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A perfect foresight model of regional development and skill specialization

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Abstract

This paper proposes a perfect foresight model of a two-region two-sector economy, where localized externalities in the acquisition of skills cause specialization and uneven regional development. The introduction of a new technology either reinforces or reverses this development pattern. Wealth differences are reinforced if, in spite of higher wages, the new technology locates in the advanced region, attracted by skills similar to the needs of the new industry. Otherwise the new technology locates where wages are lower, in which case the lagging region overtakes the leading one. In spite of perfect foresight, history alone determines the outcome in this economy. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

Episodes of uneven development and overtaking between regions are not exceptional. Belgium is an interesting case in point. In 1950 Belgium's industrialized southern region still had a GDP per capita of 114% relative to its more rural northern neighbor. However, technological change made many of its

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traditional heavy industries obsolete. Plastics and lighter metals, for instance, successfully substituted for steel in many of its applications. These new industries got attracted to the northern region by its low wages, whereas the southern part of the country started losing ground. By 1960 the relative GDP per capita of the southern region had dropped to 104%, and this figure plunged further to 74% by 1990.

However, technological change does not always spell bad fortune for advanced high-wage regions or countries. Japan, for instance, building on its strength in cameras, successfully moved into copiers and fax machines (Porter, 1990). In spite of its high wages, the expertise and skills of its labor force gave it a clear advantage in those new industries. Given that skills are at least partly technology- or sector-specific, the ease of re-allocating labor from one technology (or sector) to another depends on the degree of similarity between the two technologies.

When does technological change cause leapfrogging between regions? And when, on the contrary, does it reinforce a region's leading position? Before addressing these questions, a more fundamental problem needs to be answered: how did regions with similar technologies and preferences develop differently in the first place? This paper proposes a framework that analyzes these issues by formalizing the links between technological change, skill specialization and regional development.

We consider an economy with two regions, East and West, and two sectors, food and manufacturing. Although labor is the only factor of production, there are two types of skills, which are imperfect substitutes. Each region is populated by a continuum of overlapping agents. Endowed with perfect foresight, agents make an irreversible skill investment when they are born by choosing between manufacturing and food skills. There are localized externalities in the acquisition of manufacturing skills; in each region, the greater the number of workers employed in manufacturing, the easier it becomes to acquire manufacturing skills. A slight difference in the concentration of manufacturing skills across regions is, therefore, enough to start off a spiral of uneven development, and over time the economy diverges into a rich manufacturing and a poor agricultural region.

The introduction of a new manufacturing technology may either switch around or reinforce the existing development pattern. A region's attractiveness as a location for the new industry depends not only on its wage level, but also on the productivity of its existing skills when applied to the new technology. This gives rise to two possible, opposite scenarios. If the richer region's skills fit the needs of the new technology well, the new industry is adopted in the advanced region in spite of its higher wages. Externalities then encourage future generations in that region to increasingly specialize in the new technology, so that regional wealth differences get reinforced. If not, the new industry locates in the backward region, taking advantage of the lower wages. The lock-in of this specialization pattern then leads to the industrialization of the lagging region, which eventually overtakes the richer region.

This paper is closely related to the literature on trade and uneven development. It more particularly draws on the work of Brezis et al. (1993), who propose a two-region two-sector model, where learning-by-doing drives uneven development. When then a new technology is introduced, it gets adopted in the low-wage region, so that leapfrogging occurs. We depart from Brezis et al. in two important ways.

First, we believe there is no compelling reason why technological change should always benefit the low-wage region. As suggested above by the Japanese case, the advanced region may very well remain in the lead if its skills are more suitable to the new technology. Other examples of this phenomenon include Ireland, Scotland and Israel, where a high proportion of English-speaking engineers have contributed to the emergence of high-tech clusters. Similar conclusions are reached by Carlton (1983) in a formal study of start-up firms in SMSAs; he finds that existing concentrations of people with specific skills matter a great deal in the choice of firm location.

Second, in Brezis et al. all knowledge is disembodied; the localized learning-by-doing externality extends to the entire labor force, so that all workers of a given region are identical. Not only is this at odds with the micro-evidence on sector-specific skills,[1] it also allows Brezis et al. to completely sidestep the issue of forward-looking behavior. Since an agent's skill is completely determined by the region where she is born, and is thus independent of her own decisions, there is no need to be forward-looking. We amend this shortcoming by introducing optimizing agents who decide in which type of skill to invest.

By investing in a specific skill, an agent limits her mobility between sectors and thus incurs a sunk cost. Although sunk costs imply that agents should be forward-looking, the older trade literature on sector-specific factors of production has generally focused on myopic Marshallian adjustment processes: in Mussa (1974), for instance, capital moves slowly to the sector where the current real return is higher. As pointed out by Krugman (1991), one reason for assuming Marshallian dynamics is to avoid expectational problems and multiplicity of equilibria, which typically arise when perfect foresight is introduced (Matsuyama, 1991). Apart from the additional complexity, the existence of multiple equilibria make comparative statics impossible.

Interestingly, in spite of introducing perfect foresight, there is no role for expectations in our model; the outcome is completely history dependent. This result holds because the source of the externality is the fraction of the region's labor force currently employed in manufacturing. Therefore, no matter what expectations agents have about the future, the region with more manufacturing employment always benefits from a greater externality. The problem of expectational equilibria arises in many other models because externalities are generally

[1] See the empirical literature on the mismatch between the demand and the supply of specific types of labor (e.g., Jackman et al., 1991; Bean and Pissarides, 1991).

modeled to enter the production function. In that case, one region or the other may have a greater externality, depending on expectations.

A crucial assumption in our model needing some additional justification is the localized externality in the acquisition of skills; in each region, learning manufacturing skills becomes easier as more people produce manufactures. The more general assumption of localized externalities in the acquisition of human capital is common in the literature on endogenous growth (Lucas, 1988) and urban economics (Bénabou, 1993). We make a more specific assumption though, by claiming that localized externalities also apply to particular types of skills. Marshall (1890) already noted the importance of this phenomenon when observing that children learn local skills 'unconsciously.'[2] More recently, Porter (1990) has provided compelling anecdotal evidence suggesting that regions tend to have superior schooling in the specific skills used by local industry.

The rest of the paper is organized in the following way. Section 2 sets out the building blocks of the two-region economy and shows how externalities in the acquisition of skills can lock in the specialization pattern, causing uneven development. In Section 3 the introduction of a new technology may reinforce or reverse the existing development pattern. Section 4 concludes and suggests some possible extensions.

2. Skills specialization and uneven development

2.1. The static economy

Consider an economy with two regions, East and West, and two sectors, food and manufacturing. By convention, variables with a star ('*') will denote the West, and unstarred variables will indicate either the East or will be common to both regions. The East and the West have identical labor forces:

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

workers are mobile between regions.[3] Although labor is the only factor of production, some workers have food skills and others have manufacturing skills. In the static economy the distribution of skills is taken as given.

