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Rapid Catch–Up, Fast Convergence, and Persistent Underdevelopment*

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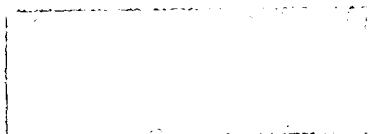
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Abstract

A theory of growth in underdeveloped countries must explain both rapid catch–up and persistent underdevelopment. I propose and <u>test</u> the following theory: Low barriers to technology transfer have enabled rapidly growing underdeveloped countries to adopt the <u>more human and physical capital intensive production methods</u> of more developed countries; they are now <u>converging fast</u> to long run income levels between 50 and 100 percent of US long run income. The return to investing in stagnating underdeveloped countries is low because their barriers to technology transfer translate into <u>less human and physical capital intensive production methods</u>.

1 Introduction

I propose the following theory of rapid catch-up and persistent stagnation among underdeveloped countries: Low barriers to technology transfer have enabled rapidly growing underdeveloped countries to adopt the more human and physical capital intensive production methods of more developed countries; they are now converging fast to long run income levels between 50 and 100 percent of US long run income. The return to investing in stagnating underdeveloped countries is low because their barriers to technology transfer translate into less human and physical capital intensive production methods.[1]

Using data on 62 countries over a period of 25 years, I find empirical support for the two main building blocks of this theory: Less developed countries use production methods that are less human and physical capital intensive at all factor prices and countries converge rapidly to their long run income level. I estimate an average rate of convergence of 6 percent annually using a very simple but consistent estimator. This estimate triples the 2 percent estimate by Barro and Sala-i-Martin (1992) and Mankiw, Romer, and Weil (1992). The difference can be explained by the downward bias of their estimators.[2]

Miracle Accounting

What explains rapid growth in Japan or Korea for example? I argue that lower barriers to technology transfer have enabled Japanese and Korean firms to adopt more capital intensive production methods. This brought Japanese and Korean long run income levels closer to the US level. Fast convergence to higher long run income levels explains their rapid growth.

"The Miracle of Japanese Growth" can be accounted for by Japan converging to the same long run per capita income as the US. This can be seen by comparing Japan's actual

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1. Relatively less capital intensive production methods use capital relatively less intensively at all factor prices.
2. The bias arises because they do not control for differences in initial total factor productivity. This forces their estimators to attribute all differences in growth rates to capital. See footnote 7 for an explanation.

growth rate with the growth rate predicted by the model proposed in this paper. According to the proposed model, fast growth of per capita income in Japan relative to the US $\hat{Y}_{JP} - \hat{Y}_{US}$ could have been due to two factors: Starting behind, a low initial level of per capita income relative to the US Y_{JP}/Y_{US}; or forging ahead, a high long run level of per capita income relative to the US Y_{JP}^*/Y_{US}^*:

$$\hat{Y}_{JP} - \hat{Y}_{US} = \text{Rate of Convergence} \times (\log (Y_{JP}^* / Y_{US}^*) - \log (Y_{JP} / Y_{US})).^3 \qquad (\clubsuit)$$

Japanese per capita income went from 25 percent of the US level in 1958 to 80 percent of the US level in 1990. It had probably never reached 25 percent of the US level before that: It stood at 23 percent in 1900 and 24 percent in 1929.[4] Applying ($\clubsuit$) with <u>the estimated rate of convergence of 6 percent</u> from 1958 to 1990 and assuming that Japan is converging to the same long run income as the US exactly matches the actual average Japanese growth rate over the period (figure 1a).[5] Korean per capita income rose from 10 percent of US per capita income between 1953 and 1968 to 40 percent of US per capita income in 1990. Similar calculations account for the Korean miracle by Korean long run per capita income rising from 10 percent to 60 percent of US long run income.[6] The proposed theory will be consistent with fast convergence.[7]

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3. This formula corresponds to a log-linear approximation of the growth rate at the balanced growth equilibrium. The same formula applies to the neoclassical growth model, see Mankiw, Romer, and Weil.

4. The data before WW II is from Maddison (1989) and after WW II from the Penn World Tables, Mark 5.6.

5. The same calculations, with the same data sources, yield that Italy is converging to more than 80 percent of US long run income and Germany to more than 90 percent of US long run income. See figures 1b –1c.

