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ABSTRACT

Many technologies used by the LDCs are developed in the OECD economies, and as such are designed to make optimal use of the skills of these richer countries' workforces. Due to differences in the supply of skills, some of the tasks performed by skilled workers in the OECD economies will be carried out by unskilled workers in the LDCs. Since the technologies in these tasks are designed to be used by skilled workers, productivity in the LDCs will be low. Even when all countries have equal access to new technologies, this mismatch between skills and technology can lead to sizable differences in total factor productivity and output per worker. Our theory also suggests that productivity differences should be highest in medium-tech sectors, and that the trade regime and the degree of intellectual property right enforcement in the LDCs have an important effect on the direction of technical change and on productivity differences.

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I. Introduction

Most economists view technological differences as an important part of the large disparities in per capita income across countries. For example, Paul Romer (1993, p. 543) argues that many nations are poor, in large part, "...because their citizens do not have access to the ideas that are used in industrial nations to generate economic value." (see also Prescott, 1998). This view receives support from a number of recent studies, such as Klenow and Rodriguez (1997), Caselli et al. (1997), and Hall and Jones (1998), which find significant "total factor productivity" (TFP) differences across countries. Large cross-country differences in technology are difficult to understand, however. Ideas, perhaps the most important ingredient of technologies, can flow freely across countries, and machines, which embed better technologies, can be imported by less developed countries. This compelling argument has motivated papers such as Mankiw, Romer and Weil (1992), Mankiw (1995), Chari, Kehoe and McGrattan (1997), Parente, Rogerson and Wright (1998) and Jovanovic and Rob (1998) to model cross-country income differences as purely driven by differences in factors rather than in technology.

In this paper, we argue that even when all countries have access to the same set of technologies, there will be large productivity differences among them.[1] The center-piece of our approach is that many technologies used by less developed countries (LDCs/the South) are imported from more advanced countries (the North) and, as such, are designed to make optimal use of the prevailing factors and conditions in these richer countries. To the extent that these conditions are different in the South, the technologies developed in the North may be *inappropriate* for the LDCs. For example, the OECD economies prefer to develop new crops suitable for a temperate climate, while many LDCs would be unable to use these and instead need crops suitable to the tropics. Although there are many dimensions in which technological needs of the South differ from those of the North, including climate, geography, and culture, we focus on differences in skill scarcity, which we believe to be important in practice. The North is more abundant in skills and tends to develop relatively skill-complementary (*skill-biased*) technologies, but these are only of limited use to the LDCs.

The main result of our paper is that the mismatch between technologies developed in the North and the skills of the South's labor force will lead to productivity differences between the North and the South even in the absence of any barriers to technology

[1] To focus on our mechanism, we abstract from other important determinants of productivity differences. Significant productivity differences across countries may arise due to institutional differences, for example in the degree of property right enforcement, corruption, efficiency of the public administration, barriers to technology adoption, agency costs, etc.. See, for example, Parente and Prescott (1994) on barriers to technology adoption, and Acemoglu and Zilibotti (1999) on agency costs.

transfer. The South must use unskilled workers in tasks performed by skilled workers in the North. Since the technologies imported from the North are not suited to the needs of the unskilled workers performing these tasks, the South will have low productivity, even once we control for the contribution of physical and human capital to output. This mismatch between technologies and skills in the South will also naturally amplify the differences in per capita income.

It is also important to investigate whether the differences in productivity and output per worker predicted by our model could be sizeable. Our model gives a simple expression for output per worker as a function of the ratio of capital per worker, ratio of skilled to unskilled workers, and the equilibrium skill-bias in the North's technology. By considering the U.S. as the North, we perform some back-of-the-envelope calculations. These exercises suggest that the differences predicted by our model are sizeable, and significantly larger than those predicted by a simple "neoclassical" model. More concretely, for example, using cross-country variations in physical and human capital (secondary school attainment), we find that the neo-classical model predicts, on average, that output per worker in the LDCs should be approximately 40% of the U.S. while our model predicts the same number to be 23%, much closer to the 21% number we observe in the data. Moreover, our calculations suggest that if technologies were not biased towards the needs of the U.S. economy, output per worker differences would be much smaller. For example, when technologies are appropriate to the needs of the "average" country in our sample, predicted differences in output per worker are reduced by a factor of more than two.

A number of other interesting results also follow from of our analysis. First, the LDCs are predicted to have productivity levels comparable to the OECD countries in very unskilled and very skilled sectors and tasks, but lower productivity in medium skilled tasks. In the most complex tasks, even the very skill-scarce LDCs have to employ skilled workers, who will use the skill-complementary technologies developed in the North and achieve a high level of productivity. In contrast, there will be large productivity differences in sectors where workers are skilled in the North but unskilled in the South, because the technologies are not developed for the unskilled workers in these sectors. This pattern receives some support from the casual observation that there are pockets of efficient high-tech industries such as software programming in India.

Second, we show that international trade reduces productivity differences because the LDCs specialize in sectors where technology is appropriate to unskilled workers. Interestingly, despite reducing productivity differences, international trade causes *divergence in output per worker.* Trade reduces the prices of unskilled goods in the North, and discourages investment in unskilled technologies, which were those most beneficial to the South. As a result, trade increases the relative productivity and pay of skilled workers, and widens the output gap between poor and rich countries. Although other, beneficial, effects of international trade may be more important in practice, this novel effect of trade on per capita income in the South, via its impact on the skill-bias of new technologies, is also worth bearing in mind.

Third, intellectual property rights emerge as an important determinant of technological development. When property rights are enforced internationally, firms in the North have more incentive to develop technologies suited to the South, and output per worker differences decline. However, each less developed country individually benefits from not enforcing these rights, creating a potential for a classic Prisoner's Dilemma.

Finally, our theory suggests a stylized pattern of cross-country convergence in productivity and GDP. A less developed country diverges from the technological leader when it chooses to use local technologies for which there is no (or little) R&D, but eventually cross-country productivity and income differences tend to become stable as the LDCs start importing the technologies developed in the North. On the other hand, productivity (and income) convergence occurs when a country improves its skill base relative to the North, which concurs with the experiences of Korea and Japan (see for example, Rhee, Ross-Larson and Pursell, 1984; Lockwood, 1968).

The two building blocks of our approach, that most technologies are developed in the North and that these technologies are designed for the needs of these richer economies (*directed technical change*), appear plausible. For example, over 90% of the R&D expenditure in the world is carried on in the OECD, and over 35% is in the U.S..[2] Moreover, many recent technologies developed in the North appear to be highly skill-complementary and substitute skilled workers for tasks previously performed by the unskilled (e.g. Katz and Murphy, 1992; Berman, Bound and Machin, 1998). So it should perhaps not be surprising that there are many examples of developing countries, abundant in unskilled workers, which adopt labor-saving technologies requiring specialized technical skills. This has led many development economists, like Frances Stewart (1977, p. xii), to conclude that "...the technology Third World countries get from rich countries is inappropriate", which is consistent with the approach in this paper.

A number of other papers have emphasized the difficulties in adapting advanced technologies to the needs of the LDCs. Evanson and Westphal (1995) suggest that new technologies require a large amount of tacit knowledge, which cannot be transferred, slowing down the process of technological convergence. The importance of "appropriateness" of technology has also received some attention, for example Salter (1966), Atkinson and Stiglitz (1969) and David (1974). Diwan and Rodrik (1991) use some of the insights of

[2] Authors' calculation from UNESCO (1997). UNESCO (1997) gives R&D expenditure as a percentage of GNP, and we calculated the OECD share using the Summers and Heston (1991) data on GNP.

this literature to discuss the incentives of Southern countries to enforce intellectual property rights, as we do in Section V. An important recent contribution to the appropriate technology literature is Basu and Weil (1998), who adopt the formulation of Atkinson and Stiglitz whereby technological change takes the form of learning-by-doing and influences productivity at the capital labor ratio currently in use (see also Temple, 1998). Basu and Weil characterize the equilibrium in a two-country world where the less advanced economy receives productivity gains from the improvements in the more advanced economy. Our paper differs from Basu and Weil, in particular, and the rest of the appropriate technology literature, in general, in a number of ways. First, what matters in our theory is not capital-labor ratios (as in Atkinson and Stiglitz and Basu and Weil) or size of plants (as in Stewart), but relative supplies of skills, which we believe to be more important in practice. Second, our results do not follow because productivity depends on the exact capital-labor or skilled-unskilled labor ratios in use, but because skilled workers use different technologies than unskilled workers, and in the North skilled workers perform some of the tasks performed by unskilled workers in the South. Third, and perhaps most important, technological change is not an unintentional by-product of production, but a purposeful activity. In particular, R&D firms in the North direct their innovations towards different technologies depending on relative profitability. All our results originate from the fact that the relative abundance of skills in the North induces "skill-biased" innovations. In this respect, our model is closely related to Acemoglu (1998), which models directed technical change, but primarily focuses on its implications for wage inequality.[3]

Finally, there is now a large literature on innovation, imitation and technology transfer, for example, Vernon (1966), Krugman (1979), Grossman and Helpman (1991), Rivera-Batiz and Romer (1991), Eaton and Kortum (1997) and Barro and Sala-i-Martin (1997). Some of these models, as well as the more traditional models of trade and innovations, such as Krugman (1987), Feenstra (1991) and Young (1991), obtain the result that trade may reduce the growth rate of less developed countries, but the channel is very different. Moreover, in our model, trade affects TFP and GDP in opposite directions, and affects only relative GDP levels, not long-run growth. The most important difference from our work, however, is that these papers do not analyze an economy in which technological knowledge flows freely across countries, and they do not allow technical progress to be

[3]We should further note that as is known from trade theory, when there are deviations from factor price equalization, there will also be factor productivity differences due to different factor proportions in production. These same forces are present in our economy. But more importantly, directed technical change, the fact that new technologies are developed for the North's skilled workers, ensures that productivity in the North is always higher than in the South, and amplifies the differences in output per worker. Without directed technical change, there is no reason for these factor productivity to be larger in countries with more skilled workers, especially once we control for the direct contribution of physical and human capital to output.

directed towards different levels of skills.

The plan of the paper is as follows. Section II introduces our basic model and characterizes the equilibrium in the North and the South in the absence of commodity trade and intellectual property rights in the South. Section III shows that productivity is higher in the North than the South and performs some simple back-of-the-envelope calculations to evaluate the potential contribution of our mechanism to the differences in output per worker. Section IV analyzes technical change and productivity differences in a world with commodity trade. Section V analyzes the impact of property rights enforcement in the South on technical change. Section VI endogenizes skill acquisition decisions and shows that improvements in the relative supply of skills in the LDCs lead to productivity convergence, and Section VII analyzes the choice between local and imported technologies in the South. Section VIII concludes, while Appendix A contains the main proofs. Appendix B, which contains some additional results, is available upon request.

II. The Basic Model

A. Countries, Agents and Preferences

We consider a world economy consisting of two groups of countries. There is one large advanced country which we call the North, and a set of small less developed countries which we refer to as the South. To simplify the analysis, we assume all Southern countries to be identical. What distinguishes the North and the South, other than their relative sizes, is the abundance of skills. The North has H^n skilled workers and L^n unskilled workers, whereas the South has H^s skilled workers and L^s unskilled workers. We assume that $H^n/L^n > H^s/L^s$, so the North is more abundant in skills.

New technologies are developed using final output. As we will see shortly, due to a market size effect in the creation of new technologies, countries in the South will perform no R&D. All technological progress will therefore originate in the North. But the South can adopt these technologies. All consumers have linear preferences given by $\int_0^\infty Ce^{-rt}dt$, where C is consumption and r is the discount rate, which will also be the interest rate. We suppress time indexes when this causes no confusion.

B. Technology

We first describe the production technology which is common across countries, and the R&D technology in the North. To simplify notation, we omit the country indexes for now. Consumption and investment come out of an output aggregate,

$$C + I + X \leq Y \equiv \exp\left[\int_0^1 \ln y(i)di\right], \tag{1}$$

where I is investment in machines, and X is expenditure on R&D. We normalize the price of the consumption aggregate in each period to 1. Good i is produced as:

$$y(i) = \left[\int_0^{N_L} k_L(i,v)^{1-\beta}dv\right] \cdot [(1-i)\cdot l(i)]^{\beta} + \left[\int_0^{N_H} k_H(i,v)^{1-\beta}dv\right] \cdot [i \cdot Z \cdot h(i)]^{\beta}, \tag{2}$$

where $k_z(i,v)$ is the quantity of machines of type v used in sector i together with workers of skill level z (i.e. this is sector and skill-specific capital). There is a continuum of machines, denoted by $j \in [0, N_L]$, that can be used with unskilled workers, and a continuum of machines (different) $j \in [0, N_H]$ used with skilled workers. Technical progress in this economy will take the form of increases in N_L and N_H, that is, technical change expands the range of machines that can be used with unskilled and skilled workers. This is similar to the expanding variety model of Romer (1990) (see also Grossman and Helpman, 1991), but allows for technical change to be skill-or labor-complementary as in Acemoglu (1998). Equation (2) also implies that each good can be produced by skilled or unskilled workers, using the technologies suited to their needs. The terms $(1-i)$ and i imply, however, that unskilled labor is relatively more productive in producing goods with low indexes. The parameter Z (where $Z \geq 1$) enables a positive skill premium. Feasibility requires that $\int_0^1 l(i)di \leq L$ and $\int_0^1 h(i)di \leq H$.

Producers of good $i \in [0,1]$ take the prices of their products, $p(i)$, wages, w_L and w_H, and the rental prices of all machines, $\chi_L(v)$ and $\chi_H(v)$, as given, and maximize profits. This gives the following sectoral demands for machines:

$$\begin{aligned} k_L(i,v) &= \left[(1-\beta)\cdot p(i) \cdot ((1-i)\cdot l(i))^{\beta}/\chi_L(v)\right]^{1/\beta} \\ k_H(i,v) &= \left[(1-\beta)\cdot p(i) \cdot (i \cdot Z \cdot h(i))^{\beta}/\chi_H(v)\right]^{1/\beta}. \end{aligned} \tag{3}$$

A (technology) monopolist owns the patent for each type of machine. We assume that it also owns machines and rents them out to users at the rental rates $\chi_z(v)$. Machines depreciate at the rate δ and investments in machines are reversible. Consider the monopolist owning the patent to a machine ν for skill class z, invented at time 0. Define the total demand for machine ν for skill type z as $K_z(\nu) = \int_0^1 k(i,\nu)di$. The monopolist chooses an investment plan and a sequence of capital stocks so as to maximize the present discounted value of profits, as given by $V_z(\nu) = \int_0^\infty e^{-rt}\left[\chi_z(\nu)K_z(\nu) - \theta I_z(\nu)\right] dt - \theta K_z^0(\nu)$, subject to $\dot{K}_z(\nu) = I_z(\nu) - \delta K_z(\nu)$ and to the set of demand constraints given by (3), where we have suppressed time indexes. θ denotes the marginal cost of machine production, assumed to be constant; $K_z^0(\nu)$ is the quantity of machines produced by the monopolist at the time when the variety ν is invented (in this case, at time 0); and $I_z(\nu)$ denotes gross investment. Since (3) defines isoelastic demands, the solution to this program involves $\chi_z(\nu) = \theta(r+\delta)/(1-\beta)$, that is, all monopolists charge a constant rental rate, equal to a mark-up over the marginal cost times the interest rate plus the depreciation rate. We assume that the marginal cost of machine production in the North is $\theta \equiv (1-\beta)^2/(r+\delta)$, so that $\chi = (1-\beta)$. Profit-maximization also implies $K_z^0(\nu) = K_z(\nu) = K_z$ and $I_z(\nu) = \delta K_z(\nu) = \delta K_z$, that is, each monopolist rents out the same quantity of machines in every period. Notice also that $V_z(\nu) = V_z$ for all ν, that is all machines produced for skill type z are equally profitable (though this profitability can change over time).