Both sectors operate under perfect competition. Food and manufacturing are characterized by simple linear CRS technologies. In the East the aggregate production functions of food and manufacturing are, respectively:

$$Q_F = L_F^f + L_F^m(1-\theta) \tag{2}$$

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

[3] However, it will turn out that nobody ever has an incentive to migrate, since wages of workers with identical skills equalize across regions.

$$Q_M = A(L_M^m + L_M^f(1-\theta)) \tag{3}$$

where Q_F and Q_M denote the quantities of food and manufactures; L_j^i is the labor force with skill i employed in sector j;[4] and A represents a productivity factor. Technologies in the West are identical to those in the East. As can be noted from (2) and (3), workers with manufacturing and food skills are imperfect substitutes. In the manufacturing sector the productivity of food-skilled agents is a fraction θ lower than the productivity of their counterparts with manufacturing skills; similarly, in the food sector manufacturing-skilled workers are a fraction θ less productive than food-skilled workers.

Since the price of food can be normalized to 1 and the labor market is perfectly competitive, Eastern wages in the food and the manufacturing sector are, respectively:

$$w_F^f = 1 \qquad w_F^m = 1-\theta \tag{4}$$

$$w_M^m = p_M A \qquad w_M^f = p_M A(1-\theta) \tag{5}$$

where w_j^i is the wage of a worker with skill i employed in sector j, and p_M is the price of a manufactured good. In the absence of transaction costs, free trade equalizes prices across regions so that wages for identical workers also equalize.

The relative supply of manufactures can easily be derived (Fig. 1), since agents maximize wages. Given that manufacturing and food skills are imperfect substitutes, agents generally work in the sector that corresponds to their skills, so that the relative supply of manufactures is $(A(L^m + L^{m*}))/(L^f + L^{f*})$. However, if the manufacturing price drops to $(1-\theta)/A$, agents with manufacturing skills become indifferent between working in either sector; if the price falls even further, manufacturing production disappears altogether. Similarly, if the price rises to $1/(A(1-\theta))$, agents with food skills may work in either sector; above that price, food production ceases completely.

The relative demand of manufactures depends on consumers' preferences, which are chosen to be Cobb–Douglas. Consumers spend a fixed share μ of their income on manufactures and the rest on food, so that:

$$\frac{C_M + C_M^*}{C_F + C_F^*} = \frac{\mu}{1-\mu}\frac{1}{p_M} \tag{6}$$

where C_M and C_F denote the consumption of manufactures and food.

The equilibrium manufacturing price can now be derived by equating relative demand and relative supply. If, as in Fig. 1, relative demand crosses relative supply in its vertical portion, i.e., if all agents work in the sector that corresponds to their skills, the manufacturing price can simply be obtained by plugging

[4] From now onwards, superscripts (lower-case) denote a 'skill type', whereas subscripts (upper-case) indicate a 'sector' or a 'product'.

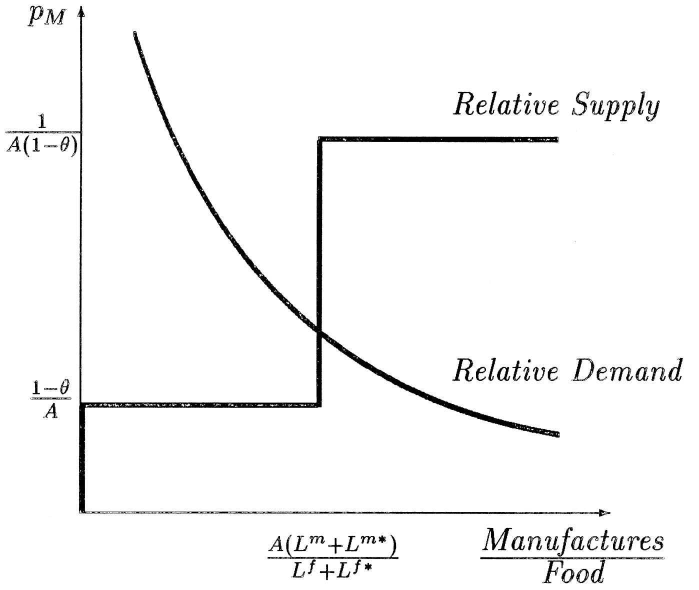

Fig. 1. Demand and supply of manufactures relative to food.

$(A(L^{m} + L^{m}*))/(L^{f} + L^{f}*)$ into (6). However, relative demand may also cross relative supply in one of its horizontal portions. Indeed, if the number of manufacturing-skilled workers is rather large, the supply schedule shifts rightward and intersects the demand curve where the manufacturing price is at its lower bound. In that case some of the agents with manufacturing skills produce food. Similarly, the price reaches its upper bound if there are relatively few agents with manufacturing skills in the economy. The full expression of the manufacturing price is, therefore:

$$p_{M} = \begin{cases} \dfrac{1}{A(1-\theta)} & \text{if } \dfrac{\mu}{1-\mu}\dfrac{2-L^{m}-L^{m}*}{A(L^{m}+L^{m}*)} > \dfrac{1}{A(1-\theta)} \\ \dfrac{\mu}{1-\mu}\dfrac{(2-L^{m}-L^{m}*)}{A(L^{m}+L^{m}*)} & \text{if } \dfrac{1-\theta}{A} \leq \dfrac{\mu}{1-\mu}\dfrac{2-L^{m}-L^{m}*}{A(L^{m}*+L^{m})} \leq \dfrac{1}{A(1-\theta)} \\ \dfrac{1-\theta}{A} & \text{if } \dfrac{\mu}{1-\mu}\dfrac{2-L^{m}-L^{m}*}{A(L^{m}*+L^{m})} < \dfrac{1-\theta}{A} \end{cases} \tag{7}$$

As mentioned before, if the price is at its lower bound, some workers with manufacturing skills are employed in the food sector. The exact number of those workers is easily determined for the economy as a whole;[5] however, how many

[5]It suffices to plug relative total production of manufactured goods (which is a function of manufacturing-skilled workers employed in food) into (6), and set the price in (6) equal to $(1-\theta)/A$. It is then easy to solve out for the number of manufacturing-skilled workers employed in food.

manufacturing-skilled agents switch to food in each region is indeterminate. It is important to resolve this indeterminacy, since in the dynamic model localized externalities will depend on manufacturing employment in each region. We, therefore, make the following tie-breaking assumption:

Assumption 1. *If there is more than one allocation of skills across sectors, that allocation is chosen which minimizes trade between the two regions.*[6]

The same assumption applies when the price is at its upper bound, and some workers with food skills are employed in the manufacturing sector. This concludes the derivation of the economy's static equilibrium.

