}{1-\mu}$)

  If $A'(S'^*(t')) < \bar{A}$, workers in the West do not have any incentive to adopt the new technology, because their accumulated experience with the old technology gives them a higher productivity. However, if $\frac{\bar{A}}{\underline{A}'} < \frac{\mu}{1-\mu}$, the new technology is attractive to the low-paid workers in the East because it improves their wages.[16]

[15] Learning spillovers between sectors have been analyzed in a theoretical framework by, for instance, Boldrin and Scheinkman (1988). Empirical evidence can be found in Jaffe, Trajtenberg and Henderson (1993) and Glaeser, Kallal, Scheinkman and Schleifer (1991).

[16] The new technology improves food workers' wages if $p_M \underline{A}' > 1$, where p_M is the price before any worker in

Although initially the West still has a comparative advantage in manufacturing, over time the East moves up the productivity curve of the new technology, whereas productivity in the West remains stagnant at its upper bound $\bar{A}$. As the East catches up with the West in terms of productivity, the per capita income gap between both regions narrows. Given the superiority of the new technology ($\bar{A}' > \bar{A}$), productivity in the East eventually rises above productivity in the West. At that point, the trade and development patterns get reversed. The East starts to export manufactured goods, and it overtakes the West in terms of income per capita.

- **Case 2: Convergence or reinforcement of development pattern** $(A'(S^*(t')) > \bar{A})$

  In this case the outcome depends crucially on whether spillovers are zero or strictly positive.

  If there are no spillovers, as in Brezis *et al.*, the East and the West have identical productivities in food and manufactures. Since neither of the regions has a comparative advantage in manufacturing, it does not matter who produces what, so that there is a continuum of possible equilibria. To break this indeterminacy, we choose the equilibrium that minimizes trade between the two regions.[17] The economy thus reverts to autarky, and each region becomes fully self-sufficient. Since both regions produce the same amount of manufactures, they move up the industry's learning curve in a synchronized manner, so that neither is able to gain a comparative advantage in the new industry.[18] Both regions have become identical; the development gap has vanished and income per capita has converged.[19]

  However, if spillovers are strictly positive, it is clear that the West retains its comparative

the East has switched to the new technology, i.e., $p_M = \frac{\mu}{1-\mu}\frac{1}{\bar{A}}$.

[17]This can be thought of as the limit of a sequence of economies where there are transportation costs, but these costs tend to zero. A similar argument is used by Helpman and Krugman (1985) to determine the degree of decentralization of multinational corporations.

[18]If the regions were of different sizes, the bigger country would gain a comparative advantage in the new industry, and the results would be substantially different. See footnote (7) for further discussion of this point.

[19]This equilibrium is unstable though; any small deviation causes regional specialization and uneven development, similar to the description in the last paragraph of *Section 2*.

advantage in manufacturing. Therefore, all workers in the West adopt the new technology, whereas the East may either remain fully specialized in food or partially adopt the new technology. Although under partial specialization the regional income gap initially decreases, the following condition ensures that the East eventually stops producing manufactures, so that the relative income advantage of the West is as great as before:

Condition 1' (sufficiency)

$$\mathrm{Max}_t\left[\frac{\bar{A}' - (\bar{A}' - \underline{A}')(1 + (t - t'))^{-\lambda}}{\bar{A}' - (\bar{A}' - \underline{A}')(1 + (t - t')(2\mu - 1))^{-\lambda}}\right] \geq \frac{\mu}{1 - \mu}$$

As mentioned before, the likelihood of the West remaining in the lead increases in the degree of learning spillovers; equivalently, the chance of the East overtaking diminishes as learning spillovers become more important.

- **Case 3: Status quo ($A'(S^*(t')) \leq \bar{A}$ and $\frac{\bar{A}}{\underline{A}'} \geq \frac{\mu}{1-\mu}$)**

  In this case neither of the regions adopts the new technology. The economy remains in a status quo.