6. To account for the Japanese and Korean miracle with an estimated rate of convergence of 2 percent, Japanese and Korean long run income would have to be, respectively, 3 and 4 times the US level. Rapid growth in Canada, Finland, France, Norway, the Southern European countries and the Asian Tigers (except Korea) could only be explained by long run income levels between 120 percent (Germany, Italy, Portugal, and Spain) and 4 times (Hong-Kong) US long run income. With a rate of convergence of 6 percent, these values are between 50 percent and 110 percent (Hong-Kong).

7. The formula in ($\clubsuit$) can also be used to explain why <u>the estimators in Barro and Sala-i-Martin and Mankiw, Romer, and Weil are biased downwards</u>. According to the neoclassical growth model, Y_i^* / Y_{US}^* is determined by two factors: First, all economic policies in the two countries which affect physical and human capital accumulation; second, <u>initial</u> differences in total factor productivity A, i.e.

$$Y_i^* / Y_{US}^* = (A_i / A_{US}) \times f(\text{all policies which affect cap. accmlt.}).$$

Barro and Sala-i-Martin and Mankiw, Romer, and Weil estimate the rate of convergence in ($\clubsuit$) controlling for $\log f(\circ) - \log(Y_i / Y_{US})$ only (I will call this quantity $CGap_i$): <u>They do not control for the initial differences in</u>

Figure 1a: Japan after WW II. It took Japan approximately 13 years to reduce the (relative) gap with the US to the prewar level. Since 1958, Japan has been converging fast—at the rate of 6 percent annually—to the same long run income as the US.

Figure 1b: Germany after WW II. It took Germany approximately 11 years to reduce the (relative) gap with the US to the prewar level. Since 1956, Germany has been converging at the rate of 6 percent annually to 90 percent of US long run income.
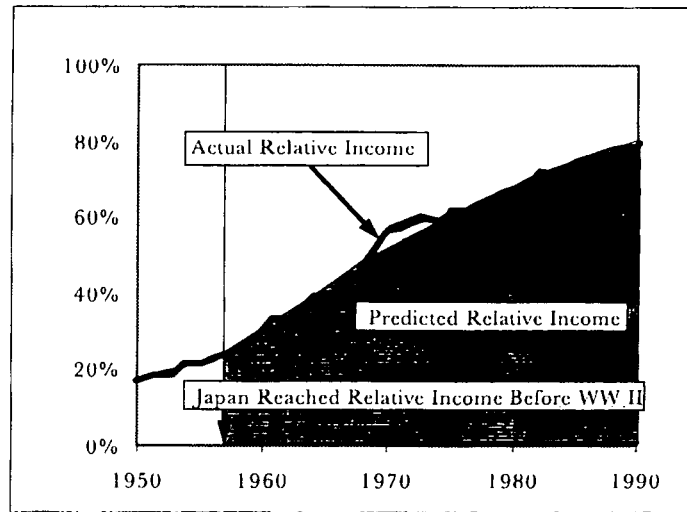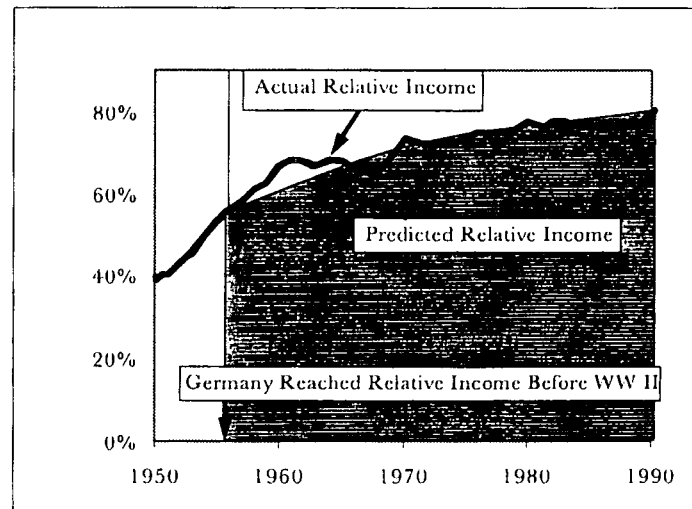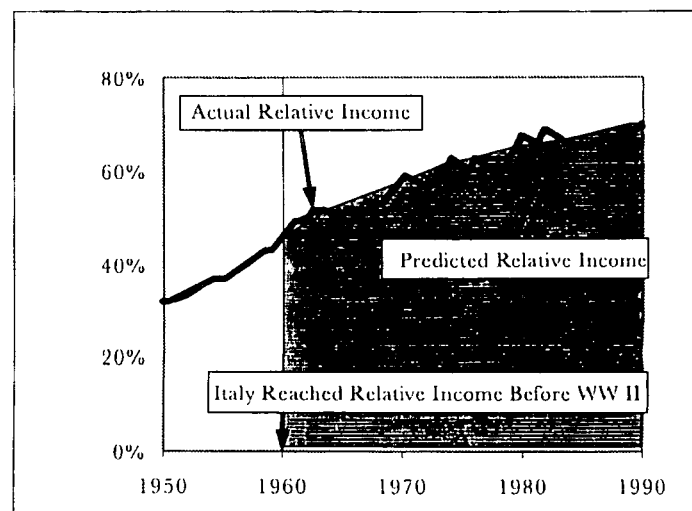