2.2. The dynamic economy

Dynamics are introduced by the skills decisions of new generations.[7] This is a continuous-time model, where each region is populated by a continuum of overlapping agents. Every agent faces a constant probability of death δ throughout her life-time. Assuming that the population in each region remains constant, this implies that at each moment in time δ people die and δ are born. At the beginning of life each agent decides which skill to obtain by maximizing her life-time utility. Before turning to the agent's optimization problem, several assumptions are introduced:

- (A1) As in Matsuyama (1991), the skill investment is irreversible; no retraining is allowed in the model.
- (A2) The cost of obtaining manufacturing skills for an agent born at time t decreases in the number of people in her region working in the manufacturing sector. The idea that the transmission of skills is facilitated through localized human contact has been discussed in some detail in the introduction. Although we have mentioned before that workers never have an incentive to move between regions, agents might want to migrate in order to acquire skills. This possibility is not considered in our model; agents benefit exclusively from the externality in the region where they are born.
- (A3) The cost of education is modeled as a simple reduction in the agent's life-time utility, rather than as a specific financial investment.
- (A4) As life-time real income increases, the disutility from investing in education becomes greater. This income effect means that when you become richer, you become more reluctant to 'suffer' through the education process.[8]

[6] A similar argument is used by Helpman and Krugman (1985) to determine the degree of decentralization in multinational corporations.

[7] Some of the techniques in this section follow Matsuyama (1991).

[8] The last two assumptions have been made to keep the algebra tractable.

We now return to the agent's maximization problem. An agent born in the East at time t chooses manufacturing skills if and only if she gets a higher expected discounted life-time utility from manufacturing skills than from food skills:

$$\left[\max_{\{C_M(s),C_F(s)|s\geq t\}} \int_t^\infty C_M(s)^\mu C_F(s)^{1-\mu}\, e^{-\rho(s-t)}\, ds - E^m(t)\right.$$
$$\left.\text{s.t.}\quad p_M(s)C_M(s) + C_F(s) = w^m(s)\quad \forall s\geq t\right]$$
$$>\left[\max_{\{C_M(s),C_F(s)|s\geq t\}} \int_t^\infty C_M(s)^\mu C_F(s)^{1-\mu}\, e^{-\rho(s-t)} - E^f(t)\right.$$
$$\left.\text{s.t.}\quad p_M(s)C_M(s) + C_F(s) = w^f(s)\quad \forall s\geq t\right] \tag{8}$$

where $E^m(t)$ and $E^f(t)$ are the utility costs of acquiring manufacturing or food skills for an agent born at time t; w^m and w^f are the wages of agents with manufacturing or food skills; and ρ is the agent's discount rate.[9] We do not allow for savings, so that budget constraints are binding at alltimes.

Before solving the optimization problem, we must specify the exact expressions for w^m and w^f. Although an agent with a specific skill may work in different sectors, Cobb–Douglas preferences insure that an agent's wage is always equal to the wage she would earn in the sector that corresponds to her skills, so that $w^m = Ap_M$ and $w^f = 1$. For instance, if in equilibrium there are some workers with food skills employed in manufacturing, they will face the same wages as their counterparts in the food sector.[10]

The agent's maximization problem (8) boils down to choosing manufacturing skills, rather than food skills, if this yields a higher expected discounted real life-time income net of the cost of education. For simplicity, it is assumed that obtaining food skills is free.[11] Following (A3), the cost of acquiring manufacturing skills in the East decreases in the number of people employed in manufacturing in that region; moreover, in accordance with (A4), the cost is a fraction of an agent's real life-time income. Denoting that fraction $\beta(1 - L_M(t))$, an agent born in the East at time t chooses manufacturing skills if and only if:

$$(1 - \beta(1 - L_M(t))) \int_t^\infty \frac{Ap_M(s)}{\phi(s)}\, e^{-\rho(s-t)}\, ds > \int_t^\infty \frac{1}{\phi(s)}\, e^{-\rho(s-t)}\, ds \tag{9}$$

[9]As pointed out by Matsuyama (1991), the agent's rate of time preference is $\rho - \delta$.

[10]This is easily understood. Cobb–Douglas preferences imply that there will always be some food produced in the economy, so that in equilibrium we will never have all workers with food skills switching to manufacturing. Consequently, agents with food skills employed in manufacturing should face the same wages as agents with food skills who work in the food sector.

[11]This does not undo assumption (A1): the acquisition of food skills is still irreversible.

where ϕ is the price index corresponding to Cobb–Douglas preferences. Condition (9) can easily be re-written as:

$$W_M(t) > \frac{1}{(1-\beta(1-L_M(t)))} \tag{10}$$

where $W_M(t)$ is simply the discounted real life-time income from manufacturing skills relative to food skills. The role of the localized externality is now clear: as more people in the East work in manufacturing, the inequality (10) becomes less stringent, so that new generations in the East are more likely to specialize in manufacturing skills. Since all agents are identical at birth, the fraction of new-born in the East that go into manufacturing skills at time t is:[12]

$$r(t) = \begin{cases} 1 & \text{if } W_M(t) > \dfrac{1}{1-\beta(1-L_M(t))} \\ L^m(t) & \text{if } W_M(t) = \dfrac{1}{1-\beta(1-L_M(t))} \\ 0 & \text{if } W_M(t) < \dfrac{1}{1-\beta(1-L_M(t))} \end{cases} \tag{11}$$

Agents in the West solve the same optimization problem, with the difference that the cost of acquiring manufacturing skills depends on L_M^*, rather than on L_M. The laws of motion of the number of skilled manufacturing workers in the East and the West are then:

$$\dot{L}^m(t) = \delta(r(t) - L^m(t)) \tag{12}$$

$$\dot{L}^{m*}(t) = \delta(r^*(t) - L^{m*}(t)) \tag{13}$$

The first term in (12) and (13) is the 'entry' term, i.e., the agents of the new generation who choose manufacturing skills; the second term is the 'exit' term, i.e., the workers with manufacturing skills who die. Defining $\Omega_M = \ln W_M$ and applying Leibnitz' rule, we can write the law of motion of the co-state variable Ω_M:

$$\dot{\Omega}_M(t) = a(t)(W_M(t) - Ap_M(t)) \tag{14}$$

where $a(t) = (p_M^{-\mu}(t))/(\int_t^\infty p_M(s)\,e^{-\rho(s-t)}\,ds)$. The economy's equilibrium can now be formally defined as:

Definition 1. For a given initial distribution of skills, an equilibrium of the economy is defined as any path satisfying (12)–(14), where $\Omega_M(t) \in [\ln 1 - \theta, \ln(1/(1-\theta))]$, $\forall t \geq 0$.

[12] When agents are indifferent between both skills, the skill distribution does not change.