The introduction of spillovers therefore addresses two fundamental criticisms to the Brezis *et al.* model. First, in Brezis *et al.* technological change always benefits the lagging region. Abstracting from *Case 3*, the absence of spillovers implies that the backward region either catches up *(Case 2)* or overtakes the leading region *(Case 1)*. This seems at odds with casual observation; experience with older technologies often give advanced regions an edge over their backward neighbors in the adoption of new technologies. For instance, Switzerland used its strength in the dye industry to move into pharmaceuticals. In our model, the existence of spillovers allows for this possibility, and thus gives rise to a much wider variety of development patterns.

Second, if the new technology proves attractive to both regions, the absence of spillovers in Brezis *et al.* implies that all differences between the East and the West are erased. Notice that in their paper Brezis *et al.* focus exclusively on *Case 1*, and avoid talking about this possibility.

This is not surprising; the idea that the new technology has exactly the same productivity in the West and the East seems unplausible. It implies that whatever experience each region's labor force has, or whatever each region's economic structure is, it is irrelevant to the adoption of the new technology. In contrast to this, the introduction of spillovers in our model gives an explicit role to differences in the expertise of regions.

In addition to allowing for a much wider variety of development patterns, our model provides insights as to when technological change benefits the advanced or the backward region. If the new and the old technology are similar, spillovers are sufficient for the advanced region to overcome its cost disadvantage, adopt the new technology and remain in the lead. If, on the contrary, both technologies are quite different, past experience with the old technology is irrelevant, and the new industry locates wherever wages are lower.

4 Introducing capital into the model

One obvious limitation of the Ricardian approach is that there is no capital in the model. The importance of capital in growth, development and industrialization hardly needs any further explanation. It will now be shown that the introduction of capital which is mobile between regions does not affect the main conclusions in any significant way.

Before analyzing the model though, we must justify why we assume capital to be geographically mobile. Although much of the older literature has focused on domestic capital accumulation as the main engine of growth (Solow, 1956), recent work has shown increasing interest in foreign direct investment and capital mobility (Barro, Mankiw and Sala-i-Martin, 1995, Fafchamps, 1995). An interesting case of foreign direct investment is the U.S. tire industry, which migrated from Akron (Ohio) to the South after the introduction of the radial-tire technology by foreign firms such as Michelin and Pirelli (Rubenstein, 1992, Crandall, 1993, Rubenstein, 1996). Going back to our first example, the role of foreign capital in Belgium's industrialization has been well documented (Mabille, 1986, Cameron, 1989). Moreover, given that "regions" are relatively small in our model, it seems plausible to assume that capital has at least some degree of mobility.

Let us, then, consider a Heckscher-Ohlin framework, where manufacturing technologies may differ across regions, reflecting localized learning externalities. The aggregate production functions of food and manufacturing in the East and the West are:

$$
\begin{aligned}
Q_F &= K_F^{\alpha} L_F^{1-\alpha} \\
Q_F^* &= K_F^{*\alpha} L_F^{*(1-\alpha)} \\
Q_M &= A K_M^{\beta} L_M^{1-\beta} \\
Q_M^* &= A^* K_M^{*\beta} L_M^{*(1-\beta)}
\end{aligned} \tag{19}
$$

where K_i and L_i are the capital and labor employed in sector i. Again, unstarred and starred variables refer to, respectively, the East and the West. Manufacturing is relatively capital-intensive, so that $\beta > \alpha$. As in (6) and (7), A^* and A benefit from localized learning externalities.[20] Labor and capital markets are perfectly competitive, and factors are fully employed. As before, we assume that $L = L^* = 1$. Capital is perfectly mobile between regions, in contrast to labor, which is not allowed to migrate.