Figure 1c: Italy after WW II. It took Italy approximately 15 years to reduce the (relative) gap with the US to the prewar level. Since 1960, Italy has been converging at the rate of 6 percent annually to 80 percent of US long run income.

... and Barriers to Technology Transfer

Can lower barriers to technology transfer explain the large increase in Korean long run income? I argue that lower barriers to technology transfer induce shifts towards more human and physical capital intensive production methods. Such shifts can explain large long run income effects of relatively minor reductions in barriers to technology transfer.

The shift towards more human capital intensive sectors in Korea is easy to illustrate, even if we leave aside the very large shift from agriculture to manufacturing and concentrate on the composition of the manufacturing sector only:[8] In 1960, 25 percent of Korean value added in manufacturing was in the textile and leather sector and 10 percent in the machinery and metal product sector. By 1987, these shares were 15 percent and 30 percent respectively. There is no Korean data on the skilled labor share in these sectors, but Kahn and Lim (1994) estimate the skilled labor share in the corresponding American two digit industries at 18 and 35 percent respectively.[9] Below, I develop a more precise way to compare the human and physical capital intensity of production methods across countries and stages of development (section 4B). I find that more developed countries use relatively more capital intensive production methods.

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total factor productivity (due to different technologies, institutions, laws, resource endowments, histories, luck...). It is straightforward to show that this implies that their estimates converge to:

$$\boxed{\text{DownB. Estimate} = \text{Rate of Convergence} \times (\text{Var}(CGap_i) - \text{Cov}(\log(Y_i / Y_{US}), \log(A_i / A_{US}))) / \text{Var}(CGap_i)}$$

which is smaller than the true rate of convergence because countries with relatively higher initial total factor productivity will have relatively higher initial income per capita, i.e. $\text{Cov}(\log(Y_i / Y_{US}), \log(A_i / A_{US})) > 0$.

8. I will use production methods and sectors in an interchangeable way. See footnote 27 for an explanation.

9. Data on Korea from Song (1990). The American two digit sectors are "Apparel and Other Textile Products" and "Machinery Except Electrical." Similar changes took place in Hong Kong and Singapore: they moved from mainly producing textiles in 1950 to mainly producing electronics; see Chen (1979). Kahn and Lim have estimated the skilled labor share in the American "Electric and Electronic Equipment" industry as 40 percent. Thailand and Malaysia are undergoing a similar transformation. In 1990, computers and parts overtook garments as the main Thai export to the US, and after 1975, Malaysian value added in electronics grew at the rate of 16 percent annually compared with the 7 percent growth of value added in textiles (UNIDO (1991 and 1992)). The Industrial Revolution in Germany was also accompanied by a shift towards more human capital intensive sectors. In 1846, textile production employed about 22 percent of the work force and machinery about 9 percent. By 1913 the role of these sectors for employment was reversed. In 1933, the production of textiles employed 2 skilled workers for every 10 unskilled workers, while the production of machinery employed 18 skilled workers for every 10 unskilled workers; see Lee (1978).