The three Eqs. (12)–(14) define a dynamical system in $(L^{\mathrm{m}}, L^{\mathrm{m}*}, \Omega_{\mathrm{M}})$ on $[0,1]\times[0,1]\times[\ln 1-\theta,\ \ln(1/(1-\theta))]$ where the initial value of Ω_{M} has to be chosen to make the path consistent with the equilibrium defined above. For given initial values $(L^{\mathrm{m}}(0), L^{\mathrm{m}*}(0))$ the number of $\Omega_{\mathrm{M}}(0)$ satisfying Definition 1 equals the number of possible equilibria. Although there are multiple steady states in this economy (Proposition 1), there is only one equilibrium path corresponding to any given initial condition $(L^{\mathrm{m}}(0), L^{\mathrm{m}*}(0))$ (Proposition 2).

Proposition 1. *If* $(\theta(1-\mu\theta))/(1-\mu)>\beta>0$ *and* $1/2<\mu\leq 1/(2-\beta)$, *there are three possible steady states*: *one where both regions produce both goods*, *and two where both regions are fully specialized*.

Proposition 2. *Under the parameter values of Proposition* 1:

(*a*) *If* $L^{m*}(0)>L^{m}(0)$ (*initial conditions*), *then in steady state the West is completely specialized in manufacturing skills*, *and the East in food skills*.
(*b*) *If* $L^{m*}(0)<L^{m}(0)$ (*initial conditions*), *the reverse applies*.

The dynamics in this model involve a system of three non-linear differential equations for which there are no ready-to-use solutions. Instead, we need to rely on more involved analytical methods, similar to the ones used, for instance, by Gale (1996). Though the formal proofs are provided in Appendix A, it is useful to explain the main results verbally.

Under the given parameter values there are three possible steady states: one is interior, and the other two correspond to full specialization in both regions.[13] Which one of the steady states is reached depends solely on history. Suppose the West starts off with a slightly greater supply of manufacturing skills than the East. Initially both regions are at comparable levels of development, since their skill distributions differ only marginally. The West's small advantage in manufacturing skills gets locked in as Westerners increasingly specialize in manufacturing skills,[14]

[13]The parameter restrictions require some further explanation. If the cost of acquiring manufacturing skills is too high relative to the productivity loss of having food skills and working in manufacturing, all agents may prefer to acquire food skills, thus eliminating skill specialization. In order to avoid this equilibrium we impose $\beta<(\theta(1-\mu\theta))/(1-\mu)$. The condition $1/2<\mu<1/(2-\beta)$ insures that full specialization is an equilibrium: demand for manufactures is strong enough so that all current agents choose manufacturing skills if past agents have done so too, but demand is not too strong so that all current agents choose food skills if past agents have done so.

[14]It may seem odd that Proposition 2 suggests that the West specializes in manufacturing skills if it has a greater number of people with manufacturing skills $(L^{\mathrm{m}*}>L^{\mathrm{m}})$, whereas the cost of acquiring manufacturing skills is lower in the West if it has more people employed in manufacturing $(L_{\mathrm{M}*}>L_{\mathrm{M}})$. In general this difference does not matter since $L^{\mathrm{m}*}>L^{\mathrm{m}}$ implies $L_{\mathrm{M}*}>L_{\mathrm{M}}$; in the exceptional case where $L^{\mathrm{m}*}>L^{\mathrm{m}}$ and $L_{\mathrm{M}*}\leq L_{\mathrm{M}}$, it can be shown that $r*=r=0$. Therefore, as long as $L^{\mathrm{m}*}>L^{\mathrm{m}}$, new generations in the West have a weakly stronger preference to choose manufacturing skills.

whereas Easterners go into food skills. This process causes the skill composition to diverge between both regions, and leads the economy into a spiral of uneven development. In steady state, the West is fully specialized in manufacturing and the East in food; the relative utility or income per capita is then:

$$\frac{U^*}{U} = \frac{\mu}{1-\mu} \tag{15}$$

Since $1 > \mu > 1/2$, it is clear that the West has a higher per capita utility (and income) level. In spite of the higher wages in the manufacturing sector, new generations in the East continue to specialize in food because the cost of acquiring manufacturing skills is prohibitively high.

One interesting aspect of this model is that the outcome is completely history dependent, in spite of perfect foresight. The intuition underlying this result can be clarified by considering the agents' decision rules: agents born at time t in the East choose manufacturing skills if $W_{\mathrm{M}}(t) > 1/(1-(1-\beta L_{\mathrm{M}}(t)))$; their counterparts in the West do the same if $W_{\mathrm{M}}(t) > 1/(1-(1-\beta L^*_{\mathrm{M}}(t)))$. Therefore, if $L^*_{\mathrm{M}}(t) > L_{\mathrm{M}}(t)$, the externality in the East is greater than in the West, irrelevant of expectations of future wages and prices. If, however, as in Matsuyama (1991), future manufacturing productivity were to depend on the future fraction of the labor force employed in manufacturing, expectations could be self-fulfilling. If everybody were to expect the East to specialize in manufacturing, then expected future manufacturing productivity would be higher in the East than in the West, and people's beliefs would get validated; the contrary would occur were agents to expect the West to specialize in manufacturing. Expectations would, therefore, determine the economy's specialization pattern, and we would get the typical result of multiplicity of equilibria often associated with perfect foresight. The irrelevance of expectations in our model reconciles myopic expectations and perfect foresight in the sense that both assumptions give identical steady-state results.

3. Technological change: reinforcing or reversing development patterns?

3.1. Initial location of the new technology

In this section a new superior manufacturing technology is exogenously introduced: $A' > A$. This innovation can be interpreted in two different ways. It could either be a new technology that produces the same good, such as the mini-mill technology replacing the integrated steel plant; or it could be a new technology that produces a perfect substitute for the original manufactured good, such as the replacement of steel by plastics and composite materials.[15] Whether

[15] From a modeling perspective both interpretations are equivalent, since identical goods and perfect substitutes are indistinguishable in the consumer's utility function.

this new technology is initially adopted in the East or the West depends on two factors: the present wage level and the adaptability of skills in both regions. On the one hand, the new industry might be attracted to the region where wages are low, as suggested by Brezis et al. (1993). On the other hand though, skills in the rich region may be closely related to the needs of the new technology, in which case the innovation gets adopted in the West in spite of its higher wages.

How well a specific skill fits a certain technology is represented graphically in Fig. 2. As can be noted, the distance between 'old' manufacturing and food skills is θ, since using food ('old' manufacturing) skills in the 'old' manufacturing (food) sector lowers productivity by a fraction θ. As for the 'new' manufacturing technology, its productivity is maximized if it uses a new type of skill, different from the two original ones. How productive 'old' manufacturing and food skills are when employed in the new sector depends on their respective distances to this new skill. Assuming, as in Fig. 2, that 'new' manufacturing skills are located at a point θ' somewhere in between the two original skills, workers with 'old' manufacturing and food skills have a productivity in the new sector of, respectively, $A'(1-(\theta-\theta'))$ and $A'(1-\theta')$.