We first analyze the static free trade equilibrium assuming that A^* is slightly bigger than A, reflecting an initially greater capital stock in the West. Since the food price is normalized to 1, the Lerner diagram is drawn for a given (relative) manufacturing price *(Figure 3)*. Lines (or curves) with a light font refer to the East, and lines (or curves) with a darker font to the West. Because of the normalization of food prices, the unit iso-value curve for food is simply the unit isoquant. Since food technologies do not differ between the two regions, the food iso-value curve in the East (F) is identical to the one in the West (F^*). The iso-value curve for manufactures represents the possible combinations of capital and labor necessary to produce manufactured goods worth one unit of food. In other words, the manufacturing iso-value curve is equivalent to

[20] To simplify notation, $A = A(E)$ and $A^* = A(E^*)$.

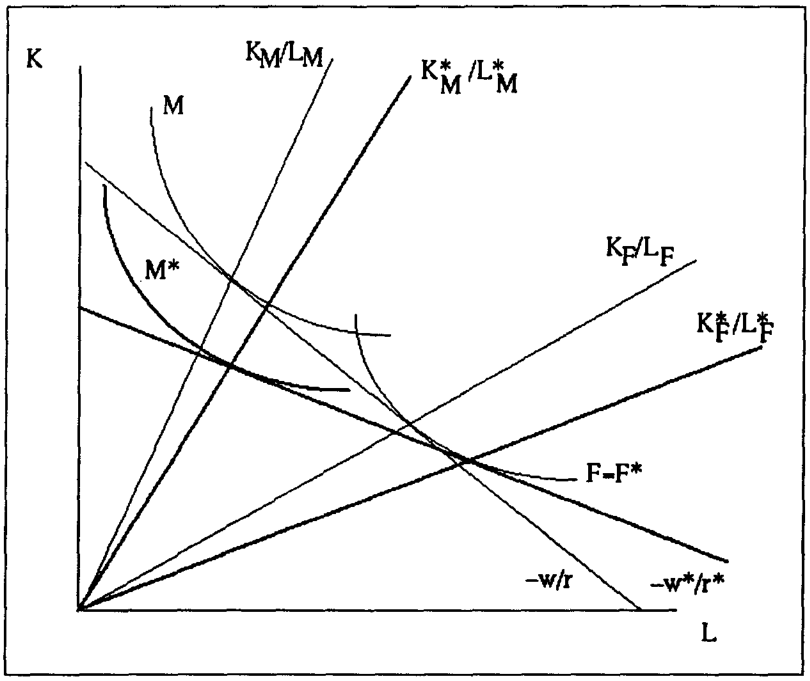

Figure 3: Lerner diagram: M and M^* represent the unit iso-value curves of manufactures in, respectively, the East and the West, whereas $F = F^*$ represents the unit iso-value curve of food in both regions. If a region produces both goods, the wage/rental ratio is the absolute value of the slope of the only iso-cost curve tangent to the iso-value curves of both goods; these tangency points also determine the capital/labor ratios in both sectors.

the manufacturing isoquant $Q_M = 1/p_M$. Since $A^* > A$, the iso-value curve for manufactures is lower in the West (M^*) than in the East (M).

As a starting point, assume that both regions produce both goods and that capital is immobile.[21] As is well known in the case of partial specialization, the wage/rental ratio in a given region can be derived by drawing the line which is tangent to both the iso-value curve of food and manufacturing in that region.[22] The absolute value of the slope of that line is the wage/rental ratio. Since the tangent in the West is less steep than in the East, the wage/rental

[21]Assuming that both regions produce both goods amounts to limiting the capital/labor ratios in each region to specific intervals. This assumption is not restrictive, since once capital mobility is introduced, the economy's equilibrium will be uniquely determined independently of whether regions were initially specialized or not.

[22]Note that in order for a region to produce both goods, its overall capital/labor ratio must be in between the capital/labor ratios of both sectors, i.e., the overall capital/labor ratio must be within the cone of diversification.

ratio is lower in the West than in the East. Furthermore, the capital/labor ratio in food is lower in the West than in the East. Since the food technology is identical in both regions, this implies that the rental price of capital is higher in the West than in the East.