How can lower barriers to technology transfer translate into large long run income effects? Part of my argument can be illustrated graphically using an example with two sectors. Suppose that workers in a small open economy can earn income in two sectors; that earned income increases with the worker's human capital H and hours worked L; that earned income is equal to LH^{α} in the first sector and LH^{a} in the second sector; and that the first sector is relatively more human capital intensive $\alpha > a$. Let workers decide how much to invest in human capital and in which sector to work. What will be their level of human capital and which sector will they work in? A partial answer is that workers may end up working with a low level of human capital in the less human capital intensive sector or a high level of human capital in the more human capital intensive sector. See figure 2a; The figure also illustrates the optimal level of human capital in each sector, assuming a constant opportunity cost of human capital investment.

Assume also that average labor productivity in the two sectors increases with technology transfer from abroad and that technology transfer is subject to a fixed cost. What happens to average labor productivity in the two sectors? I argue that the relatively low average level of human capital in less human capital intensive sectors induces relatively less technology transfer (section 4A). This decreases labor productivity in the less human capital intensive sector relative to the more human capital intensive sector (figure 2b).

Finally, I argue that economic policies which increase the cost of technology transfer decrease wages in both sectors. They shift the human capital/wage schedules in both sectors down (figure 2c and section 4A). More importantly, I also argue that they decrease wages relatively more in relatively more capital intensive sectors (section 4B): They therefore decrease the human capital/wage premium; fewer workers find it worthwhile to accumulate human capital in order to work in the more human capital intensive sector; and production shifts towards less human capital intensive sectors.[10] This is illustrated in figure 2c where the cost of technology transfer is so high that all workers end up working in the less capital intensive sector. Policies that cut the cost of technology transfer have the

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10. This will not imply that the human capital/wage premium is generally lower in underdeveloped countries.

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Figure 2a: Workers supply a fixed amount of labor L^F. They may end up working in the less human capital intensive sector with a low level of human capital or in the more human capital intensive sector with a high level of human capital. H^{IC} is the minimum level of human capital for workers to find it worthwhile to work in the more human capital intensive sector. H^* denotes the optimal level of human capital in the two sectors given the constant opportunity cost of investment; H^* is the point where the opportunity cost of investment is equal to the marginal productivity of human capital (both are equal to the slope of the tangent at H^*). At H^* the productivity of human capital investment is the same in the two sectors.
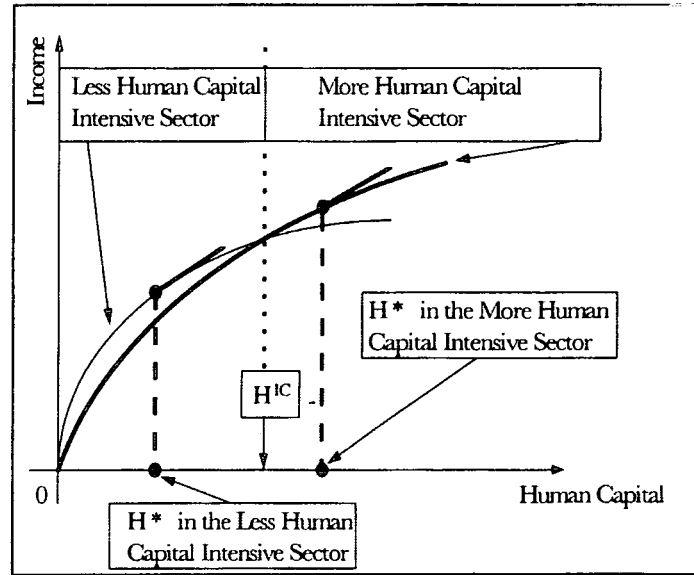
Figure 2b: Technology transfer magnifies the differences in average labor productivity across sectors. This is because—other things being equal—the profits from transferring technologies increase with the workers' human capital. This increases average labor productivity in the more human capital intensive sector relative to the less human capital sector. (The wage schedule in the less human capital intensive sector is shifting down because I take the symmetric situation in figure 2a as a starting point.)
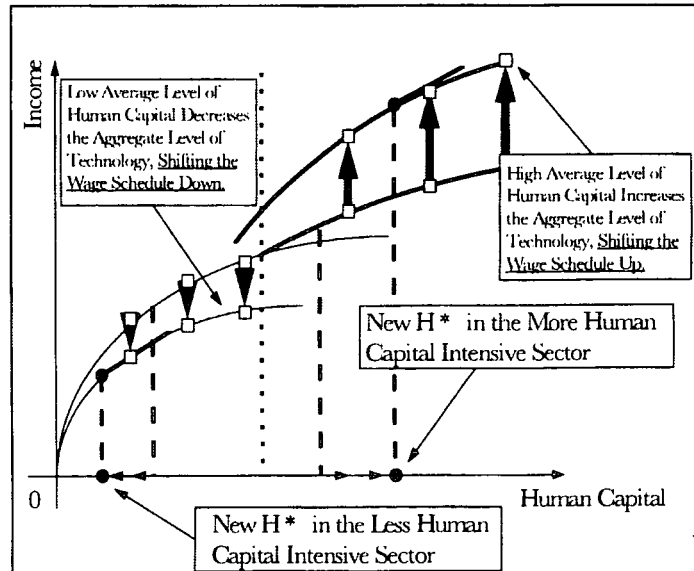
Figure 2c: High barriers to technology transfer shift the human capital/wage schedules down in both sectors, but relatively more in the more capital intensive sector. The latter shifts H^{IC} (defined in figure 2a) to the right, and the former shifts the H^* (the optimal level of human capital in each sector, also in figure 2a) in both sectors to the left. In particular, high barriers shift the H^* in the more human capital intensive sector below H^{IC}. This is why no-one finds it worthwhile to invest in human capital in order to work in the more capital intensive sector.