At the time the new technology is introduced, the entire labor force in the West is specialized in old manufacturing skills, whereas all workers in the East have food skills. In order to determine which region adopts the new technology, let us view our model as a Ricardian trade model. Instead of considering skills to be different and technologies to be identical across regions, we can view skills to be identical and technologies to be different.[16] In other words, labor productivity in the different industries in the East and the West is:

	East	West
Food	1	$1-\theta$
Manufacturing	$A'(1-\theta')$	$\max[A,A'(1-(\theta-\theta'))]$

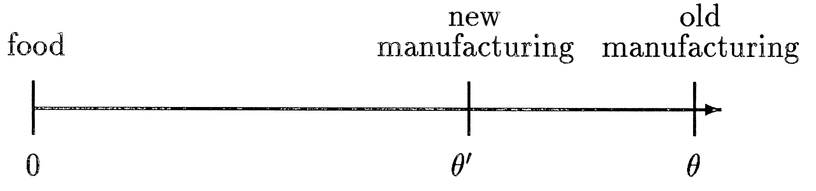

Fig. 2. Skills line.

[16]Note that this particular interpretation is only possible because all agents in a given region have the same skills, so that the labor force in each region is homogeneous.

The West adopts the new technology if:

$$A'(1-(\theta-\theta'))>A \tag{16}$$

In other words, the West switches to the new technology if old and new manufacturing are sufficiently closely related (θ' is big); otherwise, it simply continues to produce manufactured goods using the old technology. Either way, the West initially retains its comparative advantage in manufacturing, given that its relative productivity in manufacturing is higher than that of the East.

The East, for its part, may become partially specialized in manufacturing if its workers can earn a higher wage by adopting the new technology:

$$p_{\mathrm{M}}A'(1-\theta')>1 \tag{17}$$

Given that the manufacturing price depends on whether the West adopts the new technology or not, $p_{\mathrm{M}}=(\mu/(1-\mu))(1/(\max[A,A'(1-(\theta-\theta'))]))$. This allows us to re-write condition (17) as:

$$A'(1-\theta')>\frac{1-\mu}{\mu}\max[A,A'(1-(\theta-\theta'))] \tag{18}$$

The East, therefore, adopts the new technology if its wage level relative to the West is low ($(1-\mu)/\mu$ is small), or if food and new manufacturing skills are closely related (θ' is small); otherwise, it remains completely specialized in food.

In the next two sections we will see how the initial location of the new industry may get locked in, thus affecting the long-run development of both regions.

3.2. Reversal of the development pattern

Suppose that the new and the old technology are relatively unrelated (condition (16) does not hold). To go back to our steel example, this is the case where being familiar with integrated steel plants does not make you an expert in mini-mills. In that case workers in the West do not see any benefit in switching to the new technology. Assume, however, that wages in the backward region are low enough, so that the East adopts the new technology (condition (18) holds). If the externality created by this initial location provides sufficient incentive for future generations to choose new manufacturing skills, the East becomes increasingly specialized in new manufacturing, whereas the West reverts to agriculture. At some point in this process the East overtakes the West.

The story of Belgium and The Netherlands in the first half of the 19th century fits this description surprisingly well. At the end of the 18th century the Dutch enjoyed the highest consumption per capita on the European continent. They were world leaders in a number of industries, such as cotton-printing and paper. Belgium, however, was largely rural and its peasantry lived in dismal poverty. Yet, by the middle of the 19th century Belgium had become the most industrialized nation on the European continent, and the Dutch had lost many of its industries to its southern neighbor. Mokyr (1976) convincingly argues that this happened because of Belgium's lower wages.

The new technology adds a third production function to the economy:

$$Q_{\mathrm{F}} = L_{\mathrm{F}}^{\mathrm{f}} + L_{\mathrm{F}}^{\mathrm{m}'}(1-\theta') \tag{19}$$

$$Q_{\mathrm{M}} = AL^{\mathrm{m}} \tag{20}$$

$$Q_{\mathrm{M}'} = A'(L_{\mathrm{M}'}^{\mathrm{m}'} + L_{\mathrm{M}'}^{\mathrm{f}}(1-\theta')) \tag{21}$$

Note that not each type of worker is present in all production functions. Since condition (16) fails to hold, it is never profitable for agents with old manufacturing skills to switch to the new sector; a fortiori workers with new manufacturing skills never use the old technology. Finally, food-skilled agents are absent from the old manufacturing sector, and vice versa.[17]

The demand side of the economy hardly changes, since old and new manufactures are indistinguishable in the consumer's utility function. The manufacturing price is then:

$$p_{\mathrm{M}} = \begin{cases} \dfrac{1}{A'(1-\theta')} & \text{if } \dfrac{\mu}{1-\mu}\dfrac{(2-(L^{\mathrm{m}'}+L^{\mathrm{m}'}*)-L^{\mathrm{m}}*)}{A'(L^{\mathrm{m}'}+L^{\mathrm{m}'}*)+AL^{\mathrm{m}}*} > \dfrac{1}{A'(1-\theta')} \\ \dfrac{\mu}{1-\mu}\dfrac{(2-(L^{\mathrm{m}'}+L^{\mathrm{m}'}*)-L^{\mathrm{m}}*)}{A'(L^{\mathrm{m}'}+L^{\mathrm{m}'}*)+AL^{\mathrm{m}}*} & \text{if } \dfrac{1-\theta'}{A'} \le \dfrac{\mu}{1-\mu}\dfrac{(2-(L^{\mathrm{m}'}+L^{\mathrm{m}'}*)-L^{\mathrm{m}}*)}{A'(L^{\mathrm{m}'}+L^{\mathrm{m}'}*)+L^{\mathrm{m}}*} \le \dfrac{1}{A'(1-\theta')} \\ \dfrac{1-\theta'}{A'} & \text{if } \dfrac{\mu}{1-\mu}\dfrac{(2-(L^{\mathrm{m}'}+L^{\mathrm{m}'}*)-L^{\mathrm{m}}*)}{A'(L^{\mathrm{m}'}+L^{\mathrm{m}'}*)+AL^{\mathrm{m}}*} < \dfrac{1-\theta'}{A'} \end{cases} \tag{22}$$

As before, if the price is at its upper or lower bound, the exact allocation of skills across sectors in each region is pinned down by Assumption 1.

Note that in the price expression (22) there are no workers with old manufacturing skills in the East. At the time the new technology is introduced the labor force in the East is fully specialized in food skills. Moreover, it is assumed that the productivity of the new technology is sufficiently great so that new generations never prefer old over new manufacturing skills:

[17] If the manufacturing price rises too high, agents switch from food to new manufacturing, rather than to old manufacturing. If the price drops too low, new manufacturing workers change to the food sector; it can be shown that the price never drops far enough to give old manufacturing workers the incentive to move.