Introducing capital mobility between regions, capital flows out of the East and into the West. The overall capital/labor ratio in the East declines, whereas it rises in the West. The relative production of manufactured goods increases in the West and decreases in the East.[23] However, as long as the overall capital/labor ratios in the East and the West remain in between the capital/labor ratios of manufacturing and food, both regions continue to produce both goods. The rental price of capital therefore remains higher in the West than in the East,[24] so that capital continues to migrate. At some point, either the West becomes fully specialized in manufactures, or the East becomes fully specialized in food. Which one of the two situations arises depends to a large extent on demand conditions. If consumers spend a sufficiently large fraction of their income on manufactured goods, the West specializes exclusively in manufacturing; the exact condition is given by (proof in Appendix):

Condition 2

$$\mu > \frac{1-\alpha}{2-\alpha-\beta}$$

Capital flows continue till the rental prices of capital equalize between the East and the West:

$$r^* = p_M \beta A^* (\frac{1}{K^*})^{1-\beta} = r = p_M \beta A (\frac{L_M}{K_M})^{1-\beta} = \alpha (\frac{L_F}{K_F})^{1-\alpha} \tag{20}$$

Wages in the East and the West are:

$$w = p_M (1-\beta) A (\frac{K_M}{L_M})^{\beta} = (1-\alpha)(\frac{K_F}{L_F})^{\alpha} \tag{21}$$

$$w^* = p_M (1-\beta) A^* (K^*)^{\beta} \tag{22}$$

[23]Note that of course this change in production affects the relative price of manufacturing.

[24]This result does not depend on the manufacturing price.

Since $r^* = r$ and $A^* > A$, it must be that the capital/labor ratio in manufactures is greater in the West than in the East, so that wages are higher in the West:

$$\frac{w^*}{w} = [\frac{A^*}{A}]^{\frac{1}{1-\beta}} \tag{23}$$

Assuming that returns to capital accrue to the original owners, income from capital is greater in the region with the higher *initial* capital stock. Given the initially greater capital stock in the West[25] and the higher wages, it follows that income per capita is higher in the West than in the East.

We now introduce dynamics into the model. Manufacturing productivity benefits from dynamic gains from learning. As before, learning depends on direct experience and spillovers and has exactly the same form as in (6) and (7). In other words, in spite of introducing capital, we maintain the assumption that learning is a simple function of the labor force employed in the manufacturing sector. Since the West is fully specialized in manufacturing, productivity increases faster than in the East, which is partially specialized in food.[26] The difference between A^* and A increases over time, thus further widening the wage gap (see (23)). As long as both regions are not fully specialized, it follows from Cobb-Douglas preferences that as A^* increases, p_M decreases, but $p_M A^*$ increases.[27] Therefore, the rental price of capital increases in the West.

[25]This is based on our assumption that the initial advantage in manufacturing productivity was due to an initially greater capital stock.

[26]As before, the full specialization of the West is not enough to ensure that the productivity gap increases over time, since the learning curve is concave. However, *Condition 3* (see below) validates our claim.

[27]From Cobb-Douglas preferences we know that if world manufacturing production increases by $x\%$ (and world food production remains the same), the relative manufacturing price drops by $x\%$. If A^* goes up by $x\%$, manufacturing production in the West increases by $x\%$. At the same time A goes up by $y\%$, where $y < x$. We now show that $p_M A^*$ cannot go down. In order for $p_M A^*$ to drop, it must be that p_M decreases by more than $x\%$. This, in its turn, implies that manufacturing production in the East should increase by more than $y\%$. However, we can show that even if p_M only drops by $y\%$, manufacturing production in the East goes up by less than $y\%$, so that it is impossible that $p_M A^*$ drops. Indeed, if p_M drops by $y\%$, $p_M A$ remains the same, so that production of manufactures relative to food does not change in the East; since A went up though, this implies that both food and manufacturing production increased in the East; the increased production of food means less factors of production allocated to manufacturing in the East, so that manufacturing production must have gone up by less than $y\%$.