Substituting (3) and the machine prices into (2), we obtain

$$y(i) = p(i)^{(1-\beta)/\beta} \cdot N_L \cdot (1-i) \cdot l(i) + p(i)^{(1-\beta)/\beta} \cdot N_H \cdot i \cdot Z \cdot h(i).$$

Therefore, increases in N_H (N_L) improve the productivity of skilled (unskilled) workers in all sectors. N_H and N_L are the only state variables of this economy.

R&D (in the North) leads to the discovery of new machine types (blueprints). We assume that technical change is *directed*, in the sense that the degree to which new technologies are skill-complementary is determined endogenously (see Acemoglu, 1998). Some firms improve technologies complementing unskilled workers, while others work to invent skill-complementary machines. The cost of discovering a new machine complementing workers of group z ($z = L$ or H) is $1/\phi_z$ units of final output, so $\dot{N}_z = \phi_z \cdot X_z$ where X_z denotes total output devoted to improving the technology of group z. We assume that $\phi_z = \phi(x_z)$, $\phi' \leq 0$, where $x_z \equiv X_z/N_z$, which implies that within a period (i.e., given N_z) there are constant or decreasing returns to research in the aggregate.

There is a large number of small firms which can enter to perform R&D for either sector, and each firm ignores the effect of its expenditure on the productivity of others. More formally, each R&D firm takes $\phi(x_z)$ as given when it decides its research expenditure. A firm which discovers a new machine becomes the monopolist producer of that machine. We assume $\phi(x_z) = \Gamma x_z^{-\gamma}$, where $0 \leq \gamma < 1$. This parameterization of the ϕ function simplifies the analysis of transitory dynamics.[4] We can then write the law of motion of technologies (new technologies) as:

$$\dot{N}_z = \Gamma \cdot x_z^{1-\gamma} \cdot N_z. \tag{4}$$

Observe that directed technical change is a crucial ingredient in our results; it will enable

[4] We will focus on the case where $\gamma > 0$. If $\gamma = 0$, then our balanced growth path results are unchanged, but there are no transitory dynamics. If we change preferences to Constant Relative Risk Aversion, then there are transitory dynamics even when $\gamma = 0$, but these are somewhat more complicated.

the North to develop the technologies most suited to its needs, which are different from those suited to the countries in the South.

C. Analysis

We first take the technology variables N_L and N_H as given and characterize the equilibrium in the North, and we continue to suppress country indexes. We also assume that there is no commodity trade between the North and the South. We start with an intuitive lemma. As with other proofs, the proof of this lemma is in Appendix A.

Lemma 1 There exists J such that for $i < J$, $h(i) = 0$ and $i > J$, $l(i) = 0$.

In words, all goods with indexes below the threshold J are produced with unskilled labor, and those with indexes above J are produced with skilled labor only. Using this lemma, we can write the production in sector i as:

$$y(i) = \begin{cases} p(i)^{(1-\beta)/\beta} \cdot (1-i) \cdot N_L \cdot l(i) & \text{if } \; 0 \leq i \leq J \\ p(i)^{(1-\beta)/\beta} \cdot i \cdot N_H \cdot Z \cdot h(i) & \text{if } \; J < i \leq 1 \end{cases} . \tag{5}$$

Utility maximization, in turn, gives the consumer indifference condition: $p(i)y(i) = Y$ for all $i \in [0, 1]$. These equations enable us to prove:

Lemma 2 In equilibrium,

$$\text{for any } i < J,\ p(i) = P_L \cdot (1-i)^{-\beta} \text{and } l(i) = L/J, \text{and} \tag{6}$$

$$\text{for any } i > J,\ p(i) = P_H \cdot i^{-\beta} \text{and } h(i) = H/(1-J), \tag{7}$$

where P_L and P_H are appropriately defined price indexes, and

$$\frac{P_H}{P_L} = \left(\frac{N_H}{N_L} \frac{J}{1-J} \frac{ZH}{L} \right)^{-\beta} . \tag{8}$$

Goods with higher indexes produced with unskilled labor have lower productivity, and command higher prices. The converse is true for skilled goods. Equation (8) is then obtained using the consumer indifference condition. It exploits the fact that goods markets have to clear in the North and the South separately.

To fully characterize the equilibrium for given N_L and N_H, we must determine J. Good J can be produced by either skilled or unskilled workers, and must yield zero profit in either case, thus, when $i = J$, both (6) and (7) apply. This implies:

$$\frac{P_H}{P_L} = \left(\frac{J}{1-J} \right) \beta. \tag{9}$$

(8) and (9) therefore determine equilibrium relative prices and the threshold sector for a given state of relative technology, N_H/N_L. Using the fact that the consumption aggregate is the numeraire, we obtain:[5]

$$P_L = \exp(-\beta) \cdot J^{-\beta} \text{ and } P_H = \exp(-\beta) \cdot (1-J)^{-\beta}. \tag{10}$$

Noting that $Y = \int_0^1 p(i)y(i)di$, and combining this with (5), (8), (9) and (10), and then simplifying, we obtain a simple reduced form equation for GDP:

$$Y = \exp(-\beta)\left[(N_L L)^{1/2} + (N_H Z H)^{1/2}\right]^2. \tag{11}$$

Output per worker is then simply given as $Y/(L+H)$. Since wages are equal to marginal products, we also have:

$$\frac{w_H}{w_L} = Z\left(\frac{N_H}{N_L}\right)^{1/2}\left(\frac{ZH}{L}\right)^{-1/2}. \tag{12}$$

Finally, notice that combining (12) with (8) and (9), we find that the equilibrium share of skilled workers in labor costs is always $1-J$.

D. Technological Progress in the North

We start with the assumption that there are no intellectual property rights in the South, so R&D firms in the North cannot sell their technologies to Southern firms. The relevant market for technologies is therefore the North. Since there is no commodity trade, equilibrium R&D in the North can be determined without any reference to the South.

Recalling the above discussion regarding profits of technology monopolists, and using (6) and (7), the return to inventing a new machine for skill class z is:

$$rV_z = \pi_z + \dot{V}_z, \tag{13}$$

where $\pi_L = \beta(1-\beta)\left(P_L^n\right)^{1/\beta}\int_0^J l^n(i)di = \beta(1-\beta)\left(P_L^n\right)^{1/\beta} L^n$ and $\pi_H = \beta(1-\beta)\left(P_H^n\right)^{1/\beta}\int_J^1 h^n(i)di = \beta(1-\beta)\left(P_H^n\right)^{1/\beta} ZH^n$ are flow profits. L^n and H^n are effectively the "markets" for new technologies, since technology monopolists can only sell machines to Northern producers employing Northern workers. The time derivative captures the fact that P_H^n and P_L^n may be changing out of the balanced growth path, so that the value of the patent to a certain machine may be different in the future. Free-entry implies that the value of a technology monopolist must be equal to the marginal cost of innovation, hence $\Gamma^{-1}x_z^{-\gamma}V_z = 1$ at all points in time.[6]

[5] That is, we use the normalization $\exp\left[\int_0^1 \ln p(i)di\right] = 1$.

[6] Notice that if there were a consortium of R&D firms rather than small ones, we would have $(1-\gamma)\Gamma^{-1}x_z^{-\gamma}V_z = 1$. The qualitative results are identical in the two cases.

Along the Balanced Growth Path (BGP), N_L and N_H must grow at the same rate, thus the same research effort must be allocated to skill- and labor-complementary innovations ($x_L = x_H$). This is only possible if $\pi_L = \pi_H$ (since in BGP, $\dot{V}_L = \dot{V}_H = 0$). Hence, in BGP, we need

$$\frac{P_H^n}{P_L^n} = \left(\frac{ZH^n}{L^n}\right)^{-\beta}. \tag{14}$$

Using (8) and (9), this implies:

$$\frac{N_H}{N_L} = \frac{1-J^n}{J^n} = \frac{ZH^n}{L^n}. \tag{15}$$

This equation uniquely defines the relative productivity of skilled and unskilled workers along the BGP as a function of the relative supply of skilled workers in the North. It also determines the threshold sector J^n along the BGP.

The next proposition summarizes this result and the dynamics of the economy outside the BGP in the North.

Proposition 1 There exists a unique and globally (saddle path) stable BGP, given by (9), (10), (12) and (15), and along this growth path, output, N_L and N_H grow at the rate

$$g = \Gamma^{1/\gamma} \cdot \left[\exp(-1) \cdot \beta \cdot (1-\beta) \cdot (L^n + ZH^n)/r\right]^{(1-\gamma)/\gamma}.$$

There is a unique BGP, and starting from any N_L and N_H, the economy converges to this BGP. Along this path, a constant fraction of output is devoted to R&D, and the economy grows at the constant rate g. Since both N_L and N_H grow at the common rate g, the relative productivities of skilled and unskilled workers are constant. Relative productivities can change along the transition path, however.

As in Acemoglu (1998), an increase in H^n/L^n leads to skill-biased technical change, that is an increase in H^n/L^n raises N_H/N_L. The skill premium in the North is always $w_H^n/w_L^n = Z$. The skill-biased technical change induced by an increase in H^n/L^n therefore exactly cancels the negative direct impact of this variable on relative wages (see eq. (12)).

Finally, we can state the following corollary (proof omitted):

Corollary 1 Let $NY \equiv Y - X$ and $C \equiv Y - I - X$. Then, the BGP value of N_H/N_L (cfr. equation (15)) maximizes NY and C in the North.

Both net output, NY, and consumption, C, are maximized in the BGP, because the equilibrium skill-bias, N_H/N_L, is chosen "appropriately" for the North's skill composition.

E. Equilibrium in the South

The R&D process specified above entails a market size effect. Since there are no international intellectual property rights, the share of GDP devoted to R&D is an increasing function of the country's market size. To see this, notice that in BGP, free entry implies $x^c = \pi^c/r = \left[\exp(-1)\cdot\beta\cdot(1-\beta)^{-1}\cdot(r+\delta)\cdot\theta^c\cdot\left(L^c+ZH^c\right)/r\right]^{1/\gamma}$, where θ^c is the marginal cost of machine production in country c (a similar argument also applies away from the BGP). The share of GDP spent on R&D is therefore an increasing function of $L^c + ZH^c$. Since the South consists of a set of "small" economies, each will have an infinitesimal market for R&D, and the South, collectively, will not invest in R&D. Southern producers will instead import all their technologies from the North. More generally, one could also motivate the lack of substantial R&D investments in the South by weak property rights and scarcity of skills.[7] Our assumption that each Southern country is small captures these considerations in a simple way.

To achieve a simple parameterization, we assume that new technologies developed in the North can be adapted in each Southern at some small cost ε. Since $\varepsilon > 0$, once a firm adapts a new technology, it is not profitable for any others to do so as this would lead to Bertrand competition and negative net profits. Hence, machines in South will also be supplied by a (local) monopolist. However, the marginal cost of machine production for this local monopolist may be larger than for the inventor, as it does not have access to the inventor's knowledge base, or because of other distortions. In particular, we assume that the marginal cost of machine production in the South is θ^s.[8] Define $\rho \equiv [\theta^s(r+\delta)/(1-\beta)^2]^{(1-\beta)/\beta}$. Recalling that marginal cost of machine production in the North is $\theta \equiv (1-\beta)^2/(r+\delta)$, we have $\rho \geq 1$. Since this local monopolist also faces isoelastic demands, machine prices in the South are $\chi^s = (1-\beta)\rho^{\beta/(1-\beta)} = \rho^{\beta/(1-\beta)}\chi^n$. If $\rho = 1$, the same physical to human capital ratios will be used in the South and the North. In practice, the evidence suggests that the relative price of capital goods is higher in the LDCs (e.g. Jones, 1995), so $\rho > 1$ may be more relevant, though this is not necessary for any of our qualitative results. Equations from subsection C therefore apply with a small modification to introduce ρ, while N_H and N_L are still given by R&D in the North as in subsection D. Thus (proof omitted):

[7] In particular, similar results would be obtained if R&D were performed by skilled workers rather by using final output. In the North, h skilled workers would perform R&D while the remaining $H-h$ would work in skilled tasks. With our assumption that each Southern country is small and does not enforce international property rights, the South would once again *not* allocate any of its skilled workers to R&D, and we obtain exactly the same results as here. Moreover, with this formulation, even when the South consists of large countries, there will only be limited R&D investments in the South because skilled wages are high. We prefer the specification in the text as it leads to simpler expressions.

[8] Alternativley, we could assume that the technologu sector in the South is competitive, with cost $\theta^s/(1-\beta)$, with identical results.

Proposition 2 There exists a unique equilibrium in the South where J^s is given by

$$\frac{1-J^s}{J^s} = \left(\frac{N_H}{N_L}\frac{ZH^s}{L^s}\right)^{1/2}, \tag{16}$$

where for all $i < J^s$, $h_i = 0$ and $l_i = L^s/J^s$, and for all $i > J^s$, $l_i = 0$ and $h_i = H^s/(1-J^s)$, and technologies N_H and N_L are determined in the North (e.g. given by (15) in BGP). The level of output is:

$$Y^s = \exp(-\beta) \cdot \rho^{-1} \cdot \left[(N_L L^s)^{1/2} + (N_H Z H^s)^{1/2}\right]^2 \tag{17}$$

Output grows at the same rate g as in the North.

The equilibrium in the South therefore takes a very similar form to that in the North, except that the technology parameters, N_H and N_L, are taken from the North, and the cost of capital may differ (i.e. $\rho > 1$ is possible). Hence, when the North is in BGP, the South is also in BGP. In particular, J^s is constant (though $J^s > J^n$), and the growth rate is equal to that of the North, g. The ratio of consumption to GDP is higher in the South, however, because there is no R&D there.

We can also note that in contrast to Corollary 1, which showed that the North's net output was maximized, the world's net output is not maximized. Defining the world's net output as $NY^w \equiv Y^n + Y^s - X^n$ or $C^w \equiv Y^n + Y^s - I^n - I^s - X^n$, we immediately see that neither of these are maximized when N_H/N_L is at its BGP value given by (15). The reason is that while new technologies developed by the North are appropriate to its needs, they are inappropriate for those of the South.

III. Productivity Differences Between the North and the South

A. Productivity Differences

In this section, we show that in our economy, productivity is higher in the North than in the South, and the mismatch between the technologies of the North and the skills of the South amplifies the output gap across countries.

First define:

$$A(H, L, N_L, N_H \mid \rho) \equiv \frac{Y}{L+ZH} = \exp(-\beta) \cdot \rho^{-1} \cdot \frac{\left[(N_L L)^{1/2} + (N_H Z H)^{1/2}\right]^2}{L+ZH},$$

$$y(H, L, N_L, N_H \mid \rho) \equiv \frac{Y}{L+H} = \exp(-\beta) \cdot \rho^{-1} \cdot \frac{\left[(N_L L)^{1/2} + (N_H Z H)^{1/2}\right]^2}{L+H}.$$

where Y is total output, A is output per efficiency unit of labor, and y is output per worker. We condition on ρ because this variable determines the equilibrium capital labor ratio, which affects labor productivity. Straightforward differentiation establishes that given N_H/N_L, $A(H, L, N_L, N_H \mid \rho)$ is an inverse U-shaped function of H/L with a maximum at $H/L = N_H/N_L$, whereas $y(H, L, N_L, N_H \mid \rho)$ is an inverse U-shaped function of H/L with a maximum at $H/L = ZN_H/N_L$. These observations immediately establish the following Proposition (proof omitted):

Proposition 3 Assume that N_H/N_L is given as in (15), then:

1. $A(H, L, N_L, N_H \mid \rho)$ is an inverse U-shaped function of H/L with a maximum at H^n/L^n. Hence, for any $H/L \neq H^n/L^n$, we have $A(H^n, L^n, N_L, N_H \mid \rho) > A(H, L, N_L, N_H \mid \rho)$.