Lemma 1. *If $A'(1-\beta) > A$ then no agent in the East or the West ever has an incentive to choose old manufacturing skills.*[18]

This lemma implies that new generations in both regions choose between new manufacturing and food skills. The optimization problem of an agent born at time t in the East, therefore, simplifies to choosing new manufacturing skills, rather than food skills, if and only if:

$$(1-\beta(1-L'_{\mathrm{M}}(t)))\int_t^{\infty}\frac{A' p_{\mathrm{M}}(s)}{\phi(s)}\,\mathrm{e}^{-\rho(s-t)}\,\mathrm{d}s > \int_t^{\infty}\frac{1}{\phi(s)}\,\mathrm{e}^{-\rho(s-t)}\,\mathrm{d}s \tag{23}$$

The fraction of new born in the East that chooses new manufacturing skills at time t is:

$$r'(t)=\begin{cases}1 & \text{if } W_{\mathrm{M}'}(t) > \dfrac{1}{1-\beta(1-L_{\mathrm{M}'}(t))}\\ L^{\mathrm{m}'}(t) & \text{if } W_{\mathrm{M}'}(t) = \dfrac{1}{1-\beta(1-L_{\mathrm{M}'}(t))}\\ 0 & \text{if } W_{\mathrm{M}'}(t) < \dfrac{1}{1-\beta(1-L_{\mathrm{M}'}(t))}\end{cases} \tag{24}$$

where $W_{\mathrm{M}'}$ is now the relative discounted life-time income of a worker with new manufacturing skills. Solving the optimization problem of an agent born in the West at time t is analogue to (23)–(24), so that the laws of motion of the dynamic system are:

$$\dot{L}^{\mathrm{m}'}(t)=\delta(r(t)-L^{\mathrm{m}'}(t)) \tag{25}$$

$$\dot{L}^{\mathrm{m}'*}(t)=\delta(r^{*\prime}(t)-L^{\mathrm{m}'*}(t)) \tag{26}$$

$$\dot{L}^{\mathrm{m}*}(t)=-\delta L^{\mathrm{m}*}(t) \tag{27}$$

$$\dot{\Omega}_{\mathrm{M}'(t)}=a(t)(W_{\mathrm{M}'}(t)-A' p_{\mathrm{M}}(t)) \tag{28}$$

where $\Omega_{\mathrm{M}'}=\ln W_{\mathrm{M}'}$. The economy's equilibrium can easily be defined by analogy with Definition 1.

For the given initial conditions, there is only one possible steady state:

Proposition 3. *If the new technology initially exclusively locates in the East, if the*

[18]It suffices to show this result in the extreme case where the entire labor force is employed in old manufacturing; even in that case the substantial cost advantage in acquiring old manufacturing is not enough to compensate the higher productivity of new manufacturing skills.

conditions of Lemma 1 *hold, and if* $\beta < (\theta'(1-\mu\theta'))/(1-\mu)$,[19] *then the economy reaches a steady state where the East is completely specialized in new manufacturing and the West in food.*

This result is easily understood. The adoption of the new technology by a number of workers in the East gives new generations in that region an advantage in the acquisition of new manufacturing skills. The West, on the contrary, moves into food skills. Over time the East becomes increasingly specialized in manufacturing, whereas the West goes through a process of de-industrialization. Although initially the East still exports food, at some point the trade pattern turns around. Eventually the East overtakes the West, and in steady state the per capita income (or utility) of the West relative to the East is the inverse of (15).

3.3. Reinforcement of the development pattern

In this section we study the case where old and new manufacturing skills are relatively similar (condition (16) holds), so that the new technology gets adopted in the West.[20] Eventually the West becomes completely specialized in the new manufacturing sector, whereas the East remains trapped in agriculture. The regional development gap is thus preserved.

If workers with old manufacturing skills become more productive by adopting the new technology, then the West's labor force switches en masse to the new sector. The old manufacturing industry disappears instantaneously, and the economy is left with two production technologies:

$$Q_{\mathrm{F}} = L_{\mathrm{F}}^{\mathrm{f}} + L_{\mathrm{F}}^{\mathrm{m}'}(1-\theta') \tag{29}$$

$$Q_{\mathrm{M}'} = A'(L_{\mathrm{M}'}^{\mathrm{m}'} + L_{\mathrm{M}'}^{\mathrm{m}}(1-(\theta-\theta')) + L_{\mathrm{M}'}^{\mathrm{f}}(1-\theta')) \tag{30}$$

It is easy to see that new generations in both the East and the West will never have an incentive to acquire old manufacturing skills.[21] The optimization problem of an agent born at time t in the East is, therefore, equivalent to (23), and the derivation of the laws of motion of the dynamic economy is identical to (24)–(28). We can thus immediately jump to the results:

Proposition 4. *Given that the new technology initially locates in the West, the*

[19] This condition is analogous to the one in Proposition 1. See Footnote (13) for further details.

[20] Whether the new technology locates exclusively in the West, or in both regions, turns out to be irrelevant.

[21] Since all workers in the West have adopted the new technology, externalities in the acquisition of old manufacturing skills have disappeared; it will thus always be profitable to acquire new, rather than old, manufacturing skills.

economy reaches a steady state where the West is completely specialized in new manufacturing, and the East in agriculture.

The initial adoption of the new technology by the entire labor force in the West creates an important externality for future generations to acquire those new skills. Over time the West fully specializes in new manufacturing, and thus reinforces the existing development pattern.

4. Concluding remarks and possible extensions

The purpose of this paper has been to propose a framework to analyze the dynamics of regional development. The lock-in of specialization patterns, driven by localized externalities in the acquisition of skills, causes uneven development. However, technological change may change the pattern of specialization, and thus lead to a reinforcement or a reversal of the original pattern of uneven development.

We see several promising extensions originating from this work. The framework could be used to study the welfare implications of a number of regional policy issues, such as inter-regional transfers, subsidies to save jobs in declining industries, and inter-regional competition to attract new technologies. Another interesting extension would be to analyze the case where parents migrate in order to improve the educational perspectives of their offspring. This would tend to mitigate regional wage differences and would furthermore give rise to multiple equilibria.

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Appendix. Proofs of propositions

More detailed proofs are available from the author upon request.