Figure 2d: Low barriers to technology transfer shift the human capital/wage schedules up in both sectors, but relatively more in the more capital intensive sector. The latter shifts H^{IC} (defined in figure 2a) to the left, and the former shifts the H^* (the optimal level of human capital in each sector, also in figure 2a) in both sectors to the right. In particular, low barriers shift the H^* in the less human capital intensive sector above H^{IC}. This is why everyone finds it worthwhile to invest in human capital in order to work in the more capital intensive sector.

opposite effect. They increase wages in both sectors (section 4A) but relatively more in relatively more capital intensive sectors (section 4B): The human capital/wage premium increases, shifting production towar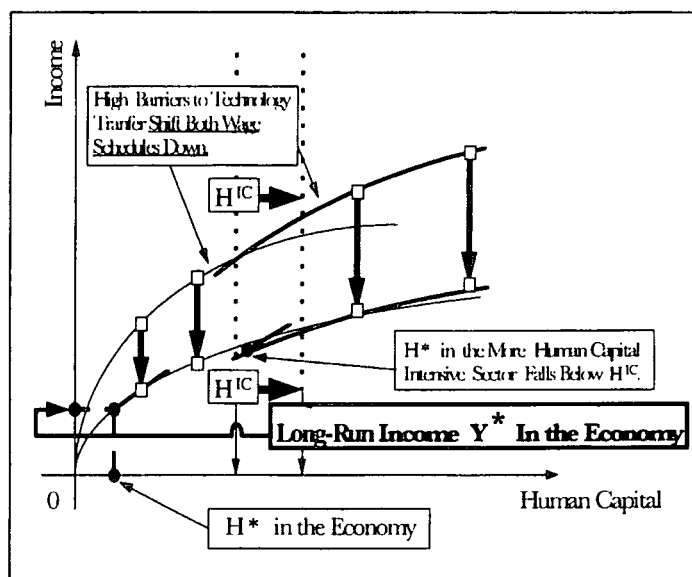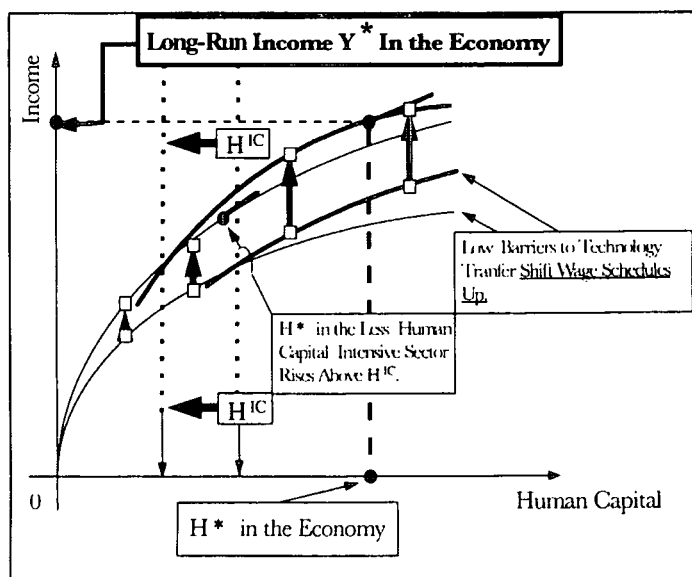ds more human capital intensive sectors. This is illustrated in figure 2d where the cost of technology transfer is so low that all workers end up working in the more human capital intensive sector.