2. $y(H, L, N_L, N_H \mid \rho)$ is an inverse U-shaped function of H/L with a maximum at Z^2H^n/L^n. Hence, for any $H/L < H^n/L^n$, we have $y(H^n, L^n, N_L, N_H \mid \rho) > y(H, L, N_L, N_H \mid \rho)$.

When N_H/N_L is chosen according to the North's needs, both output per efficiency unit of labor and output per worker are higher in the North than in the South. Moreover, output per efficiency unit is maximized in the North, whereas output per worker would be maximized by a skill endowment which is larger than the relative skill endowment in the North (recall that $Z \geq 1$). Furthermore, both $A(H^n, L^n, N_L, N_H \mid \rho)/A(H, L, N_L, N_H \mid \rho)$ and $y(H^n, L^n, N_L, N_H \mid \rho)/y(H, L, N_L, N_H \mid \rho)$, productivity and output per worker in the North relative to the South, are strictly increasing in N_H/N_L. Hence, as technologies become more skill-biased, the gap in output per efficiency unit of labor and output per worker between the North and the South widen. These exercises compare two economies with the same cost of capital ρ. It is also immediate that, since $\rho = 1$ in the North and $\rho \geq 1$ in the South, we have $A(H^n, L^n, N_L, N_H \mid \rho = 1) > A(H^s, L^s, N_L, N_H \mid \rho^s)$ and $y(H^n, L^n, N_L, N_H \mid \rho = 1) > y(H^s, L^s, N_L, N_H \mid \rho^s)$ a fortiori when $\rho^s > 1$.

Finally, we consider another measure of productivity, TFP, and in the process we attempt to clarify the origins of the productivity differences between the North and the South in our model. Rewrite (5) to obtain:

$$y_L(i) = b_L(i) \cdot K_L(i)^{1-\beta} \cdot l(i)\beta \text{ and } y_H(i) = b_H(i) \cdot K_H(i)^{1-\beta} \cdot [Z \cdot h(i)]\,\beta, \qquad (18)$$

where the $b_z(i)$'s are the sectoral TFPs given by $b_L(i) = [(1-i) \cdot N_L]\,\beta$ and $b_H = [i \cdot N_H]\,\beta$, and $K_z(i)$'s are the sectoral capital stocks given by $K_z(i) \equiv \int_0^{N_z} k_z(i, v)\, d\nu$, where $z \in [H, L]$.[9] Lemmas 1 and 2, together with equation (3), imply that $K_z(i) = K_z$,

[9]Notice that $Z \cdot h(i)$ is the "quantity of human capital" employed in sector i using Z as the skill-premium. Z should not be part of sectoral TFP, since otherwise sectors and countries with more skilled workers would mechanically have higher TFP.

$l(i) = l$ and $h(i) = h$. Thus, using (1), we can write total output as:

$$Y = \exp\left(\int_0^J \ln y_L(i)\,di + \int_J^1 \ln y_H(i)\,di\right) = B(J, N_L, N_H)\cdot\left(K_L^{1-\beta} l\beta\right)^J \left(K_H^{1-\beta}(Zh)\,\beta\right)^{1-J} \tag{19}$$

where $B(J, N_L, N_H) \equiv \exp\left(\int_0^J \ln b_L(i)\,di + \int_J^1 \ln b_H(i)\,di\right)$ is aggregate TFP, obtained from separating the terms with factor content from the technology terms. By solving the integral we obtain:

$$B(J, N_L, N_H) \equiv \left[N_L^J N_H^{1-J}(1-J)^{-(1-J)} J^{-J}\right]\beta\cdot\exp[-\beta]. \tag{20}$$

Notice that (19) factors out skills using the correct factor shares, βJ for unskilled workers, and $\beta(1-J)$ for skilled workers, which means that the direct effect of differences in skill supplies on output are already controlled for. (20) therefore does not directly depend on H and L, and TFP differences will not arise in our model due to mismeasurement of the human capital of workers. Also, as the contribution of capital is factored out, TFP does not depend on ρ either. Instead, TFP differences will arise because productivity depends on the threshold sector, J. J determines the extent to which skilled and unskilled workers are employed in sectors (tasks) for which they may or may not have a comparative advantage. The level of J therefore affects aggregate productivity, and economies with different threshold sectors will have different TFP levels.

Straightforward differentiation establishes that, as with output per efficiency unit of labor, TFP is maximized in the North (proof omitted):

Proposition 4 *For given N_H and N_L, $B(J, N_L, N_H)$ (TFP) is an inverse U shaped functions of J with a maximum at $J^m \equiv N_L/(N_L + N_H)$. Therefore, when N_H/N_L is given by the BGP equilibrium condition in the North, (15), we have $J^s > J^n = J^m \equiv \arg\max B(J, N_L, N_H)$.*

This proposition has an intuitive geometric representation. Figure 1 plots a monotonic transformation of the sectoral TFPs ($b(i)^{1/\beta}$) defined in (18). At $J^m \equiv N_L/(N_L + N_H)$, the two schedules cross. Hence, TFP is maximized, when an economy adopts the unskilled technology in all sectors $j \le J^m$ and the skilled technology in all sectors $j > J^m$. The figure also draws an arbitrary value of the threshold sector, $\hat{J}$, where TFP is not maximized. Since $J^m = J^n$, when N_H/N_L is chosen by the North, North's TFP is maximized.

Intuitively, when most R&D is carried out in the North only, and is *directed*, TFP will be larger in the North than in the South, even though there are no barriers to technology transfer. In particular, as $H^s/L^s < H^n/L^n$, productivity is larger in the North than in the South, because some sectors in the South employ unskilled workers,

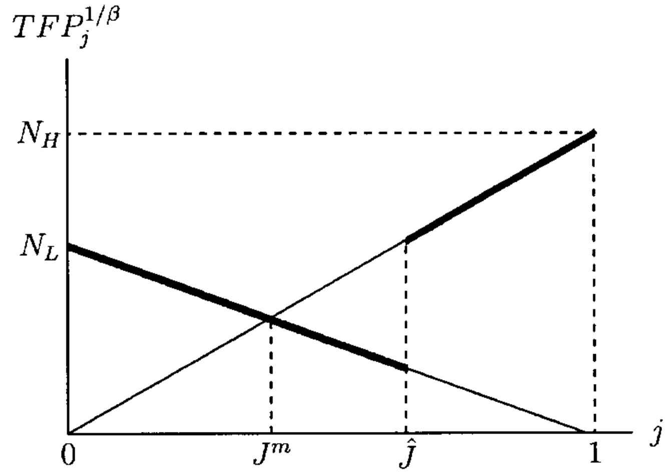

Figure 1: Sectoral TFP's.

though productivity would be higher if production were carried out by skilled workers using skilled technologies.[10] As we will see in more detail in Section V, if R&D firms could sell to Southern producers, they would invest more in unskilled technologies, and productivity in the South would not be as low. Similarly, as noted above, if the South could perform R&D, it would direct it to unskilled machines, and the productivity gap would be smaller. It is therefore the combination of the South importing technologies from the North and directed technical change in the North that leads to the productivity differences between the South and the North.

Proposition 4 has an immediate corollary (proof omitted):

Corollary 2 There are no TFP differences between the North and the South in sector i for all $i \leq J^s$ or $i \geq J^n$. Sectoral TFP is larger in the North than in the South for all $i \in (J^s, J^n)$.

This Corollary can also be illustrated using Figure 1. When $J^s = \hat{J}$, sectoral TFPs will be as drawn by thick lines in the figure. The South is using unskilled workers in sectors $j \in \left(J^m, \hat{J}\right)$, where the technologies developed by the North make it more productive to use skilled workers. All productivity differences between the South and the North therefore originate in these "medium-tech" sectors, $i \in (J^s, J^n)$. The South concentrates

[10]Naturally, there is an insufficient number of skilled workers in the South to allocate to all tasks performed by skilled workers in the North. Also, as noted in the introduction, there will be TFP and productivity differences between two economies even in the absence of directed technical change. This can be seen by noting that the productivity differences between the North and the South would arise even for arbitrary N_H and N_L. However, in this case, the South could have higher TFP, even higher output per worker, than then North. The novel feature of our model, directed technical change, ensures that the North has higher productivity than the South, as it implies that N_H/N_L takes the value that maximizes productivity in the North.

its scarce endowment of skilled workers in a few highly complex tasks. Since technology is common knowledge, in these complex tasks and in the sectors where the North also uses unskilled workers, the South is as productive as the North. The productivity gap emerges instead in those sectors where it is easier to substitute unskilled workers for skilled workers— i.e. those tasks with intermediate i's. This pattern may explain why India, which has relatively few skilled workers and low productivity compared to the U.S. has a relatively efficient software industry, but appears to have low productivity in a range of more traditional industries.

Therefore, overall, because new technologies are developed for the North's needs, productivity is higher in the North than in the South. A reduction in the degree of skill-bias, which would make technologies more suited to the South's needs, would reduce the differences in output per worker, output per efficiency unit of labor, and TFP between the North and the South.

B. A Simple Quantitative Assessment

In this subsection, we investigate whether the theoretical mechanism we developed could be quantitatively significant. It is important at this point to note that we are not testing our mechanism, which is an altogether harder task, left for future work. Instead, we simply assess the likely contribution of the mismatch between the North's technologies and the South's skills to output per worker differences.

To make our model empirically operational, we need to determine how the ratio of skilled to unskilled workers varies across countries. The skills that are important for our mechanism are those which facilitate the use of new technologies, such as, computer controlled machines, PCs, automatic retrieval systems, and even perhaps modern organizational forms. In the data, we only observe schooling, however. So, we use four different measures of "skill" (H/L) to reduce the sensitivity of our results to this partly arbitrary choice. These are, respectively, the ratio of the population over 25 with at least some primary school attainment to those over 25 with no primary school attainment; the ratio of the population over 25 with at least some secondary school attainment to those over 25 with no secondary school attainment; the ratio of the population over 25 with at least secondary school completion to those over 25 with no secondary school completion; and the ratio of the population over 25 with some higher education to those with none, all from the Barro-Lee data set.[11] The second, third and fourth measures may be more appropriate for the skilled-unskilled distinction in our model, since the technologies that workers with high school or college can use efficiently would be quite different than those appro-

[11] Web address for Barro-Lee data http://www.worldbank.org/html/prdmg/grthweb/ddbarle2.htm, see also Barro and Lee (1993).

priate for those with less than high school. Nevertheless, we also look at primary school attainment, which minimizes the cross-country variability in skills, in order to obtain a highly conservative estimate of the differences in the supply of skilled workers between the North and the South.[12] We will see below that with all measures, our model predicts significantly larger variations in output per worker than the neoclassical model.

Table A1 in the Appendix gives output per worker calculated from the Summers-Heston data set, and our skill measures for a sample of 103 countries.[13] As noted by many authors before us, there are large differences in output per worker across countries. A significant part of this variation is due to differences in physical and human capital per worker, which can be captured by a simple neoclassical model where countries only differ in factor endowments. For this reason, we take as our benchmark a neoclassical model where all countries have access to the same technology, as captured by Q, and output is Cobb-Douglas in total human and physical capital. Then country c's output would be

$$Y^c_{NC} = Q \cdot (K^c)^\alpha \cdot (L^c + ZH^c)^{1-\alpha}.$$

This is effectively the model used by Mankiw, Romer and Weil (1992) and Hall and Jones (1998), among many others, adapted to our environment with two types of workers. We use K^c, L^c and H^c from the data, and set $\alpha = 0.33$ (which is equivalent to $1-\beta$ in our model), since this is the share of capital in the model. Z is chosen to match the relevant wage premium observed in the U.S.. Given K^c, L^c, H^c, Z and α, we can calculate the GDP per worker as predicted by the neoclassical benchmark model, $\hat{y}^c_{NC}$, as:

$$\begin{aligned} \hat{y}^c_{NC} &= \frac{Y^c_{NC}}{L^c + H^c} = Q \cdot \left(\frac{K^c}{L^c + H^c}\right)^\alpha \cdot \left(\frac{L^c + ZH^c}{L^c + H^c}\right)^{1-\alpha} = \\ &= Q \cdot (\rho^c)^{-1} \cdot \left(\frac{K^{US}}{L^c + H^c}\right)^\alpha \cdot \left(\frac{L^c + ZH^c}{L^c + H^c}\right)^{1-\alpha} \end{aligned}$$

where Q is chosen to normalize $\hat{y}^{US}_{NC} = 1$. The second equality follows from the fact that, since ρ measures of cost of capital relative to the U.S., $K^c = (\rho^c)^{-1/\alpha} K^{US}$.

In contrast, our model predicts output per worker, $\hat{y}^c_{AZ}$, to be:

$$\hat{y}^c_{AZ} = \frac{Y^c_{AZ}}{L^c + H^c} = \frac{\exp(-\beta) \cdot (\rho^c)^{-1} \cdot \left[(N_L L^c)^{1/2} + (N_H Z H^c)^{1/2}\right]^2}{L^c + H^c}. \tag{21}$$

[12]This is partly motivated by Klenow and Rodriguez (1997)'s critique of Mankiw, Romer and Weil (1992), which argues that the success of this paper in explaining output per worker differences is due to their use of secondary schooling only.

[13]Following Hall and Jones (1998), we calculate capital stock in 1985 using the perpetual inventory method from investment data, and we subtract the contribution of the mining sector from the GDP and the capital numbers, to exclude differences in output per worker caused by differences in natural resource endowments.

where we treat the U.S. as the North, and therefore set $N_H/N_L = ZH_{US}/L_{US}$, as in equation (15). The level of N_L is set to normalize $\hat{y}_{AZ}^{US} = 1$.

The relative productivity of skilled workers, Z, corresponds, in our model, to the skill premium in the North (see section II.D). In the U.S., the mean earnings of workers with high school attainment (10th grade) or more divided by the mean earnings of workers with no high school attainment (9th grade or less) is over 2, while the mean earnings of full time workers with some college or more divided by the mean earnings of full time workers with no college is approximately 1.75 (all numbers calculated from Current Population Survey of the U.S., 1996). These numbers are quite large in part because in the U.S. relatively few workers have less than 9th grade and the earnings of workers with high school only have been falling. Since choosing a large value of Z amplifies the differences in skill endowments across countries, and may overemphasize the importance of our mechanism, we use a range of different values for Z. We use $Z = 1.8$ as an upper bound of the relative productivity of skilled workers. We also use $Z = 1.5$, which we view as a more reasonable estimate of the relative productivity of "skilled" workers, especially when we use secondary school attainment, since the average earnings of those with high school attainment and completion to those with no high school (less than 9th grade) in the U.S. is approximately 1.5. Finally, to check the robustness of the results we also experiment $Z = 1$, which is clearly implausibly low, as it suggests no skill premium. Nevertheless, even in this case, H-workers use different technologies than L-workers, and are more abundant in the North. Therefore, the fact that new technologies developed in the North will be more appropriate to the H-workers will lead to productivity differences, and our mechanism will contribute to output differences. We report this case as a lower bound on the importance of our mechanism.