Proof of Proposition 1. (L^{m*}, L^{m}) is a steady state if it satisfies the conditions

$\dot{L}^{\mathrm{m}} = 0$, $\dot{L}^{\mathrm{m}*} = 0$ and $\dot{\Omega}_{\mathrm{M}} = 0$. Because of (14), the latter condition is equivalent to $W_{\mathrm{M}} = Ap_{\mathrm{M}}$, where p_{M} is given by (7). Using (11)–(14), this allows us to represent the loci $\dot{L}^{\mathrm{m}*} = 0$ and $\dot{L}^{\mathrm{m}} = 0$ graphically. Two cases can be distinguished:

- Case 1: $\beta < \theta$: if $\beta < \theta$, both loci are in the subspace where $(1-\theta)/A < p_{\mathrm{M}} < 1/(A(1-\theta))$ (Fig. 3). There is one interior steady state, where $L^{\mathrm{m}*} = L^{\mathrm{m}}$ (because of the symmetry of (11)), and there are two corner steady states, where both regions are fully specialized (since $1/2 < \mu \le 1/(2-\beta)$).
- Case 2: $\theta \le \beta < (\theta(1-\mu\theta))/(1-\mu)$: the loci $\dot{L}^{\mathrm{m}} = 0$ and $\dot{L}^{\mathrm{m}*} = 0$ look slightly different from the previous case (Fig. 4). Consider the upper left-hand part of Fig. 4, where L^{m} is fairly high and L^{*}_{M} is fairly low. Even though p_{M} is at its maximum, agents in the West may not find it beneficial to acquire manufacturing skills due to the higher β (compared to Case 1). This explains the upper left-hand kink in locus $\dot{L}^{\mathrm{m}*} = 0$. By symmetry, the other locus also has a kink. In spite of the different shape of the loci, the steady states are identical to the ones in Case 1. $\square$

Proof of Proposition 2. We will limit ourselves to proving part (b) of Proposition 2 for the case where $\beta < \theta$. Let $\mathcal{S} \equiv \{(L^{\mathrm{m}*}, L^{\mathrm{m}}) | 0 \le L^{\mathrm{m}} \le 1, 0 \le L^{\mathrm{m}*} \le 1, L^{\mathrm{m}*} < L^{\mathrm{m}}\}$ denote the feasible set of labor distributions where $L^{\mathrm{m}} > L^{\mathrm{m}*}$. Define the following subsets (Fig. 5):

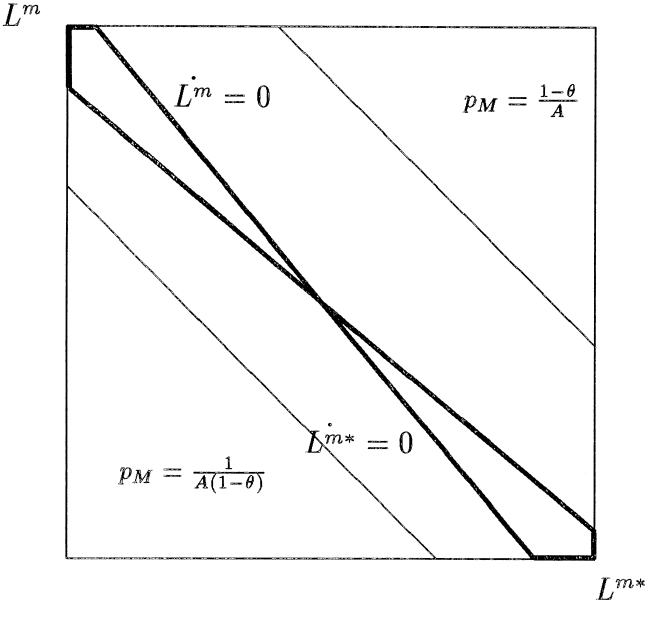

Fig. 3. Case 1, Proposition 1.

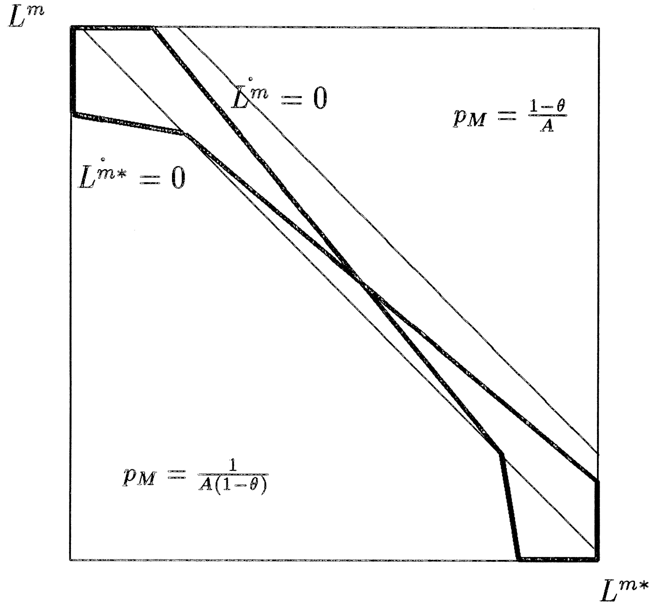

Fig. 4. Case 2, Proposition 1.

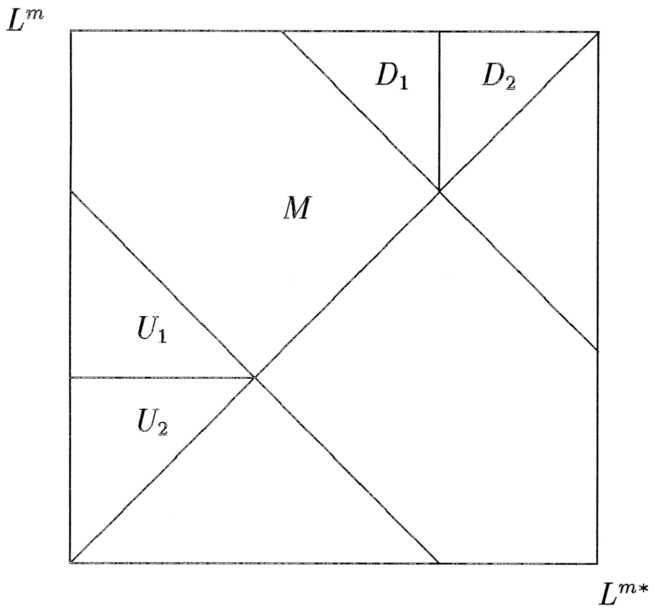

Fig. 5. Subsets of S in Proposition 2.

$$M \equiv \left\{ (L^{m*}, L^{m}) \in \mathcal{S} \,\middle|\, \frac{1-\theta}{A} < p_M < \frac{1}{A(1-\theta)} \right\} \tag{31}$$

$$U_1 \equiv \left\{ (L^{m*}, L^{m}) \in \mathcal{S} \,\middle|\, p_M = \frac{1}{A(1-\theta)} \quad \text{and} \quad L^{m} \geq \frac{1-\theta}{1-\mu\theta}\mu \right\} \tag{32}$$

$$U_2 \equiv \left\{ (L^{m*}, L^{m}) \in \mathcal{S} \,\middle|\, p_M = \frac{1}{A(1-\theta)} \quad \text{and} \quad L^{m} < \frac{1-\theta}{1-\mu\theta}\mu \right\} \tag{33}$$

$$D_1 \equiv \left\{ (L^{m*}, L^{m}) \in \mathcal{S} \,\middle|\, p_M = \frac{1-\theta}{A} \quad \text{and} \quad L^{m*} < \frac{\mu}{1-\theta+\mu\theta} \right\} \tag{34}$$

$$D_2 \equiv \left\{ (L^{m*}, L^{m}) \in \mathcal{S} \,\middle|\, p_M = \frac{1-\theta}{A} \quad \text{and} \quad L^{m*} \geq \frac{\mu}{1-\theta+\mu\theta} \right\} \tag{35}$$

In M all agents work in the sector that corresponds to their skills; in U_1 some food-skilled workers in the West do manufacturing; in U_2 some food-skilled workers in both the East and the West do manufacturing; in D_1 some manufacturing-skilled workers in the East produce food; in D_2 some manufacturing-skilled workers in both the East and the West produce food. Note that $D = D_1 \cup D_2$ and $U = U_1 \cup U_2$.