In order for the rental prices to equalize between the West and the East, it follows from (20) that either the labor/capital ratios in the East in both food and manufacturing should go up, or capital should flow from East to West (or both phenomena should happen simultaneously). From this we can draw two conclusions. First, income per capita in the West relative to the East increases, since returns to capital increase and wages in the West grow faster than in the East. Second, the East becomes increasingly specialized in food. If the productivity gap increases enough, at some point the East stops producing manufactures; a sufficient condition for this to occur is:

Condition 3 (sufficiency)

$$\mathrm{Max}_t[\frac{\bar{A}' - (\bar{A}' - \underline{A}')(1+t)^{-\lambda}}{\bar{A}' - (\bar{A}' - \underline{A}')(1+tL_M(0))^{-\lambda}}] \geq [\frac{\mu}{1-\mu}\frac{1-\beta}{1-\alpha}]^{1-\beta}$$

where $L_M(0) = \frac{\mu(1-\beta)-(1-\mu)(1-\alpha)}{\mu(1-\beta)+(1-\mu)(1-\alpha)}$.

If both regions are fully specialized, the relative manufacturing price is:

$$p_M = \frac{\mu}{1-\mu}\frac{K^{\alpha}}{A^* K^{*\beta}} \tag{24}$$

Since rental prices equalize across regions, the capital stock in the West relative to the East is:

$$\frac{K^*}{K} = \frac{\mu}{1-\mu}\frac{\beta}{\alpha} \tag{25}$$

Relative wages are then:

$$\frac{w^*}{w} = \frac{\mu}{1-\mu}\frac{1-\beta}{1-\alpha} \tag{26}$$

Therefore, if initially A^* is only slightly greater than A, both regions start off at very similar wage levels. As time goes by, the wage gap increases (see (23)) until both regions become fully specialized.[28] Similarly, the rental price of capital increases until both regions become fully specialized.[29]

[28]Note that our assumption that μ should be sufficiently great is now clear, since the relative wage in (26) should be greater than 1; if not, food would be produced in both regions.

[29]The rental price of capital stops rising once both regions are fully specialized. Under full specialization with Cobb-Douglas preferences, the increase in manufacturing productivity causes a compensating decrease in the relative manufacturing price.

When at time t' a new manufacturing technology is introduced, the same reasoning as before applies. Assuming learning spillovers may exist between the old and the new technology, the productivities of manufacturing and food in the two regions are identical to the ones given in *Figure 2*. There are again two possibilities.

On the one hand, if $A'(S'^*(t')) > A(E^*(t'))$, the new technology is adopted in the West. In other words, the new technology locates in the advanced region if its productivity (taking into account possible learning spillovers from the old technology) is superior to the productivity of the old technology (taking into account accumulated experience). Given the mobility of capital, the West remains completely specialized in the production of manufactures. Even if the East partially adopts the new technology, it will only do so temporarily. As before, under a condition analogue to *Condition 3* the productivity gap between both regions increases, and the West eventually drives the backward region out of manufacturing. The West thus remains in the lead.

On the other hand, even if the new technology is not attractive to the West, it may still be profitable to low-wage workers in the East. In that case the backward region adopts the new technology. Given the steepness of the learning curve, the East starts catching up in terms of manufacturing productivity, and eventually it becomes more productive than the West. There is a reversal in comparative advantage, and wages in the East are now higher than in the West. Whether this also implies that the East has overtaken the West in terms of income per capita will depend on the difference in the rents from capital. Since those rents go to the original capital owner, income from capital will still be higher in the West than in the East.