In Table I, we report three statistics for each experiment, $\hat{y}^{LDC}$, $\hat{y}^{5th-}$ and $\Re_s^2$, separately for the neoclassical model and our model. $\hat{y}^{LDC}$ denotes the average non-OECD GDP per worker relative to the U.S., and $\hat{y}^{5th-}$ denotes output per worker relative to the U.S. in the 5th poorest country in the sample. $\Re_s^2$, "constrained R^2", is a more general measure of goodness of fit. In particular, let y^c denote output per worker from the data and $s \in \{NC, AZ\}$, then $\Re_s^2 = 1 - \sum_c (y^c - y_s^c)^2 / \sum (y^c)^2$ is the R^2 from a regression of output per worker in the data on predicted values when we constrain the slope to be equal to 1 and the constant to be 0. $\Re^2$ would be equal to 1, if there were a perfect fit between the model and the data, though this measure could also be negative if the fit was particularly bad.

Table I. Output per worker in our model and in the neoclassical model.

		Neoclassical model			Our model		
H/L	Z	$\hat{y}_{NC}^{LDC}$	$\hat{y}_{NC}^{5th-}$	$\Re^2_{NC}$	$\hat{y}_{AZ}^{LDC}$	$\hat{y}_{AZ}^{5th-}$	$\Re^2_{AZ}$
Primary	1.8	0.45	0.16	0.651	0.37	0.06	0.750
Sec. att.	1.8	0.39	0.15	0.816	0.22	0.03	0.936$^{(**)}$
Sec. compl.	1.8	0.39	0.15	0.808	0.24	0.05	0.944$^{(**)}$
Higher	1.8	0.43	0.18	0.718	0.34	0.11	0.881
Primary	1.5	0.46	0.17	0.625	0.37	0.06	0.749
Sec. att.	1.5	0.41	0.16	0.757	0.23	0.03	0.937$^{(**)}$
Sec. compl.	1.5	0.42	0.17	0.745	0.26	0.06	0.940
Higher	1.5	0.45	0.19	0.666	0.36	0.12	0.847
Primary	1.0	0.49	0.21	0.540	0.37	0.06	0.744
Sec. att.	1.0	0.49	0.21	0.540	0.26	0.04	0.935$^{(*)}$
Sec. compl.	1.0	0.49	0.21	0.540	0.32	0.08	0.903
Higher	1.0	0.49	0.21	0.540	0.42	0.15	0.744

Notes: $\hat{y}^{LDC}$ is the predicted average GDP per worker in non-OECD countries and $\hat{y}^{5th-}$ is the predicted GDP per worker of the 5th poorest country in the sample. In the data, $y^{LDC} = 0.21$ and $y^{5th-} = 0.03$. H/L is the relevant ratio of skilled to unskilled workers, and Z is the skill-premium. (*) and (**) denote that the joint hypothesis a=0 and b=1 in the regression $y^c = a + b y^c_s + \varepsilon$ cannot be rejected at the 99% and the 90% confidence levels.

The average output per worker among the non-OECD countries in the sample is about 21% of the U.S., and output per worker in the fifth poorest country is about 1/30th of the U.S. level. The neoclassical model predicts average output among the non-OECD countries to be between 40% and 50%, and output per worker in the fifth poorest country to be between 1/5th and 1/7th of the U.S. level. Like the neoclassical model, our model also underestimates the output gap between rich and poor countries, but much less so. When the skill endowment is measured by secondary school attainment or completion, our model predicts output per worker differences very close to those we observe in practice. For example, with secondary school attainment and $Z = 1.5$, we obtain $\hat{y}_{AZ}^{LDC} = 0.23$, or with $Z = 1.8$, we have $\hat{y}_{AZ}^{LDC} = 0.22$. Also, in this case our model predicts $\hat{y}_{AZ}^{5th-} = 0.03$ for both values of Z. Although in other cases the differences predicted by our model are less than the differences in the data, these predictions are consistently better than those of the neoclassical model with the corresponding skill measure.

Using our constrained R^2, the neoclassical model also appears to perform reasonably well, since the differences in physical and human capital are important determinants of output per worker. For example, using secondary school attainment and $Z = 1.5$, we obtain $\Re^2_{NC} = 0.74$, though the fit is lower with the alternative measures. Incorporat-

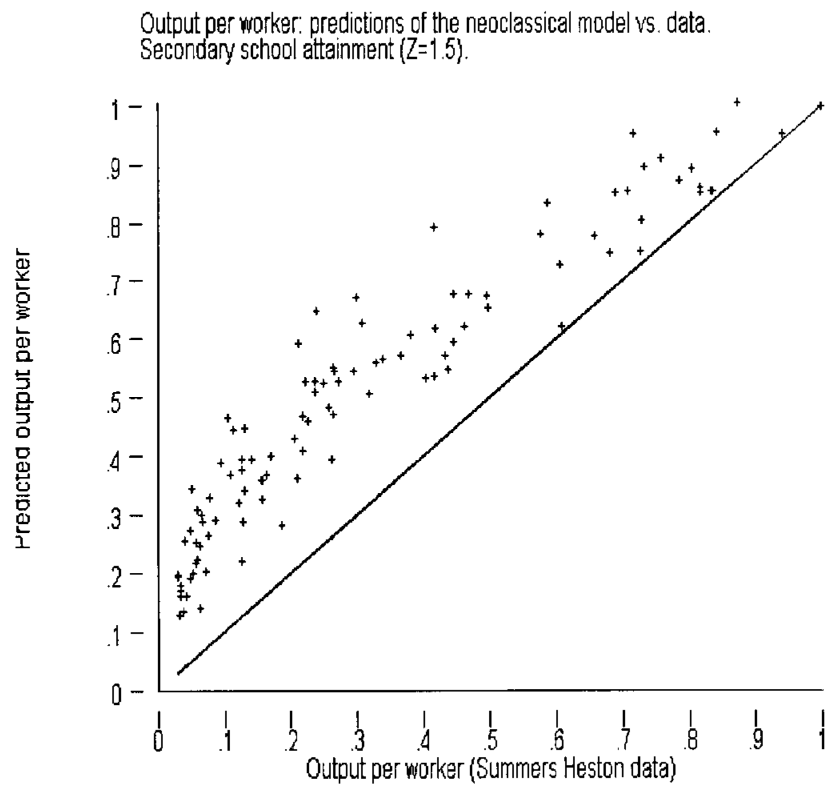

Figure 2: Output per worker: y^c_{NC} vs. y^c.

ing the fact that technologies are not appropriate to the LDCs' needs improves the fit substantially; with secondary school measure and $Z = 1.5$, the constrained R^2 rises to $\Re^2_{AZ} = 0.94$. The improvement is also significant in all other cases, including the most conservative case which minimizes the skill differences between the North and the South by using primary school attainment. Notice also that the results are very robust to different values of Z. In particular, the performance of our model remains very good even with $Z = 1$.[14]

Figures 2 and 3 plot output per worker y^c and the predicted values from the two models, $\hat{y}^c_{NC}$ and $\hat{y}^c_{AZ}$. They show, once again, that our mechanism contributes significantly

[14]We have repeated the calculations in Table I using other measures of skills, for example, primary and college completion rather than attendance, and using other values of Z. In all cases, the results are very similar. We have also looked at the performance of the neoclassical model using the measure of average human capital per worker calculated by Hall and Jones (1998), which aggregates workers with different schooling using different weights. It is difficult to use this measure in our model since there is no distinction between "skilled" and "unskilled" workers with this measure. The results of the neoclassical model with this measure are $\hat{y}^{LDC}_{NC} = 0.34$, $\hat{y}^{5th-} = 0.10$ and $\Re^2 = 0.877$, thus slightly better than the numbers for the neoclassical model in Table I, but still substantially worse than our model's predictions exploiting the equivalent variation.

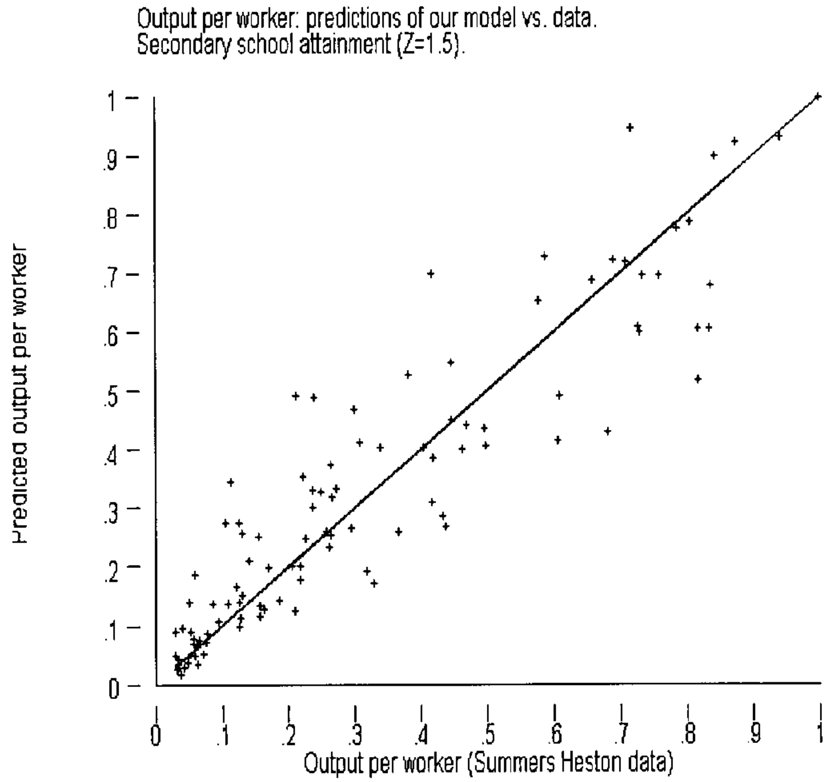

Figure 3: Output per worker: y^c_{AZ} vs. y^c.

to differences in output per worker (recall that $y^{US} = \hat{y}^{US}_{NC} = \hat{y}^c_{AZ} = 1$). In particular, the neoclassical model systematically underpredicts the differences in output per worker between the U.S. and the LDCs (figure 2), while our model predicts differences in line with those in the data (figure 3). We therefore conclude that the mismatch between the technologies developed in the North and the skills of the LDCs could be an important factor in explaining the large differences in output per worker and income per capita across countries. In fact, it appears that our mechanism, combined with the physical and human capital differences we observe in practice, could account for a very large fraction of the differences in output per worker in the data.

Finally, to assess the importance of directed technical change in these results, we perform another simple exercise. We calculate y^c_{ND} (where ND stands for no-directed technical change) following equation (21), with the only differences that technologies are now appropriate for the average country rather than for the U.S. That is, we choose $N_H/N_L = Z\bar{H}/\bar{L}$, where $\bar{H}/\bar{L} = \left(\Sigma^n_{c=1} H^c/L^c\right)/n$ is the (unweighted) average skill endowment of the countries in the sample. With skills measured by secondary school attainment and $Z = 1.5$ (the case reported in figures 2 and 3), we obtain that the average output per worker in non-OECD countries would be 53% of the U.S. level instead of 23% predicted by our model above, and the fifth poorest country's productivity would be 16% of the U.S., as opposed to the prediction of 3% with directed technical change above (and also $\Re^2 = 0.26$, instead of $\Re^2_{AZ} = 0.94$!). Directed technical change is also very important, using higher education attainment measure, but somewhat less so when skills are measured by primary education attainment.[15] These results therefore demonstrate that directed technical change, which makes new technologies appropriate for the North and not the South, is crucial for our results and in fact, without this effect, our model would explain substantially less than the simple neoclassical model. These findings also suggest that making technologies more appropriate to the South's needs may be an important step in closing the very large output gaps between rich and poor economies.

IV. Trade and Technology

We now consider a world where all commodities $i \in [0,1]$ are traded internationally. We continue to assume that intellectual property rights are not enforced in the South. The main result in this section is that free trade implies *productivity convergence,* but causes *divergence in output per worker.*

We use the convention that H^s is the total number of skilled workers in the South and L^s is the supply of unskilled workers, as well as the supplies in a representative country in the South. Moreover, we normalize $\rho = 1$ so that the price of capital goods is the same in all countries. International trade implies that commodity prices are equalized in all countries. Since different commodities can be produced by skilled or unskilled workers only, factor price equalization is always guaranteed. As a result, countries will now adopt the same technology (same threshold J^T). More specifically, we have

$$\frac{P_H^T}{P_L^T} = \left(\frac{J^T}{1-J^T}\right)^{\beta} = \left(\frac{N_H^T}{N_L^T}\frac{ZH^w}{L^w}\right)^{-\beta/2}, \tag{22}$$

and

$$\frac{w_H^T}{w_L^T} = Z\left(\frac{N_H^T}{N_L^T}\right)^{1/2}\left(\frac{ZH^w}{L^w}\right)^{-1/2},$$

[15]With higher education attainment and $Z = 1.5$, we have $y_{ND}^{LDC} = 0.52$, $y_{ND}^{5th-} = 0.21$ and $\Re^2_{ND} = 0.42$. When skills are measured by primary education attainment, we have $y_{ND}^{LDC} = 0.40$, $y_{ND}^{5th-} = 0.08$ and $\Re^2_{ND} = 0.71$. The reason why directed technical change appears less important with primary attainment is that most countries in the sample have very high primary attainment (for example, $H/L = 249$ in Japan, while only $H/L = 65$ in the U.S.). Thus, the world average H/L is not very different from the H/L in the U.S., and directing technical change to the skill endowment of the average country rather than that of the U.S. only makes a small difference. The result changes significantly, if technical change is directed to the endowment of the median country, which is substantially lower than that of the U.S.. In this case, we would have $y_{ND}^{LDC} = 0.48$, $y_{ND}^{5th-} = 0.13$ and $\Re^2_{ND} = 0.54$, significantly worse than the model with directed technical change.

where $L^w = L^s + L^n$ and $H^w = H^s + H^n$ are the world supplies, P_H^T and P_L^T are the world prices, and w_H^T and w_L^T are the world wages with free trade.

As patents are not enforced internationally, the balanced growth equilibrium condition, (14), is unchanged; Northern R&D firms continue to consider H^n and L^n as their markets. Thus, (world) prices have to adjust to satisfy (14). This implies that in the BGP, world relative prices will only depend on the factor endowment of the North:

$$\frac{P_H^T}{P_L^T} = \left(\frac{J^T}{1 - J^T}\right)^{\beta} = \left(\frac{ZH^n}{L^n}\right)^{-\beta}. \tag{23}$$

This equation implies that along BGP with trade, world prices and threshold sector, J^T, will be equal to those prevailing in the North before trade. However, world prices must also satisfy the world market clearing equation, (22), which now depends on world supplies rather than the supplies of the North only. The state of relative technology therefore has to change. In particular, since the supply of unskilled workers has increased, the relative productivity of skilled workers has to increase to ensure that (23) is satisfied. More specifically, (22) and (23) imply

$$\frac{N_H^T}{N_L^T} = \left(\frac{ZH^n}{L^n}\right)^{1/2} \left[\frac{H^n}{L^n}\left(\frac{H^w}{L^w}\right)^{-1}\right]^{1/2}, \tag{24}$$

which is larger than the closed economy ratio, since $(H^n/L^n) > (H^w/L^w)$. In other words, *trade induces skill-biased technical change.*[16] More specifically, the direction of technical change depends on the relative market sizes, H/L, and relative prices, p_H/p_L (recall π_L and π_H above). Market sizes for technologies do not change, because inventors continue to sell their machines in the North only. But trade, at first, increases the relative price of skill intensive goods —i.e. equation (22) at a given N_H/N_L. This makes skill-complementary innovations more profitable and accelerates the creation of skill-complementary machines. In the after-trade BGP, the South, therefore, concentrates its unskilled production in fewer sectors and uses a larger number of skill-complementary machines, while the structure of production in the North reverts back to its pre-trade form. Nevertheless, since technologies are now more skill-complementary, skilled workers have higher relative productivities and wages.