The initial conditions can be classified in two categories. In each case it is shown that the sequence $\{(L^{m*}(t), L^{m}(t))\}$ converges to (0,1):

- Case 1: $(L^{m*}(0), L^{m}(0)) \in M$: first it is shown that the sequence can never leave M, once it is in M. (i) If the sequence were to enter U, where p_M is at its maximum, W_M would in the limit go to $-\infty$. This possibility can be discarded. (ii) If the sequence were to enter D, where p_M is at its minimum, W_M would in the limit go to $+\infty$. This possibility can also be discarded. (iii) The last way to leave M is to reach $L^{m} = L^{m*}$. However, this is impossible because $r \geq r^*$, $\forall (L^{m*}, L^{m}) \in M$.

  Now it is shown that if the sequence $\{(L^{m*}(t), L^{m}(t))\}$ remains in region M, it converges to (0,1). We already know that $r \geq r^*$. Since $r = r^* = 1$ would lead the sequence into D and $r = r^* = 0$ would lead the sequence into U, it must be that at some point $\bar{t}$ we have $r > r^*$. Then $\forall t \geq \bar{t}$, $r(t) > r^*(t)$. Imagine the contrary. If at some point $t > \bar{t}$ we had $r(t) = r^*(t) = 0$, then it must be that $\dot{W}_M(t) < 0$, so that eventually the sequence would enter U, a possibility to be discarded. Similarly, if at $t > \bar{t}$, we had $r(t) = r^*(t) = 1$, the sequence would enter D, which can also be discarded. Therefore, since $r(t) > r^*(t)$ $\forall t > \bar{t}$, the sequence $\{(L^{m*}(t), L^{m}(t))\}$ converges to the only stationary point in M: (0,1).
- Case 2: $(L^{m*}(0), L^{m}(0)) \in U$ or $(L^{m*}(0), L^{m}(0)) \in D$: the sequence must leave U or D and enter M at some point; otherwise W_M would go to, respectively, $-\infty$ and $+\infty$. As soon as the sequence enters M, we are back in Case 1, so that the convergence result holds. □

Proof of Proposition 3. Again, two cases are considered:

- Case 1: $\beta < \theta'$: first the possible steady states are determined. In steady state nobody has old manufacturing skills (Lemma 1). It suffices to replace θ by θ' and old by new manufacturing in Proposition 1, to see that the possible steady states are identical to the ones in Proposition 1. Given the initial conditions, it is shown subsequently that the steady state is reached where the East is specialized in new manufacturing and the West in food.

  At time t_1 when the new technology is introduced $L_{M'}(t_1) > L_{M'*}(t_1)$. This implies that at some point $\bar{t} \geq t_1$, we must have $L^{m'}(\bar{t}) > L^{m'*}(\bar{t})$. (Otherwise, the whole economy becomes fully specialized in either food skills or new manufacturing skills; this possibility can be discarded.)

  Now it is shown that if $L^{m'}(\bar{t}) > L^{m'*}(\bar{t})$, the economy never reaches $L^{m'}(t) = L^{m'*}(t)\ \forall\ t > \bar{t}$. If $L^{m*} = 0$, and $L^{m'} > L^{m'*}$, then the economy is identical to the one described in Proposition 2(b) (again, after replacing θ by θ' and old by new manufacturing), so that the line $L^{m'} = L^{m'*}$ is never reached. If $L^{m*} > 0$, then this result holds a fortiori. Therefore, if $L^{m'}(\bar{t}) > L^{m'*}(\bar{t})$, then $L^{m'}(t) > L^{m'*}(t)\ \forall t > \bar{t}$.

  Since $\lim_{t\to\infty} L^{m*}(t) = 0$, and $L^{m'}(t) > L^{m'*}(t)\ \forall t > \bar{t}$, it follows that in the limit the economy is identical to the one in Proposition 2(b) (after making the above-mentioned changes). In steady state, the East will, therefore, be completely specialized in new manufacturing skills, and the West in food skills.
- Case 2: $\theta' \leq \beta < (\theta'(1-\mu\theta'))/(1-\mu)$: again the possible steady states are identical to the ones in Proposition 1. The rest of the proof follows by analogy with Case 1. □

Proof of Proposition 4. Given that old manufacturing skills disappear, the possible steady states are identical to the ones in Proposition 3.

It will now be shown that $r'^*(t) = 1\ \forall t$. Define M as the set of feasible skill distributions where all manufacturing-skilled workers are employed in new manufacturing and all food-skilled workers in food; U as the set of feasible skill distributions where some food-skilled workers are employed in new manufacturing; and D as the set of feasible skill distributions where some manufacturing-skilled workers are employed in food. At time t_1 the new technology is introduced, and all agents in the West switch from old to new manufacturing so that $L^*_{M'}(t_1) = 1$. Suppose $r'^*(t_1) = 0$. In that case $\dot{W}_{M'}(t_1) < 0$, so that $r'(t) = r'^*(t) = 0$ $\forall t \geq t_1$. That would imply $\dot{W}_{M'}(t) < 0\ \forall t \geq t_1$, which leads to an impossibility as $\lim_{t\to\infty} W_{M'}(t) = -\infty$. Therefore, $r'^*(t_1) = 1$.

Now it is shown that as long as the sequence $\{(L^{m*}(t), L^{m'*}(t), L^{m'}(t))\}$ remains in U or M and $L^*_{M'} = 1$, then $r'^* = 1$. Indeed, in order for r'^* to drop below 1, $W_{M'} < A' p_M$, so that $\dot{W}_{M'} < 0$. This leads to $\lim_{t\to\infty} W_{M'}(t) = -\infty$, a possibility to be discarded. Therefore, since r'^* cannot drop below 1, $L^*_{M'}$ does not drop below 1.

Since the sequence cannot enter D (otherwise $W_{M'}$ would in the limit go to

$+\infty$), it follows that $\lim_{t\to\infty} L^{m'}*(t) = 1$. Since moreover $\lim_{t\to\infty} L^{m}*(t) = 0$, this economy is identical to the one in Proposition 2(a) (again, after replacing old by new manufacturing). Therefore, in steady state the West will be fully specialized in new manufacturing skills and the East in food skills. □

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