5 Conclusion and extensions

In this model we have extended the Brezis *et al.* framework to allow for a wider variety of development patterns. In Brezis *et al.* a new technology always locates where wages are lower, thus giving a chance to the lagging region to take off. However, if spillovers between the old and the new technology are relatively strong, the richer region may prove a more attractive location and thus reinforce its dominant position. The results are shown to be robust when the model is extended to include capital as an additional factor of production.

We see a number of interesting extensions coming out of this work. First, in the present model the localized learning-by-doing externality in manufacturing extends to the entire labor force. All workers in a given region are thus identical. This is at odds with the empirical evidence on sector-specific skills.[30] It would therefore be useful to introduce micro-foundations and have forward-looking optimizing agents invest in specific types of human capital. This issue is taken up in Desmet (1998).

Second, the framework developed seems particularly convenient to analyze a variety of regional policy questions, such as inter-regional transfers, regional investment incentives and geographical labor mobility. For instance, certain types of inter-regional transfers may have the effect of raising wages in the backward region, thus making it less likely that the lagging region ever takes off.

A Proofs

Condition 1

In this proof it is shown that Condition 1 is sufficient to ensure full specialization in both regions. Full specialization is reached at a given time $\bar{t}$ if:

$$\frac{A(E^*(\bar{t}))}{A(E(\bar{t}))} \geq \frac{\mu}{1-\mu} \tag{27}$$

Condition (27) can be re-written as:

$$\frac{\bar{A} - (\bar{A} - \underline{A})(1 + \int_0^{\bar{t}} L_M^*(s)ds + S^*(\bar{t}))^{-\lambda}}{\bar{A} - (\bar{A} - \underline{A})(1 + \int_0^{\bar{t}} L_M(s)ds + S(\bar{t}))^{-\lambda}} \geq \frac{\mu}{1-\mu} \tag{28}$$

A necessary and sufficient condition for full specialization to be reached is therefore:

$$\text{Max}_t[\frac{\bar{A} - (\bar{A} - \underline{A})(1 + \int_0^{t} L_M^*(s)ds + S^*(t))^{-\lambda}}{\bar{A} - (\bar{A} - \underline{A})(1 + \int_0^{t} L_M(s)ds + S(t))^{-\lambda}}] \geq \frac{\mu}{1-\mu} \tag{29}$$

[30] See, for example, the literature on the mismatch between the demand and the supply of specific skills (Jackman, Layard and Savouri, 1991, Bean and Pissarides, 1991).

Two simplifications are now introduced which make condition (29) more stringent:

(i) Assume that $\epsilon = 0$ in (14), so that $A(E^*(0)) = A(E(0)) = \underline{A}$. This economy can therefore be thought of as the limit of a sequence of economies where ϵ goes to zero. Along this sequence the West has a comparative advantage in manufacturing. Although in the limit trade patterns become undefined, we resolve this indeterminacy by assuming that the West retains its comparative advantage. Since $\epsilon = 0$ implies that the West starts off at the lowest possible point on its productivity curve, this assumption makes condition (29) more stringent.

(ii) It follows from simplification (i) that $L_M(0) = 2\mu - 1$. Notice that $2\mu - 1$ is the highest possible manufacturing employment in the East at any point in time, as long as the West has a comparative advantage in manufacturing. Assume that $L_M(s) = 2\mu - 1 \ \forall s$; in other words, manufacturing employment in the East remains at its highest possible level. This assumption puts an upper bound on manufacturing productivity in the East, and thus makes condition (29) more stringent.

Given that (i) and (ii) make (29) more stringent, incorporating (i) and (ii) into (29) turns it into a sufficient (rather than a necessary and sufficient) condition. Since $L_M^*(s) = 1 \ \forall s$, we get:

$$\text{Max}_t\left[\frac{\bar{A} - (\bar{A} - \underline{A})(1+t)^{-\lambda}}{\bar{A} - (\bar{A} - \underline{A})(1+t(2\mu-1))^{-\lambda}}\right] \geq \frac{\mu}{1-\mu} \tag{30}$$

Q.E.D.