In the next proposition, we characterize how the world economy adjusts to trade opening. To simplify the discussion, we limit our analysis to an unanticipated switch from a world of completely closed economies to one of free trade:

[16] This possibility was first raised by Wood (1994), though without providing a mechanism for it. Acemoglu (1998) demonstrates that trade can induce skill-biased technical change in a related model.

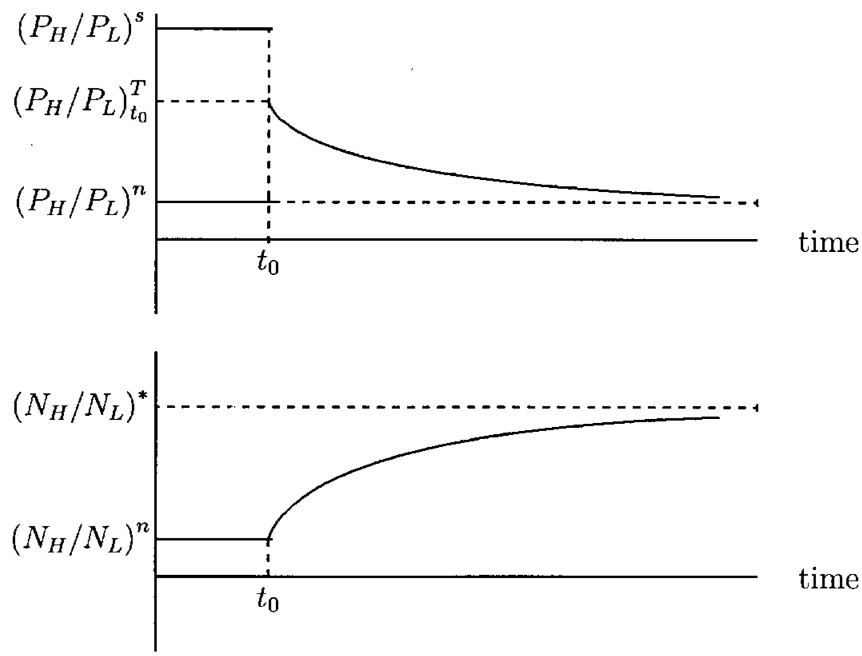

Figure 4: Dynamics of prices and technology after trade opening.

Proposition 5 Suppose that the relative technologies and prices before trade, $(N_H/N_L)^n$, relative prices and wages in the North $(P_H^n/P_L^n)^n$ and $(w_H^n/w_L^n)^n$, and the equilibrium thresholds J^n and J^s are as given by (12), (14), (15) and (16). Consider an unanticipated opening of the world economy to free trade. Then, upon trade opening P_H/P_L, J and w_H/w_L increase in the North and decrease in the South, and are equalized. The system then converges to a new balanced growth path, with $(N_H/N_L)^T > (N_H/N_L)^n$, while the world price ratio P_H/P_L decreases to $(P_H/P_L)^T = (P_H/P_L)^n$ and the world threshold sector J decreases to $J^T = J^n$. w_H/w_L, the world skill-premium, continues to increase after trade opening and reaches a new level $(w_H/w_L)^T > (w_H/w_L)^n$. The BGP growth rate of the economy is the same as before trade (g).

The dynamics of prices and technology are described in Figure 4. At the moment the trade regime changes (t_0), the level of technology is predetermined at $(N_H/N_L)^n$. The effects are therefore the same as in the standard trade theory. As the North is more abundant in skills, the relative price of skilled intensive goods and the skill premium increase in the North and fall the South (upper quadrant). What is different in our theory, however, is the adjustment after this initial response. The change in commodity prices, i.e. the higher level of P_H/P_L, encourages more skill-complementary innovations, and N_H/N_L increases (lower quadrant). The world economy reaches a balanced growth path, as the productivity of skilled workers increases sufficiently, and the relative price of skill intensive goods return to their pre-trade levels in the North, i.e. $(P_H/P_L)^T = (P_H/P_L)^n$.

The skill premium in the North increases, not only due to standard trade reasons, but also due to the induced skill-bias technical change.

Since the world relative price of skill intensive goods returns to that of the North before trade, and the North and the South use the same threshold sector J^T, free trade implies that unskilled workers are employed in fewer sectors in the South, i.e. J^s falls. Which sectors employ skilled workers in the South, however, is indeterminate as any part of the skilled production could be carried out in the North and imported to the South or vice versa. What is unambiguous is that, overall, the South will import skill-intensive goods and export unskilled goods. Finally, because the market size for new technologies is unchanged and world prices return to those of the North before trade, the long-run growth rate is unaffected and remains at g.

The next proposition compares GDP and output per worker between the South and the North before and after trade.

Proposition 6 Let Y_n be the GDP and y_n the output per worker in the North, and Y_s the GDP and y_s in the South before trade. Let Y_n^T and Y_s^T be the GDPs after trade, and y_n^T and y_s^T be the output per worker after trade. Then, we have $Y_n^T/Y_s^T > Y_n/Y_s$ and $y_n^T/y_s^T > y_n/y_s$. That is, after trade opening, the GDP and output per worker differences between the North and the South widen.

Trade therefore unambiguously *amplifies income differences* between the South and the North. As we saw above, trade induces new technologies to be further biased towards skilled workers. This reduces the productivity of unskilled workers both in the South and the North, and because the South is more abundant in unskilled workers, its relative situation with respect to the North deteriorates after this change. A number of other papers also obtain the result that trade may lead to more relative inequality among countries (e.g. Krugman (1987), Feenstra (1991) and Young (1991)). Nevertheless, the mechanism in these papers is quite different from ours. Typically, trade induces less developed countries to specialize in sectors which benefit less from learning-by-doing than the sectors in which the North specializes. In contrast, in our model, trade changes the direction of technical progress in the North, and leads to larger income differences via this channel. Additionally, in these models trade leads to both TFP and GDP divergence, which is very different from our result, as we see next:

Proposition 7 Let A_n^T and A_s^T denote after trade output per efficiency unit of labor in the North and in the South, respectively, and let B_n^T and B_s^T be TFP. Then, $A_n^T = A_s^T$ and $B_n^T = B_s^T$. That is, after trade opening, differences in output per efficiency unit of labor and TFP between the North and the South disappear.[17]

[17]If $\rho \neq 1$, then we would have $A_n^T = \rho A_s^T$.

Despite causing divergence in output per worker, trade leads to convergence in output per efficiency unit of labor and in TFP. The difference between these two sets of results is obviously due to the changes in factor prices caused by trade. In fact, not only do TFP differences decrease, but they actually *disappear*. The reason for TFP equalization is *factor price equalization*. TFP is low in the South when unskilled workers perform tasks for which they have little comparative advantage. Commodity trade, however, ensures factor price equalization and induces firms in the South to employ unskilled workers only in the tasks performed by unskilled workers in the North. Since the productivity of unskilled workers in these sectors is the same in the North and the South, and likewise for skilled workers, TFP differences disappear.

Proposition 7 shows that access to the same technology and factor price equalization ensure the production structure to be the same in all countries, so that unskilled workers work only in sectors (tasks) with $j \leq J^T$. An implication, however, is that the common intuition that technology flows eliminate productivity differences is not generally correct. Countries with different factor prices will often use available technologies in different ways, causing unequal TFPs, so factor price equalization, not only access to the same technologies, is necessary to eliminate productivity differences.

In fact, if we introduce iceberg transport costs at the rate τ in international trading (so that when 1 unit is exported, $1-\tau$ units arrive at the destination country), then we lose factor price equalization and productivity differences re-emerge. In particular, when $\tau > 0$, $H^n/L^n > H^s/L^s$ implies that $(P_H/P_L)^n < (P_H/P_L)^s$ —more specifically, if there is actual trade, it is straightforward to see that $(P_H/P_L)^n = (1-\tau)^2(P_H/P_L)^s$. Then equation (9) implies that $J^n < J^s$, so there will be TFP differences. We state this as a proposition (proof in the text):

Proposition 8 Suppose there are (iceberg) transportation costs in international trade, then for $\tau > 0$, there will be output per efficiency unit of labor and TFP differences between the North and the South.

More generally, other sources of deviations from factor price equalization will also ensure that TFPs are not equalized. Since factor price equalization is strongly rejected as a description of international factor prices (e.g. Bowen, Leamer, and Sveikauskas, 1987), we conclude that international trade will reduce productivity differences, but generally not eliminate them.

V. Intellectual Property Rights and Technology

A. Equilibrium with Full Property Right Enforcement

If intellectual property rights were enforced in the South, revenues from technology sales in these countries would accrue, not to statutory monopolists, but to the R&D firms in the North. This would encourage R&D firms to design new technologies for the Southern market as well, potentially reducing the "inappropriateness" of technologies to the South.[18] We now investigate this possibility.

We assume that there is no commodity trade, and to simplify the analysis, we once again set $\rho = 1$. The demand for machines is now the sum of the demands from the South and the North. Since demands for machines are still isoelastic, the R&D firms continue to set the same price as above. Then, profits for the two types of innovations are $\hat{\pi}_L = (1-\beta)\beta\left[\left(\hat{P}_L^s\right)^{1/\beta} L^s + \left(\hat{P}_L^n\right)^{1/\beta} L^n\right]$ and $\hat{\pi}_H = (1-\beta)\beta Z\left[\left(\hat{P}_H^s\right)^{1/\beta} H^s + \left(\hat{P}_H^n\right)^{1/\beta} H^n\right]$ where $\hat{P}_L^n$ is the price index for unskilled goods in the North under full property right enforcement, and the other price indexes are defined similarly. N_L and N_H are determined, as before, to equate returns to innovating in the two sectors, thus ensure $\hat{\pi}_H = \hat{\pi}_L$. Given $\hat{N}_H$ and $\hat{N}_L$, the equilibrium in the South and North is determined as in subsection II.C. It can be shown that the steady-state growth rate of the world economy is given by:

$$\hat{g} = \exp(-1)\cdot(1-\beta)\cdot\beta\cdot\left(L^n + L^s + Z\left(\sqrt{\sigma}H^n + \sqrt{\sigma\mu}H^s\right)\right)$$

where $\mu \equiv (H^s/L^s)/(H^n/L^n) < 1$ and σ is a constant, $\sigma \in [\mu, 1]$ which depends on the relative size of the North and the South economy. In particular, σ is increasing in L^s/L^n.[19]

The main question for the focus of the paper is how productivity and GDP differences compare between the worlds with and without international enforcement of intellectual property rights.[20]

Proposition 9 Define Y_n as the GDP in the North and Y_s the GDP in the South without property right enforcement; y_n and y_s the output per worker without property right

[18] This point, though not other results of this paper or this section, is also noted by Diwan and Rodrik (1991).

[19] The expression for $\hat{g}$ is obtained using the expressions (8), (9), (10), (15) and (16), where $\sigma \equiv (\hat{N}_H/\hat{N}_L)/N_H^*/N_L^*$ where ^denotes full property right enforcement and * denotes no property right enforcement. Lemma 3 in Appendix B provides a more detailed characterization of the term σ.

[20] An important issue in this section is the transfer of machine sales revenues from Southern monopolists to R&D firms in the North. To simplify the analysis, we assume that these monopolists continue to exist and sell the new machines to local producers, but they are now owned by Northern inventors. So their revenues are tranferred to the North. This assumption implies that GDP in the South is unaffected by whether these rents remain in the country or not, and can be compared to the GDP without property rights. However, GNP and consumption in the South cannot be directly compared, and even when there is GDP convergence, as shown here, there may be consumption divergence.

enforcement and A_n and A_s output per efficiency unit of labor without property right enforcement. Define $\tilde{Y}_n$ and $\tilde{Y}_s$ as the GDPs with property right enforcement; and $\tilde{y}_n$ and $\tilde{y}_s$, the output with property right enforcement; and $\tilde{A}_n$ and $\tilde{A}_s$ the output per efficiency unit of labor with property right enforcement. Then, we have $\tilde{Y}_n/\tilde{Y}_s < Y_n/Y_s$, $\tilde{y}_n/\tilde{y}_s < y_n/y_s$, and $\tilde{A}_n/\tilde{A}_s < A_n/A_s$.

Property right enforcement leads to convergence in output per worker and output per efficiency unit of labor. With intellectual property rights enforced in the South, technologies produced in the North are more suited to the needs of the South. This leads to faster improvements in labor-complementary technologies than skill-complementary technologies, and narrows the output gap between the South and the North.

The results on TFP convergence are more complicated. When property rights are enforced, two changes occur relative to the environment of Section II. First, more R&D is directed towards unskilled technologies —the BGP N_H/N_L ratio falls—, leading to TFP convergence. Second, both the South and the North increase the range of goods which are produced with unskilled technologies, as implied by equation (9). The effect of this second force is ambiguous, and we cannot conclude that property right enforcement always reduces TFP differences. Numerical calculations show, however, that the region of the parameter space where TFP leads to divergence is extremely small. Moreover, there exists a relatively non-restrictive parameter condition which rules out this possibility analytically. Since this condition is complicated, we state the relevant proposition and prove it in Appendix B (available upon request). Here, we simply note that for almost all parameterizations, enforcement of intellectual property rights leads not only to convergence in output per worker and per efficiency unit of labor, but also in TFP.

A number of interesting observations can be made at this point. First, although the introduction of intellectual property rights will generally reduce productivity differences, it does not, in itself, ensure equalization of output per efficiency unit of labor or of TFP. If the market size for technologies in the North is larger than the one in the South, new technologies will be designed to make use of the North's labor force even with property right enforcement, and the same argument as in the previous section will imply higher productivity in the North than in the South. For our explanation of cross-country differences in productivity to be valid we do not need property rights not to be enforced. Even with full property right enforcement, there will be productivity differences, and the mechanism we highlight contributes to differences in output per worker. Interestingly, however, if the South is much larger than the North, in a world with full property right enforcement, the South might have higher productivity than the North. The reason is that, in this case, R&D firms in the North would design technologies complementary to unskilled workers to exploit the larger Southern market, and this time, skilled workers in the North would have low productivity, leading to the reverse productivity differences.

Second, the introduction of intellectual property rights may lead to a temporary TFP slowdown in the North. If ϕ' is sufficiently negative (i.e. γ large), the eventual growth rate of output and TFP will not be much higher with property rights than without. However, in the absence of property rights, TFP in the North is maximized, whereas it is not when intellectual property rights are enforced. Therefore, during the adjustment process, productivity in the North will grow at a slower rate than usual for a while. Essentially, the introduction of intellectual property rights would direct technical change towards the needs of the South, and away from the needs of the North, which is the source of the temporary TFP slowdown.