Summarizing: Reducing barriers to technology transfer eventually takes the economy from the situation illustrated in figure 2c to the situation illustrated in figure 2d with large effects on long run income. Policies with minor effects on labor productivity in each sector may have large effects on labor productivity in the economy because they shift the sectoral structure of production towards more capital intensive sectors.[11]

This example also illustrates why countries may become trapped into persistent under-development; or—to put it differently—why the productivity of investment may be low in underdeveloped countries: They are locked into less capital intensive sectors by high barriers to technology transfer. This is why their low capital intensity does not necessarily translate into a high productivity of capital investment (figure 2a and figure 2c). Figure 3 presents evidence on the low productivity of investment in underdeveloped countries.

The paper is organized in the following way. Section 3 describes the model. Section 4 reduces the (disaggregate) model of section 3 to a simple (aggregate) neoclassical growth model with endogenous technology—the "reduced model"—and uses this reduced model to develop the main argument. Section 4A determines the long run income distribution, develops a very simple but consistent estimator of aggregate returns to scale to capital, and estimates aggregate returns to capital using data on 62 countries over 25 years. I find strong decreasing aggregate returns to scale to capital. Strong decreasing aggregate returns to scale translate into an average annual rate of convergence of 6 percent. But strong decreasing aggregate returns to scale also imply that large differences in barriers to technology transfer translate into minor differences in long run income. To explain fast

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11. A two sector model is necessary to capture large income effects due to shifts in the structure of production. A one sector model would only capture the minor effects in each sector.
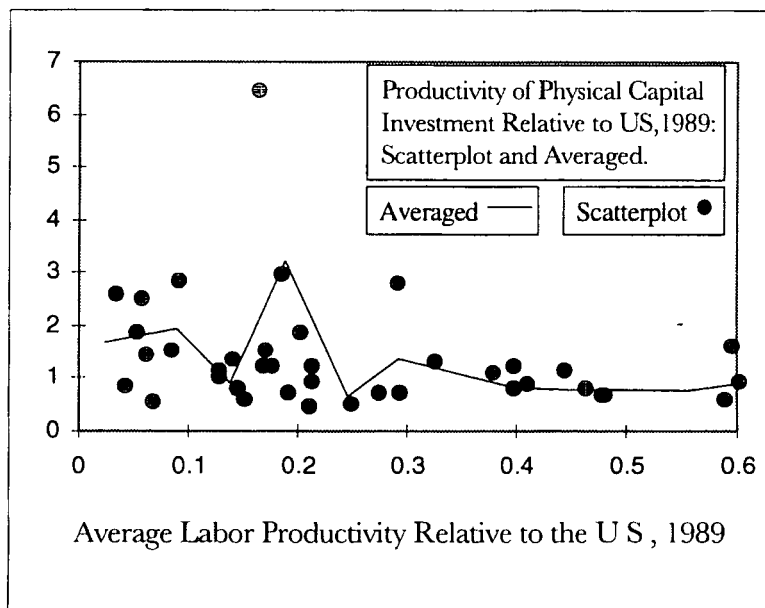
Figure 3: Productivity of investment in 38 countries. The productivity of investment is relative to the US and the average labor productivity is also relative to the US. Data on average labor productivity and capital per worker from the Penn World Tables, Mark 5.6. The calculations make use of two assumptions that are usually made in the neoclassical growth model: The first assumption is that the production function is Cobb-Douglas; this implies that the productivity of investment can be calculated as

$$(\text{Elasticity of Output w.r.t. Capital}) \times (\text{Output / Capital}).$$