Condition 2

In this proof it is shown that Condition 2 ensures that the West is completely specialized in manufacturing. Instead of showing this directly, we first derive a necessary and sufficient condition for the West to produce some food. Condition 2 will then be the negation of this necessary and sufficient condition.

Assume therefore that the East produces food and the West both food and manufactures. Given the mobility of capital, rental prices equalize across sectors and regions:

$$r = \alpha\left(\frac{1}{K_F}\right)^{1-\alpha} = \alpha\left(\frac{L_F^*}{K_F^*}\right)^{1-\alpha} = p_M A^* \beta\left(\frac{L_M^*}{K_M^*}\right)^{1-\beta} = r^* \tag{31}$$

Wages across sectors in a given region equalize. Moreover, since the food technology is identical in both regions, and since rental prices equalize across regions, it follows that food wages equalize in the East and the West. Wages are therefore identical across regions and sectors:

$$w = (1-\alpha)K_F^\alpha = (1-\alpha)\left(\frac{K_F^*}{L_F^*}\right)^\alpha = p_M A^*(1-\beta)\left(\frac{K_M^*}{L_M^*}\right)^\beta \tag{32}$$

The price expression is obtained by plugging in the production functions (19) into the inverse demand function (10):

$$p_M = \frac{\mu}{1-\mu}\frac{K_F^\alpha + K_F^{*\alpha} L_F^{*(1-\alpha)}}{A^* K_M^{*\beta} L_M^{*(1-\beta)}} \tag{33}$$

Re-writing (32) gives:

$$p_M = \frac{1-\alpha}{1-\beta} \frac{K_F^\alpha}{A^*(K_M^*/L_M^*)^\beta} \tag{34}$$

Replacing L_M^* by $1 - L_F^*$ and equalizing (33) and (34) allows us to solve out for L_F^*:

$$L_F^* = \frac{(1-\mu)(1-\alpha) - \mu(1-\beta)}{(1-\mu)(1-\alpha) + \mu(1-\beta)} \tag{35}$$

A necessary condition for the West to produce food is that $L_F^* > 0$; in other words:

$$\mu < \frac{1-\alpha}{2-\alpha-\beta} \tag{36}$$

Whether this condition is also sufficient remains to be seen. Plugging (35) into (33) gives:

$$p_M = \frac{1-\alpha}{1-\beta} \frac{K_F^\alpha}{A^*(K_M^*/L_M^*)^\beta} \tag{37}$$

From re-writing (31) we get:

$$p_M = \frac{\alpha}{\beta} \frac{(1/K_F)^{1-\alpha}}{A^*(L_M^*/K_M^*)^{1-\beta}} \tag{38}$$

Equating (37) and (38) then gives:

$$K_F = \frac{\alpha}{\beta} \frac{1-\beta}{1-\alpha} \frac{K_M^*}{L_M^*} \tag{39}$$

Of course the sum of capital used in each sector should be the sum of total capital:

$$K = K_F + K_F^* + K_M^* \tag{40}$$

Plugging (35) into (39) gives:

$$K_F = \frac{\alpha}{\beta} \frac{1}{1-\alpha} \frac{K_M^*((1-\mu)(1-\alpha) + \mu(1-\beta))}{2\mu} \tag{41}$$

From (31) we know that $K_F^* = K_F L_F^*$. From (35) and (41) we can then derive:

$$K_F^* = \frac{\alpha}{\beta} \frac{1}{1-\alpha} \frac{K_M^*((1-\mu)(1-\alpha) - \mu(1-\beta))}{2\mu} \tag{42}$$

Plugging (41) and (42) into (40) allows us to derive:

$$K_M^* = \frac{\mu\beta}{\mu\beta + \alpha(1-\mu)} K \tag{43}$$

It is obvious that the coefficient in front of K in (43) is always positive. The same is true for the coefficients in front of K_M^* in (41) and (42). Therefore, the only necessary condition to ensure

an allocation of capital and labor across the three sectors compatible with food production in the East and food and manufactures production in the West is (36).
A sufficient and necessary condition to have the West fully specialized in manufacturing is therefore the negation of (36):

$$\mu \geq \frac{1-\alpha}{2-\alpha-\beta} \tag{44}$$

Q.E.D.