Finally, if we have both free trade (factor price equalization) and property right enforcement, TFP differences will disappear (as a result of free trade—see previous section). But there will continue to be differences in output per worker. In particular, using the same arguments as above, we can show that

$$\frac{\hat{N}_H^T}{\hat{N}_L^T} = \frac{1-\hat{J}^T}{\hat{J}^T} = \frac{ZH^n + ZH^s}{L^n + L^s}.$$

This implies that the GDP gap will depend on the size of the South's population relative to that of the North. If the South is relatively small, most technologies will continue to be developed for the North's workforce, and the North will continue to be richer than the South. However, since $\hat{N}_H^T/\hat{N}_L^T$ is less than N_H/N_L as given by (15), GDP differences in this case will be smaller than those in Section II (without trade and property right enforcement).

B. Prisoner's Dilemma in Property Rights Enforcement

The analysis in the previous subsection shows that the South may benefit from the enforcement of intellectual property rights. When these rights are enforced, technologies produced in the North are more appropriate for the needs of the countries in the South. An important question is therefore why intellectual property rights may not be enforced.

The first possibility is that even if property right enforcement is beneficial to the South, contracting problems in the LDCs may make it difficult to enforce intellectual property rights. Second, even with property right enforcement, R&D firms in the North may be unable to sell their technologies to firms in the South, because differences in other factors may require adjustments in these technologies which can only be made locally.

There are also three other reasons suggested by our analysis, which deserve a brief discussion. First, a social planner aiming at maximizing the consumption of the agents in the South may not want property right enforcement. Property right enforcement would make new technologies more suited to the needs of the labor force of the South, but as noted above, it also causes a transfer of resources from the South to the North (via the payments for machines). Second, enforcement of intellectual property rights would destroy the monopoly rents accruing to the monopolies in the South. Accordingly, they may campaign against the introduction of property rights. As it is also emphasized by Mokyr (1990), Krusell and Rios-Rull (1995) among others, the presence of rents that will be destroyed by a change in economic organization may block progress.

Finally, there's also a classic prisoner's dilemma among the countries in the South. To see this, assume that property right enforcement increases the present value of consumption in the South. Suppose that property right enforcement decisions are taken by each country's government, which maximizes its citizens income. Start with a situation in which property rights are enforced in all Southern countries. It is immediate that each individual government in the South has an incentive to deviate and reduce the enforcement of property rights within its borders. This change will only have a small effect on the overall market for technologies, and hence, on the technologies developed in the North. Each country has therefore little to lose by this deviation, but gains a large amount by saving the transfer of income to the R&D firms in the North. As a result, with many small countries in the South, the unique equilibrium in the game where each government chooses the degree of enforcement will be one with no property rights enforcement. This suggests that the enforcement of intellectual property rights internationally may require a coordinated effort.

VI. Human Capital and Convergence

Since differences in skill composition are the source of income and productivity differences, it is useful to understand why countries may end up with different levels of skills. In this section, we endogenize the skill acquisition decision of individuals. In particular, we consider an overlapping generations model in continuous time, where within each generation agents are heterogeneous in the length of time that they need to spend at school in order to become skilled. We characterize the equilibrium of this economy, and show that within the context of the model, differences between the South and the North can be captured as a difference in the distribution of schooling costs. We then show that a Southern country which experiences a reduction in the costs of schooling will accumulate more skills, and the gap of GDP and productivity between this country and the North will decline.

In each country, a continuum υ of unskilled agents are born every period, and each faces a flow rate of death equal to υ, so that the population is constant at 1 (as in Blanchard, 1985). Each agent chooses upon birth whether to acquire the education required to become a skilled worker. It takes T_x periods for agent x to become skilled, and during this time, he earns no labor income. The distribution of T_x is given by the function $G_c(T)$ in country c. The distribution of T is the only source of heterogeneity in this economy, and may be due to credit market imperfections, or to differences in innate ability, and it is also influenced by government policy towards education. The rest of the setup is unchanged. To simplify the exposition, we assume that $G_c(T)$ has no mass points. We assume that there is no commodity trade, no property right enforcement in the South, and continue to set $\rho = 1$ to simplify the expressions.

We now define a BGP as a situation in which H/L and the skill premium remain constant. In BGP, there is a single-crossing property: if an individual with cost of education T_x chooses schooling, another with $T_{x'} < T_x$ must also acquire skills. Therefore, there exists a cutoff level of talent, $\bar{T}$, such that all $T_x > \bar{T}$ do not acquire education. Although H/L is in general a complicated function of past education decisions, if we assume that we are near BGP and υ is small, it takes the simple form:

$$\frac{H^c}{L^c} \approx \frac{G_c(\bar{T}_c)}{1 - G_c(\bar{T}_c)}. \tag{25}$$

The agent with talent $\bar{T}$ needs to be indifferent between acquiring skills and not. When he does not acquire any skills, his return at time t is:
$R^{ne} = \int_t^\infty \exp[-(r+\upsilon)(\tau - t)]w_L(\tau)d\tau = w_L \int_0^\infty \exp[-(r+\upsilon-g)\tau]d\tau = w_L(r+\upsilon-g)$ where $r+\upsilon$ is the effective discount rate and we have used the fact that along the BGP, wages grow at the rate g as given in Section II. If in contrast the agent with $\bar{T}$ decides to acquire education, he receives nothing for a segment of time of length $\bar{T}$, and receives w_H thereafter. Therefore, the return to agent $\bar{T}$ from acquiring education, $R^e(\bar{T})$, can be written as: $R^e(\bar{T}) = \int_{t+\bar{T}}^\infty \exp[-(r+\upsilon)(\tau-t)]w_H(\tau)d\tau = \exp[-(r+\upsilon-g)\bar{T}]w_H/(r+\upsilon-g)$. In BGP, for $\bar{T}$ to be indifferent, we need $R^e(\bar{T}) = R^{ne}$ at all times, so in country c, $w_H^c/w_L^c = \exp\left[(r+\upsilon-g)\bar{T}_c\right]$. Inverting this equation and substituting into (25), we obtain the relative supply of skills as a function of the skill premium:

$$\frac{H^c}{L^c} = \frac{G_c\left(\ln\left(w_H^c/w_L^c\right)/\left(r+\upsilon-g\right)\right)}{1 - G_c\left(\ln\left(w_H^c/w_L^c\right)/\left(r+\upsilon-g\right)\right)}. \tag{26}$$

The equilibrium of each country is given by the intersection of the relative supply (26) with the relative demand for skills determined by (12) above for a given N_H/N_L. N_H/N_L is in turn determined from (15) given H^n/L^n, which can be calculated by substituting the skill premium of the North, $w_H^n/w_L^n = Z$, into (26). Since (12) defines w_H/w_L as a decreasing function of H/L, and (26) traces an increasing relation between w_H/w_L and H/L, there is always a unique intersection for each country.

We need the supply of skills to be larger in the North, so fewer people should choose to acquire skills in the South. This implies that the function G_c in the North should first-order stochastically dominate that in the South. To see this, recall that our analysis above shows that skill premia are higher in the South (in accordance with the findings of Psacharopoulos, 1973, Table 8.4). If the South and the North had the same G function, then more, rather than less people, would acquire skills in the South. There could be a number of reasons for this difference in the propensity to invest in skills (i.e. for the differences in G's). Government subsidies for education are more extensive in the North, reducing the costs of education as captured by G, and individuals have better access to credit and typically have longer life expectancy. All these factors make individuals in the North more likely to invest in skills.

The next proposition summarizes the equilibrium in this case:

Proposition 10 World BGP equilibrium with endogenous skill acquisition is characterized as follows: $w_H^n/w_L^n = Z$ and (26) for $c = n$ determine the relative supply of skills in the North, equation (15) then determines the relative state of technology, N_H/N_L. Given N_H/N_L, equations (12) and (26) for $c = s$ determine the equilibrium in the South. The BGP is locally stable.

The most interesting conclusion of this analysis with endogenous skills is that the change in the function G_c for a country will lead to a change in its supply of skills relative to the North, and therefore to convergence or divergence in productivity and output per worker. In particular, since the balanced growth path is always stable, when the North is in BGP, a country with less than its long run relative supply of skills will gradually accumulate skills and experience faster than average productivity growth. Therefore, countries that improve their skill composition relative to the U.S. should also experience productivity convergence. This pattern receives some support from the historical accounts of development of Korea and Japan, whereby the process of adopting new technologies and productivity convergence for these countries coincided with rapid skill accumulation (see for example, Rhee, Ross-Larson and Pursell, 1984; Lockwood, 1968).

VII. Local Technologies and Divergence

So far, our analysis has assumed that firms in the South use technologies developed in the North. In practice, Southern firms may decide not to import Northern technologies, and use instead "local technologies". This is especially relevant for unskilled workers. Many new unskilled technologies turn formerly complex tasks into simpler ones that can be efficiently performed by unskilled workers. But, when these technologies are not sufficiently advanced, they may not be very useful to unskilled workers in relatively skill-intensive sectors. For example, advanced computers and software enable firms to use relatively unskilled workers, while tracking inventories automatically, but this would not have been possible with the computers of twenty years ago. A firm employing unskilled workers would then have been obliged to find other methods of inventory control.

To discuss these issues, we assume, in this section, that unskilled workers can also produce output in sector i by using local technologies. To simplify the analysis, we make local technologies symmetric to those imported from the North, that is, a local monopolist owns each local technology and sells machines embedding the relevant technology to the local producers. In particular, equation (2) now changes to:

$$\begin{aligned} y(i) &= \max\left\{\left[\int_0^{N_L} k_L(i,v)^{1-\beta}dv\right]\cdot[(1-i)\cdot l(i)]\,\beta; M(i)k_M^{1-\beta}l(i)\beta\right\} \\ &\quad+\left[\int_0^{N_H} k_H(i,v)^{1-\beta}dv\right]\cdot[i\cdot Z\cdot h(i)]\,\beta, \end{aligned}$$

where $M(i)$ is the productivity of local technology in sector i. We also assume that the marginal cost of local machines is $(r+\delta)\rho^{\beta/(1-\beta)}/(1-\beta)$, as for the machines imported from the North, so that they will have the same prices. The only difference is that technologies imported from the North improve steadily —at the rate g in BGP— while the productivity of local technologies remains constant at $M(i)$.

The next proposition follows immediately (proof omitted):

Proposition 11 Producers in the South use local technologies in sector $i \leq J^s$ as long as $M(i) > (1-i)N_L$. Eventually, all local technologies are abandoned. Suppose the North is in BGP, then, until all local technologies are abandoned, output per worker and productivity in the South diverge from their values in the North.

When local technologies are available, the South does not always use the technology of the North, even though it has access to it. In particular, when the labor-complementary technologies of the North are not very advanced, local technologies may suit the needs of a country better than the skill-complementary Northern technologies. Our assumption that most technical change takes place in the North implies that local technologies will not improve as quickly as Northern technologies. As a result, while it uses local technologies, both output per worker and productivity in the South will fall relative to the North. Nevertheless, at some point, it will become beneficial for the South to start importing technologies from the North, and income and productivity inequality between the South and the North will eventually stabilize.

VIII. Conclusion

In this paper, we have developed a model with productivity differences between less developed and advanced economies. The North has more skilled workers, and employs them in tasks performed by unskilled workers in the South. Furthermore, we made two crucial, but plausible, assumptions: most new technologies are developed in the North, and technical change is directed, in the sense that more profitable technologies get developed and upgraded faster. The larger supply of skills in the North implies that new technologies are relatively skill-complementary, whereas the South, which employs unskilled workers in most tasks and sectors, needs more labor-complementary technologies. This mismatch between the skills of the South and technologies imported from the North is the source of the productivity differences, and amplifies the differences in output per worker.

As well as proposing a new explanation for productivity differences, our model suggests a number of potentially important determinants of differences in per capita income. First, commodity trade influences technological development. In particular, free-trade implies that the South specializes in tasks that can be performed efficiently by unskilled workers, and ensures convergence in productivity. Nevertheless, trade without property right enforcement also encourages the North to develop further skill-complementary technologies, which create only limited benefits for the South. So despite causing productivity convergence, trade amplifies differences in output per worker between the South and the North. Although other, beneficial, effects of trade on output per worker in the South may be more important in practice, this effect of trade on per capita income —via its impact on the skill-bias of new technologies— is also worth bearing in mind. Second, the extent of intellectual property rights in the world is also a major factor in output per worker differences. If the South, collectively, enforces intellectual property rights, this will encourage Northern R&D firms to develop technologies more suited to the needs of the countries in the South, reducing the output gap between rich and poor countries. Finally, our model suggests a stylized pattern of convergence and divergence across countries. Southern countries which improve their skills base relative to the North will experience faster productivity growth. In contrast, countries will diverge from the North when they prefer to use local technologies, rather than import those developed in the North. But this process will eventually come to an end, and as all less developed countries start importing and using Northern technologies, cross-country income and productivity differences will stabilize.

Technologies developed in the North may be inappropriate not only to the skills, but to a range of other conditions prevailing in the South. The climate, tastes, cultures and institutions affect the relative productivities of different technologies. Whether "appropriateness" in these dimensions is equally important as the mismatch between technologies and skills is mostly an empirical question, and one which we believe deserves study.

Our model has also abstracted from other important determinants of productivity, such as institutional differences, slow diffusion of new technologies, and economic and political distortions in the process of technology adoption. This has been done to emphasize that even in this environment of free technology flows, there will be significant productivity differences between less and more developed countries, and the output per worker gap will be amplified. How slow diffusion of new technologies and distortions interact, both qualitatively and quantitatively, with forces emphasized in this paper is another area for future research.

Finally, the calculations in Section III.B suggest that the mismatch of new technologies and the South's skills may be an important factor in the income per capita differences. Encouraging the development of technologies more appropriate to the LDCs could therefore reduce the output gap. In fact, a number of international organizations are already active in developing technologies useful to the LDCs. An investigation of the empirical importance of this mechanism and the benefits of investing further in technologies appropriate for the LDCs, either by international organizations or by private R&D firms, may also be a fruitful area for further study.

Appendix A: Proofs of Main Results

Proof of Lemma 1. The profit of a firm using technology z in sector i is:

$$\Pi_z(i) = p(i)y(i) - \int_0^{N_z} \chi_z(\nu)k_z(i,\nu)d\nu - w_z z_i \tag{27}$$

where $z \in \{L, H\}$. We proved in the text that profit maximization implies $\chi_z(\nu) = (1-\beta)$ and $k_z(i,\nu) = k_z(i) = \left(p_i\left((1-i)^\beta D_z + i^\beta(1-D_z)\right)\right)^{\frac{1}{\beta}} z_j$, where $D_z = 1$ if $z = L$ and $D_z = 0$ if $z = H$. Thus, we can use (27) to write per worker profit:

$$\begin{aligned}\zeta_z(i) \equiv \frac{\Pi_z(i)}{z_i} &= \left(p(i)\left((1-i)^\beta D_z + i^\beta(1-D_z)\right)\right)^{\frac{1-\beta}{\beta}} N_z - \\ &(1-\beta)\left(p(i)\left((1-i)^\beta D_z + i^\beta(1-D_z)\right)\right)^{\frac{1}{\beta}} N_z - w_z\end{aligned} \tag{28}$$

where competition implies that, in equilibrium, $\Pi_z(i) \leq 0$, $\forall i$. Now, first note $\zeta_H(i) - \zeta_L(i)$ is a strictly increasing function of i over $[0,1]$. Next, observe that Cobb-Douglas technology in (1) implies that all goods $i \in (0,1)$ have to be produced. So $\forall i$ we must have either $\zeta_L(i) = \Pi_L(i) = 0$ or $\zeta_H(i) = \Pi_H(i) = 0$ or both. Finally, it is not possible that in equilibrium some skilled (unskilled) workers are unemployed, because this would imply that the wage of this skill class falls to zero, hence, from (28), there would exist a profitable deviation. Thus a positive measure of goods must be produced using skilled (unskilled) workers. It therefore follows that there must exist J (where $0 < J < 1$) such that $\zeta_H(J) - \zeta_L(J) = 0$, and $\zeta_H(i) - \zeta_L(i) > 0$ for all $i > J$ and vice versa for $i < J$. QED

Proof of Lemma 2. To derive a contradiction, suppose that for some $i' < i'' < J$ it is $p(i')\,(1-i')\,\beta \neq p(i'')(1-i'')\beta$. Consider two firms in sectors i', i'', both using unskilled technologies. In equilibrium, these two firms must make zero profits. However, substituting $D_z = 1$ in equation (28) gives a contradiction. Thus, for all $i \leq J$, $p(i) = P_L\,(1-i)^{-\beta}$ for some P_L. A similar argument establishes that for all $i \geq J$, $p(i) = P_H i^{-\beta}$.

We can then rewrite equation (5) as follows:

$$y(i) = \begin{cases} P_L^{(1-\beta)/\beta} N_L l(i)(1-i)^{-\beta} & \text{if } \ 0 \leq i \leq J \\ P_H^{(1-\beta)/\beta} N_H Z h(i) i^{-\beta} & \text{if } \ J < i \leq 1 \end{cases}. \tag{29}$$

Next, recall that consumers' utility maximization implies that $p(i)y(i) = Y$ for all $i \in (0,1)$. Then, since $p(i) = P_L\,(1-i)^{-\beta}$, for all $i \leq J$, we have $y(i) = y(0)(1-i)^{-\beta}$. Similarly, for all $i \geq J$, we have $y(i) = y(1)i^{-\beta}$. Furthermore, (29) implies that $y(0) = P_L^{(1-\beta)/\beta} N_L l(0)$ and $y(1) = P_H^{(1-\beta)/\beta} N_H h(1)$. Hence, $l(i)$ ($h(i)$) must be equal in all sectors using unskilled (skilled) workers. Thus, $l(i) = L/(1-J)$ and $h(i) = H/J$.

We finally need to prove that P_H/P_L is given by (8). Observe that, since $p(i)y(i) = Y$ (and, in particular, $p(0)y(0) = p(1)y(1)$), $p(0) = P_L$ and $p_1 = P_H$, then:

$$\frac{P_L}{P_H} = \frac{y(1)}{y(0)} = \frac{P_H^{(1-\beta)/\beta} N_H H/(1-J)}{P_L^{(1-\beta)/\beta} N_L L/J} \tag{30}$$

where the second equality is obtained by using (6), (7) and (29). Rearranging terms in (30) establishes (8). QED

Proof of Proposition 1. Proof of existence and uniqueness of BGP is in the text. We start with the growth rate along the BGP (g). From (4) we know that $g = \Gamma x_L^{1-\gamma} = \Gamma x_H^{1-\gamma} = \Gamma x^{1-\gamma}$ where the last equality exploits the fact that in BGP $x_H = x_L = x$. Recall, first, that free entry in R&D implies $\Gamma x_z^{-\gamma} = V_z = r/\pi_z$. Thus, in a balanced growth equilibrium, $x = (\Gamma\pi/r)^{1/\gamma}$, and $g = \Gamma^{1/\gamma}(\pi/r)^{(1-\gamma)/\gamma}$. In order to derive the expression of π, observe that $\pi = \pi_L = \exp(-1)\beta(1-\beta)L^n/J = \exp(-1)\beta(1-\beta)(L^n + ZH^n)$, where the first equality follows from (10) and the second follows from (15).

Consider now stability. Define $n \equiv N_H/N_L$ and $\kappa \equiv x_H/x_L$ (so, $\dot{n}/n = \dot{N}_H/N_H - \dot{N}_L/N_L$ and $\dot{\kappa}/\kappa \equiv \dot{x}_H/x_H - \dot{x}_L/x_L$). Recall that free entry implies $\Gamma x_z^{-\gamma} V_z = 1$ at all points, so

$$\frac{\dot{x}_z}{x_z} = \frac{\dot{V}_z}{\gamma V_z} = \frac{r}{\gamma} - \frac{\pi_z(n)}{\gamma \Gamma x_z^{\gamma}}$$

where $\pi_L(n) = \beta(1-\beta)\left(P_L^n\right)^{1/\beta} L^n = \exp[-1]\beta(1-\beta)L^n\left(1 + \sqrt{n \cdot ZH^n/L^n}\right)$ and $\pi_H(n) = \beta(1-\beta)\left(P_H^n\right)^{1/\beta} H^n = \exp[-1]\beta(1-\beta)H^n\left(1 + \left(1/\sqrt{n \cdot ZH^n/L^n}\right)\right)$(the second equalities in both expressions follow from (8)-(9)-(10)). Clearly, $\pi_L'(n) > 0$ and $\pi_H'(n) < 0$. Next, observe that (4) implies $\dot{n}/n = x_H^{1-\gamma}\left(1 - \kappa^{1-\gamma}\right)$. We can then write the following system of differential equations describing transitory dynamics:

$$\begin{aligned} \frac{\dot{n}}{n} &= x_H^{1-\gamma}\left(1 - \kappa^{1-\gamma}\right) \\ \frac{\dot{\kappa}}{\kappa} &= \left[\gamma \Gamma x_H^{\gamma}\right]^{-1}\left[\pi_H(n) - \pi_L(n)\right] \\ \frac{\dot{x}_H}{x_H} &= \frac{r}{\gamma} - \frac{\pi_H(n)}{\gamma \Gamma x_H^{\gamma}} \end{aligned} \tag{31}$$

The stability properties of this dynamic system are "block-recursive". Note, in particular, that although x_H affects the speed of growth of both n and κ in first two equations, it does not affect the sign of the dynamics of these two variables. We can therefore determine first the stability of n and κ, and then characterize the behavior of x_H. Figure 5 gives this argument diagrammatically. Recall that n is the only predetermined variable. Starting from any $n < n^*$, (e.g. n_0 in Figure 5) we have $\kappa < 1$, and the system monotonically converges to $n = n^*$ and $\kappa = 1$. The converse applies when $n > n^*$.

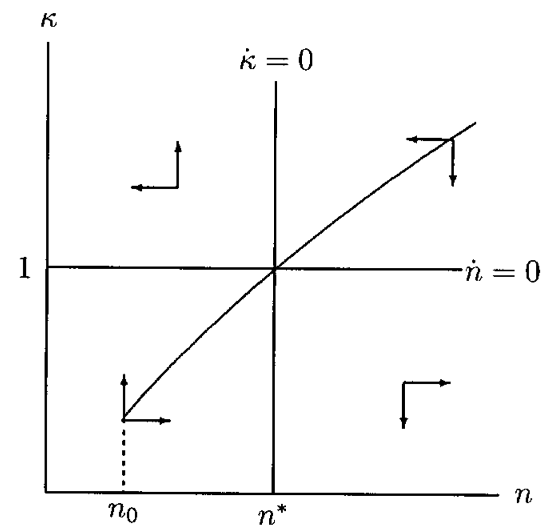

Figure 5: Transitional dynamics.

Finally, the inspection of the third equation of (31) shows that given the dynamic adjustment of n and $\pi_H(n)$, there exists a unique trajectory of x_H converging to the BGP with $\dot{x}_H = 0$. Since x_H is not predetermined, it will jump to this trajectory and follow it at every point in time. QED.

Proof of Proposition 5. First, trade ensures that commodity prices, P_L^T and P_H^T are equalized. Equation (9) in Section II.C still determines J in each country given prices. P_L and P_H are now the same in the North and the South, so $J^{Ts} = J^{Tn} = J^T$.

Next, observe that when the (unanticipated) trade opening occurs, N_H/N_L is given (predetermined). This implies – given equations (8)-(9)-(12) – that immediately after trade opening $(P_H/P_L)^n < (P_H/P_L)_{t_0}^T < (P_H/P_L)^s$, $J^n < J_{t_0}^T < J^s$ and $(w_H/w_L)^n < (w_H/w_L)_{t_0}^T < (w_H/w_L)^s$.

After the impact effect of trade opening, the state variables N_H and N_L change, as now the BGP condition, (23), is no longer satisfied. This condition will be satisfied again when $(P_H/P_L)^T = (P_H/P_L)^n$. Since after trade opening $(P_H/P_L)^T > (P_H/P_L)^n$, we have $\pi_H^T > \pi_L^T$. Transitory dynamics can be characterized by an argument identical to that of Proposition 1. In particular, (31) applies exactly except that the second differential equation has a different "zero". Therefore, our previous argument immediately implies that after trade opening $x_H^T > x_L^T$ until N_H/N_L converges to $(N_H/N_L)^T$ as given by (24). As N_H/N_L increases, the world skill premium increases, and P_H/P_L and J decline. QED

Proof of Proposition 6. Equation (11) implies that the ratio of the GDP in the North to the GDP in the South is:

$$\frac{Y_n}{Y_s} = \left[\frac{(L^n)^{1/2} + (\frac{N_H}{N_L} Z H^n)^{1/2}}{(L^s)^{1/2} + (\frac{N_H}{N_L} Z H^s)^{1/2}} \right]^2 \tag{32}$$

which is strictly increasing in N_H/N_L since $H^n/L^n > H^s/L^s$. Trade increases N_H/N_L (from Proposition 5), so it increases Y_n/Y_s. The same argument applies to the output per worker ratio, y_n/y_s.QED

Proof of Proposition 7. Recall that TFP is:

$$B(J, N_L, N_H) = \left[N_L^J N_H^{1-J} (1-J)^{-(1-J)} J^{-J} \right] \beta \cdot \exp[-1] \tag{33}$$

Since $J^s = J^n$ with trade, TFP in the North and the South are equalized The same argument applies to $A(J, N_L, N_H)$. QED

Proof of Proposition 9. Recall that relative GDPs are given by (32). Enforcement of property rights reduces N_H/N_L (see Lemma 3 in Appendix B), and hence leads to convergence in GDP, output per worker and output per efficiency unit of labor (cfr. the results in Section III) . QED

Proof of Proposition 10. As before, equilibrium in the North can be characterized without reference to the South, since there are no property rights or commodity trade. Equation (15) still determines equilibrium R&D choices for given relative supplies. The skill premium in the North is still equal to Z. Combining this with (26), for $c = n$, gives the BGP in the North. Given N_H and N_L, (12) gives the skill premium in the South, and combining this with (26) for $c = s$ gives the BGP skill premium and relative supplies in the South.

Finally, to analyze the local dynamics, augment the dynamic system in (31) with a differential equation in $\zeta = H^n/L^n$. Recall that we only need to describe North's equilibrium (the world economy continues to be block recursive, so we can solve the North's equilibrium first, without reference to the South). Around the North's BGP, we have:

$$\begin{aligned} \frac{\dot{\zeta}}{\zeta} &= \frac{\partial (H^n/L^n)/\partial t}{H^n/L^n} = \frac{\dot{H}^n}{H^n} - \frac{\dot{L}^n}{L^n} = \upsilon \Gamma_n \left[\ln (w_H^n/w_L^n) / (r + \upsilon - g) \right] / H^n - \\ & \upsilon \left[1 - \Gamma_n \left[\ln (w_H^n/w_L^n) / (r + \upsilon - g) \right] \right] / L^n \end{aligned}$$

Using a first-order Taylor approximation, we write:

$$\frac{\dot{\zeta}}{\zeta} = d_1 \left[w_H^n/w_L^n - (w_H^n/w_L^n)^{SS} \right] - d_2 \left[n - n^{SS} \right] \tag{34}$$

where $d_1 > 0$ and $d_2 > 0$, and the superscript SS denotes steady-state. Then, using equations (8) and (12) from the text, we can replace relative wages and obtain the system of linear differential equations:

$$\begin{aligned}
\frac{\dot{n}}{n} &= -B_1(\kappa - 1) \\
\frac{\dot{\kappa}}{\kappa} &= -b_1\left(n - n^{SS}\right) \\
\frac{\dot{x}_H}{x_H} &= c_1\left(n - n^{SS}\right) + c_2(x_H - x_H^{SS}) \\
\frac{\dot{\zeta}}{\zeta} &= -(d_1/2 + d_2)(\zeta - \zeta^{SS}) + d_1(n - n^{SS})/2
\end{aligned}$$

The second equation generally depends on relative skill supplies in the North, $\zeta = H^n/L^n$, but this dependence disappears in the neighborhood of the BGP. Therefore, the system continues to be block-recursive. Hence, starting from $n < n^{SS}$, we have $x_H > x_L$, $n = N_H/N_L$ increases to its BGP value. Similarly, if H^n/L^n is less than its BGP value, it also increases towards that value. Given the behavior of N_H/N_L determined in the North, H^s/L^s in the South also converges to its BGP level following equation (34). QED

References

Acemoglu, Daron (1998). "Why Do New Technologies Complement Skills? Directed Technical Change and Wage Inequality" forthcoming *Quarterly Journal of Economics,* November 1998, vol 113, pp 1055-1089.

Acemoglu, Daron and Fabrizio Zilibotti (1999). "Information Accumulation in Development" forthcoming *Journal of Economic Growth.*

Atkinson, Anthony B. and Joseph E. Stiglitz (1969). "A New View of Technological Change," *Economic Journal* 79, 573-78.

Barro, Robert J. and Xavier Sala-i-Martin (1997). "Technological Diffusion, Convergence, and Growth," *Journal of Economic Growth* 2, 1-26.

Barro, Robert J. and Jong-Wha Lee (1993). "International Comparisons of Educational Attainment," *Journal of Monetary Economics* 32, 363-94.

Basu, Susanto and David N. Weil (1998). "Appropriate Technology and Growth," forthcoming in *Quarterly Journal of Economics.*

Benhabib, Jess and Mark M. Spiegel (1994). "The Role of Human Capital in Economic Development: Evidence from Aggregate Cross-Country Data," *Journal of Monetary Economics* 34, 143-73.

Berman, Eli, John Bound and Stephen Machin (1998). "Implications of Skill-Biased Technological Change: International Evidence," forthcoming *Quarterly Journal of Economics.*

Bils, Mark and Peter Klenow (1996). "Does Schooling Cause Growth or the Other Way Around?," Mimeo, University of Chicago GSB.

Blanchard, Olivier J. (1985). "Debt, Deficits, and Finite Horizons," *Journal of Political Economy* 93, 223-47.

Bowen, Harry P., Edward E. Leamer and Leo Sveikauskas (1987). "Multicountry, Multifactor Tests of the Factor Abundance Theory," *American Economic Review* 77, 791-809.

Caselli, Francesco, Gerardo Esquivel and Fernando Lefort (1996). "Reopening the Convergence Debate: A New Look at Cross-country Growth Empirics," *Journal of Economic Growth* 1, 363-89.

Chari, V. V., Patrick Kehoe and Ellen McGrattan (1997). "The Poverty of Nations: A Quantitative Investigation," Working Paper, Federal Reserve Bank of Minneapolis.

Current Population Report (1996) *Money Income in the United States P60-197,* U.S. Deparment of Commerce.

Diwan, I and Dani Rodrik (1991) "Patents, Appropriate Technology and North-South Trade" *Journal of International Economics*, 30, 27-47.