Condition 3

In this proof it is shown that Condition 3 is sufficient to ensure full specialization of both regions in the Heckscher-Ohlin model. The proof is completely analogue to the proof of Condition 1. The only step which is worth showing is how $L_M(0)$ is determined.
At time $t = 0$ the West produces manufactures, whereas the East produces both goods. Given the mobility of capital, rental prices equalize across sectors and regions:

$$r^* = p_M A^* \beta (\frac{L_M^*}{K_M^*})^{1-\beta} = p_M A \beta (\frac{L_M}{K_M})^{1-\beta} = \alpha (\frac{L_F}{K_F})^{1-\alpha} \tag{45}$$

Wages equalize across sectors in the East:

$$w = p_M A(1-\beta)(\frac{K_M}{L_M})^{\beta} = (1-\alpha)(\frac{K_F}{L_F})^{\alpha} \tag{46}$$

Plugging production (19) into the inverse demand function (10) gives the manufacturing price:

$$p_M = \frac{\mu}{1-\mu} \frac{K_F^{\alpha} L_F^{(1-\alpha)}}{A^* K_M^{*\beta} + A K_M^{\beta} L_M^{(1-\beta)}} \tag{47}$$

From (46) we can derive:

$$\frac{K_M}{L_M} = (\frac{A}{A^*})^{\frac{1}{1-\beta}} K_M^* \tag{48}$$

From (45) and (46) we get:

$$\frac{K_M}{L_M} = \frac{1-\alpha}{1-\beta} \frac{\beta}{\alpha} \frac{K_F}{L_F} \tag{49}$$

Plugging (48) and (49) into (47) gives:

$$p_M = \frac{\mu}{1-\mu} K_M^{*(\alpha-\beta)} \frac{((1-\beta)/(1-\alpha)(\alpha/\beta))^{\alpha} (A/A^*)^{\frac{\alpha}{1-\beta}} (1-L_M)}{A + A(A/A^*)^{\frac{\beta}{1-\beta}} L_M} \tag{50}$$

From (46) we have:

$$p_M = \frac{1-\alpha}{1-\beta} \frac{1}{A} \frac{(K_F/L_F)^{\alpha}}{(K_M/L_M)^{\beta}} \tag{51}$$

Plugging (48) and (49) into (51) gives:

$$p_M = (\frac{1-\alpha}{1-\beta})^{1-\alpha}(\frac{\alpha}{\beta})^{\alpha}\frac{1}{A}(\frac{A}{A^*})^{\frac{\alpha-\beta}{1-\beta}}K_M^{*(\alpha-\beta)} \tag{52}$$

We now equalize (50) and (51). It is obvious that K_M^* drops out, so that we can solve for L_M:

$$L_M = \frac{\mu(1-\beta)AA^{*\frac{-\beta}{1-\beta}} - (1-\alpha)(1-\mu)A^{\frac{-\beta}{1-\beta}}A^*}{\mu(1-\beta)AA^{*\frac{-\beta}{1-\beta}} + (1-\alpha)(1-\mu)A^{\frac{-\beta}{1-\beta}}A^*} \tag{53}$$

Given simplification (i), we have $A = A^*$, so that (53) can be re-written as:

$$L_M = \frac{\mu(1-\beta) - (1-\alpha)(1-\mu)}{\mu(1-\beta) + (1-\alpha)(1-\mu)} \tag{54}$$

Q.E.D.

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