Eaton, Jonathan, and Samuel Kortum (1994). "International Patenting and Technology Diffusion," Mimeo.

Evenson, Robert E. and Larry E. Westphal (1995). "Technological Change and Technology Strategy," in *Handbook of Development Economics*, Volume III, edited by Behrman, Jere and T. N. Srinivansan, Elsevier Science B. V.

Feenstra, Robert C. (1990). "Trade and Uneven Growth," NBER Working Paper: 3276.

Grossman, Gene and Elhanan Helpman (1992). *Innovation and Growth in the Global Economy*, MIT Press: Cambridge, Massachusetts.

Hall, Robert and Charles I. Jones (1998). "Why Do Some Countries Produce So Much More Output per Worker Than Others?," forthcoming *Quarterly Journal of Economics.*

Jones, Charles I. (1995). "Economic Growth and the Relative Price of Capital." *Journal of Monetary Economics,* 34, 359-82.

Jovanovic, Boyan and Rafael Rob (1998). "Solow vs Solow", Working Paper, New York University.

Katz, Lawrence and Kevin Murphy (1992). "Changes in Relative Wages: Supply and Demand Factors," *Quarterly Journal of Economics* 107, 35-78.

Klenow, Peter J. and Andres Rodriquez-Clare (1997). "The Neoclassical revival in Growth Economics: Has It Gone Too Far?," *NBER Macroeconomics Annual*, pages 73-103.

Krueger Alan and Mikael Lindahl (1998); "Education for Growth: Why and For Whom" Princeton Mimeo.

Krugman, Paul (1979). "A Model of Innovation, Technology Transfer, and the World Distribution of Income," *Journal of Political Economy* 87, 253-66.

Krugman, Paul (1981). "Trade, Accumulation and Uneven Development," *Journal of Development Economics* 8, 41-55.

Krugman, Paul (1987). "The Narrow Moving Band, the Dutch disease, and the Competitive Consequences of Mrs. Thatcher," *Journal of Development Economics* 27, 41-55.

Krusell, Per and Jose-Victor Rios-Rull (1996). "Vested Interests in a Positive Theory of Stagnation and Growth," *Review of Economic Studies* 63, 301-329.

Lockwood, William W. (1968). *The Economic Development of Japan: Growth and Structural Change*, Princeton University Press, Princeton, New Jersey.

Mankiw, N. Gregory (1995). "The Growth of Nations." *Brookings Papers on Economic Activity,* 275-310.

Mankiw, N. Gregory, David Romer, and David N. Weil (1992). "A contribution to the Empirics of Economic Growth," *Quarterly Journal of Economics* 107, 407-37.

Mokyr, Joel (1990). *The Levers of Riches: Technological Creativity and Economic Progress*, Oxford University Press, New York.

Parente, Stephen L. and Edward C. Prescott (1994). "Barriers to Technology Adoption and Development," *Journal of Political Economy* 102, 298-321.

Parente, Stephen, Richard Rogerson and Randall Wright (1998). "Homework in Development Economics" Mimeo.

Prescott, Edward (1998). "Needed: A Theory of Total Factor Productivity," *International Economic Review* 39, 525-553.

Psacharopoulos, George (1973). *Returns to Education: An International Comparison*, Jossey-Bass, San Francisco.

Rhee, Yung Whee, Bruce Ross-Larson, and Garry Pursell (1984). *Korea's Competitive Edge*, The Johns Hopkins University Press, Baltimore, Maryland.

Rivera-Batiz, Luis A. and Paul M. Romer (1991). "Economic Integration and Endogenous Growth," *Quarterly Journal of Economics* 106, 531-55.

Romer, Paul M. (1990). "Endogenous Technological Change," *Journal of Political Economy* 98, S71-S102

Romer, Paul M. (1993). "Idea Gaps and Object Gaps in Economic Development" *Journal of Monetary Economics*, 32, 543-573.

Salter W. E.G. (1966). *Productivity and Technical Change*, 2nd edition, Cambridge University Press, Cambridge, United Kingdom.

Stewart, Frances (1978). *Technology and Underdevelopment*, The Macmillan Press, Ltd., London, England.

Summers, Lawrence and Alan Heston (1991). "The Penn World Table (Mark 5): An Expanded Set of International Comparisons, 1950-1988," *Quarterly Journal of Economics*, 106, 327-368.

UNESCO (1997). *UNESCO Statistical Year Book 1997*, Geneva.

Vernon, Raymond (1966). " International Investment and International Trade in the Product Cycle," *Quarterly Journal of Economics* 80, 190-207.

Young, Alwyn (1991). "Learning by Doing and the Dynamic Effects of International Trade," *Quarterly Journal of Economics* 106, 369-405.

Wood, Adrian (1994). *North-South Trade, Employment and Inequality: Changing Fortunes in a Skill Driven World*, Oxford, Clarendon Press.

Table 1A. Data.

y = 1985 RGDPW in Summers Heston PWT 5.6 (corrected following Hall and Jones, 1998).

y_{AZ} = 1985 output per worker predicted by our model when H is measured by "H/L (s)" and Z=1.5.

y_{NC} = output per worker predicted by the neoclassical model when H is measured by "H/L (s)" and Z=1.5.

K/(H+L) = 1985 capital per worker (Hall and Jones, 1998).

H/L (p) = ratio of the population over 25 with at least some primary school attainment to those over 25 with no primary school attainment (Barro-Lee).

H/L (sa) = ratio of the population over 25 with at least some secondary school attainment to those over 25 with no secondary school attainment (Barro-Lee).

H/L (sc) = ratio of the population over 25 with at least secondary school completed to those over 25 with no secondary school completed (Barro-Lee).

H/L (h) = ratio of the population over age 25 with some higher education to those with no higher education (Barro-Lee).

Country	*y*	*K/(H+L)*	*H/L (p)*	*H/L (sa)*	*H/L (sc)*	*H/L (h)*	y_{AZ}	y_{NC}
USA	1	1	65.7	10.24	2.311	0.508	1	1
Canada	0.941	0.945	82.2	3.73	0.789	0.239	0.932	0.954
Switzerland	0.874	1.236	18.6	1.83	0.862	0.134	0.922	1.006
Australia	0.843	1.009	46.6	2.36	0.745	0.279	0.901	0.954
Belgium	0.836	0.875	82.3	0.86	0.290	0.120	0.678	0.855
Italy	0.834	0.942	4.8	0.58	0.218	0.072	0.607	0.854
France	0.818	0.974	89.8	0.57	0.247	0.117	0.606	0.862
W. Germany	0.818	1.022	75.9	0.37	0.192	0.083	0.517	0.853
Netherlands	0.806	0.906	30.3	1.42	0.370	0.160	0.789	0.894
Sweden	0.787	0.833	37.5	1.49	0.866	0.203	0.776	0.873
Norway	0.759	1.086	33.5	0.75	0.355	0.156	0.697	0.910
Finland	0.734	1.020	99.0	0.80	0.515	0.160	0.697	0.895
Iceland	0.73	0.764	61.5	0.69	0.297	0.103	0.601	0.806
United Kingdom	0.727	0.577	24.7	0.94	0.307	0.147	0.608	0.750
New Zealand	0.717	0.895	98.9	5.99	0.946	0.435	0.947	0.952
Austria	0.709	0.821	99.0	1.14	0.357	0.060	0.722	0.853
Denmark	0.69	0.808	49.0	1.17	0.805	0.229	0.724	0.851
Spain	0.682	0.707	18.2	0.33	0.186	0.075	0.431	0.750
Israel	0.659	0.592	7.6	1.44	0.698	0.316	0.688	0.778
Hong Kong	0.608	0.334	4.4	0.85	0.395	0.083	0.492	0.622
Singapore	0.606	0.644	1.8	0.32	0.129	0.045	0.416	0.727
Japan	0.587	0.735	249.0	1.38	0.435	0.190	0.731	0.833
Ireland	0.577	0.639	28.4	1.06	0.383	0.106	0.652	0.782
Trinidad	0.498	0.455	26.0	0.40	0.103	0.034	0.407	0.656
Venezuela	0.495	0.489	3.3	0.44	0.225	0.111	0.435	0.675
Greece	0.469	0.491	8.4	0.46	0.300	0.095	0.442	0.678
Malta	0.463	0.377	3.6	0.45	0.202	0.035	0.402	0.620
Cyprus	0.446	0.424	15.7	0.92	0.441	0.163	0.546	0.677
Taiwan	0.445	0.300	4.2	0.72	0.397	0.124	0.450	0.594
Syria	0.438	0.289	1.0	0.23	0.148	0.083	0.270	0.548
Mexico	0.433	0.326	2.2	0.23	0.144	0.079	0.285	0.571
Argentina	0.418	0.380	13.9	0.40	0.200	0.089	0.385	0.618
USSR	0.417	0.632	70.4	1.41	0.420	0.122	0.699	0.794
Jordania	0.416	0.255	0.8	0.33	0.221	0.124	0.310	0.536

Country	y	$K/(H+L)$	H/L (p)	H/L (sa)	H/L (sc)	H/L (h)	y_{AZ}	y_{NC}
Barbados	0.404	0.214	42.4	0.74	0.193	0.058	0.405	0.532
Korea	0.38	0.282	5.5	1.33	0.595	0.133	0.528	0.606
Portugal	0.366	0.337	2.8	0.19	0.104	0.047	0.259	0.572
Uruguay	0.34	0.268	20.3	0.59	0.199	0.088	0.403	0.565
Algeria	0.328	0.343	0.5	0.08	0.055	0.024	0.172	0.560
Brazil	0.319	0.243	2.0	0.13	0.092	0.068	0.192	0.506
Hungary	0.307	0.388	54.6	0.47	0.208	0.083	0.413	0.628
Yugoslavia	0.3	0.462	5.0	0.55	0.241	0.096	0.470	0.673
Iran	0.295	0.284	0.4	0.22	0.130	0.027	0.267	0.544
Fiji	0.273	0.232	8.2	0.42	0.189	0.047	0.332	0.526
Malaysia	0.267	0.269	2.3	0.34	0.160	0.020	0.319	0.546
Colombia	0.264	0.177	3.1	0.28	0.139	0.060	0.255	0.471
Chile	0.263	0.257	10.1	0.51	0.236	0.091	0.375	0.552
Mauritius	0.262	0.099	3.7	0.36	0.205	0.032	0.234	0.393
Costa Rica	0.257	0.191	6.1	0.28	0.189	0.131	0.260	0.483
South Africa	0.25	0.230	3.1	0.41	0.065	0.024	0.329	0.524
Poland	0.238	0.389	31.3	0.72	0.267	0.081	0.490	0.647
Ecuador	0.237	0.243	3.1	0.32	0.230	0.157	0.329	0.509
Peru	0.237	0.207	3.2	0.44	0.264	0.136	0.302	0.527
Reunion	0.226	0.165	1.8	0.28	0.047	0.014	0.248	0.460
Panama	0.223	0.227	4.3	0.49	0.289	0.125	0.354	0.528
Turkey	0.218	0.187	1.2	0.17	0.093	0.043	0.201	0.468
Tunisia	0.217	0.124	0.5	0.17	0.104	0.029	0.179	0.409
Czechoslovakia	0.211	0.277	82.3	1.04	0.325	0.080	0.491	0.593
Guatemala	0.21	0.089	0.8	0.11	0.056	0.036	0.126	0.362
Dominican Rep.	0.206	0.140	1.3	0.20	0.110	0.068	0.200	0.429
Egypt	0.187	0.039	0.6	0.24	0.134	0.048	0.143	0.283
Paraguay	0.17	0.111	6.4	0.23	0.116	0.047	0.197	0.400
Swaziland	0.164	0.093	1.1	0.11	0.029	0.014	0.129	0.367
El Salvador	0.157	0.065	1.8	0.11	0.065	0.035	0.134	0.358
Thailand	0.157	0.086	3.7	0.13	0.080	0.053	0.115	0.325
Sri Lanka	0.155	0.068	6.4	0.57	0.170	0.014	0.252	0.358
Bolivia	0.14	0.104	1.3	0.27	0.152	0.081	0.211	0.395
Honduras	0.13	0.071	2.0	0.18	0.122	0.034	0.257	0.447
Jamaica	0.13	0.147	37.5	0.33	0.101	0.029	0.151	0.341
Pakistan	0.128	0.043	0.3	0.14	0.063	0.020	0.114	0.287
Bangladesh	0.127	0.019	0.5	0.19	0.075	0.017	0.100	0.220
Nicaragua	0.126	0.101	1.3	0.12	0.093	0.081	0.273	0.394
Philippines	0.126	0.092	8.9	0.54	0.379	0.217	0.140	0.378
Congo	0.122	0.056	0.7	0.25	0.083	0.031	0.165	0.321
Romania	0.113	0.122	5.5	0.79	0.266	0.064	0.344	0.443
Indonesia	0.11	0.092	2.0	0.12	0.064	0.006	0.136	0.367
Guyana	0.105	0.163	9.9	0.35	0.098	0.020	0.274	0.464
Botswana	0.094	0.114	0.9	0.07	0.020	0.007	0.108	0.387
India	0.086	0.043	0.5	0.20	0.095	0.038	0.137	0.291
Papua N. G.	0.078	0.070	0.3	0.06	0.014	0.005	0.085	0.329
Cameroon	0.076	0.036	0.7	0.06	0.022	0.007	0.073	0.264
Senegal	0.072	0.016	0.6	0.05	0.025	0.014	0.051	0.204
Sudan	0.067	0.047	0.3	0.05	0.029	0.008	0.070	0.288

Country	y	$K/(H+L)$	H/L (p)	H/L (sa)	H/L (sc)	H/L (h)	y_{AZ}	y_{NC}
Zimbabwe	0.065	0.052	1.8	0.05	0.012	0.010	0.076	0.299
Sierra Leone	0.064	0.005	0.2	0.05	0.011	0.005	0.034	0.141
Lesotho	0.063	0.029	2.0	0.06	0.019	0.005	0.066	0.246
China	0.06	0.048	1.3	0.36	0.126	0.011	0.186	0.310
Benin	0.059	0.022	0.2	0.04	0.015	0.006	0.049	0.222
Haiti	0.057	0.019	0.7	0.11	0.052	0.007	0.077	0.217
Kenia	0.056	0.031	0.8	0.06	0.012	0.007	0.068	0.253
Ghana	0.052	0.014	0.6	0.19	0.029	0.008	0.091	0.199
Zambia	0.051	0.075	1.3	0.15	0.035	0.007	0.140	0.344
Niger	0.048	0.042	0.1	0.01	0.004	0.002	0.036	0.274
Gambia	0.048	0.014	0.1	0.05	0.010	0.001	0.047	0.192
Rwanda	0.043	0.008	0.5	0.02	0.008	0.003	0.028	0.162
Togo	0.04	0.031	0.4	0.13	0.029	0.015	0.097	0.256
Mozambique	0.039	0.005	0.3	0.01	0.003	0.001	0.017	0.133
Mali	0.035	0.010	0.1	0.02	0.008	0.003	0.029	0.169
Zaire	0.033	0.008	0.6	0.06	0.020	0.006	0.043	0.162
Central Afr. Rep.	0.033	0.011	0.3	0.03	0.011	0.004	0.035	0.178
Uganda	0.032	0.004	0.5	0.03	0.005	0.003	0.025	0.129
Malawi	0.03	0.014	0.8	0.05	0.026	0.004	0.049	0.192
Burma	0.029	0.013	0.8	0.20	0.079	0.019	0.090	0.195