The second assumption is that the elasticity of output with respect to the factors of production is the same across countries; this implies that the elasticity of output with respect to capital drops out of the calculation because the figure plots the productivity of investment in poor countries relative to the US. The solid line averages the data in 5 percent intervals.

convergence and large long run income effects of relatively minor cuts in barriers to technology transfer, I extend the model to include two sectors—one more human and physical capital intensive at all factor prices than the other—in section 4B. I show that relatively minor cuts in barriers to technology transfer translate into large long run income effects because they shift the structure of production towards more capital intensive sectors. I test for differences in the capital intensity of production methods using the same data as in section 4A and find that a larger amount of capital per worker translates into production methods which are more capital intensive at all factor prices. Section 5 shows that the (stylized) transition towards more human capital intensive sectors can match the increasing investment rates and accelerating growth rates observed in the newly industrialized Asian economies. Section 6 concludes and the appendix contains all proofs. I discuss some of the related literature next.

2 Related Literature

Over the last thirty years, underdeveloped countries have on average failed to catch up with developed countries, and the gap between underdeveloped countries and developed countries has increased (figure 4). This has raised the question whether the neoclassical growth model overstates the opportunities for underdeveloped countries to catch up, and in particular whether the neoclassical growth model overstates the productivity of investment in poor countries. All the work addressing this question is related to this paper. The most influential contributions are by Lucas (1988), Rebelo (1991), and Romer (1986, 1987, and 1990), who argue that returns to investment in poor countries are low because the lack of physical capital goes together—in theory and in the data—with an unskilled and uneducated labor force and inferior technologies, and that strong complementarities between physical capital, human capital, and technology depress the return to investment. (Lucas, Rebelo, and Romer formalize this idea in models with constant aggregate returns to scale to accumulable factors.[12]) This paper is motivated by their work. But I will argue

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12. There is a simple relationship between the "strength of complementarities among accumulable factors" and the "returns to scale to accumulable factors." It is straightforward to show that $F(0) = 0$,

Figure 4a: Poor countries have not caught up on average. The figure is based on per capita income data for 114 countries from the Penn World Tables, Mark 5.6. The Lorenz-Curve plots the share of countries against their per capita income shares (the dark area is equal to the Gini-Coefficient in 1960). The Modified Lorenz-Curve plots the per capita income shares using the 1960 country ranking, not the 1989 country ranking. If poor countries had caught up on average, then the Modified Lorenz-Curve should be above the Lorenz-Curve for poor countries.
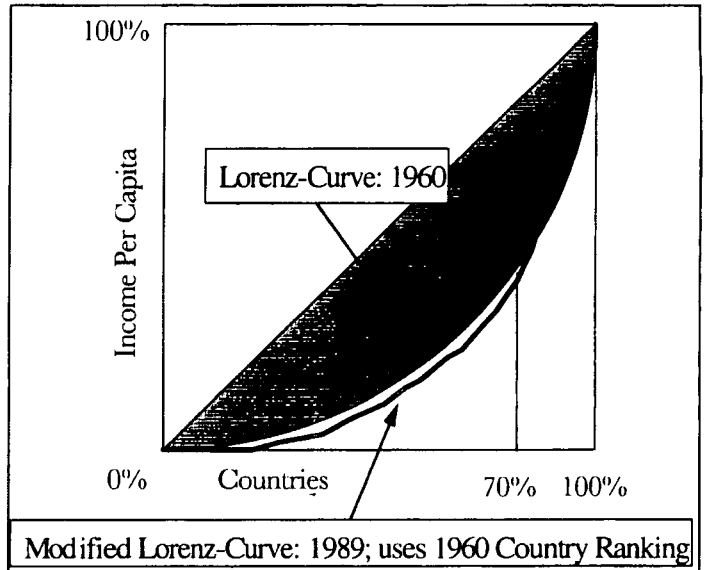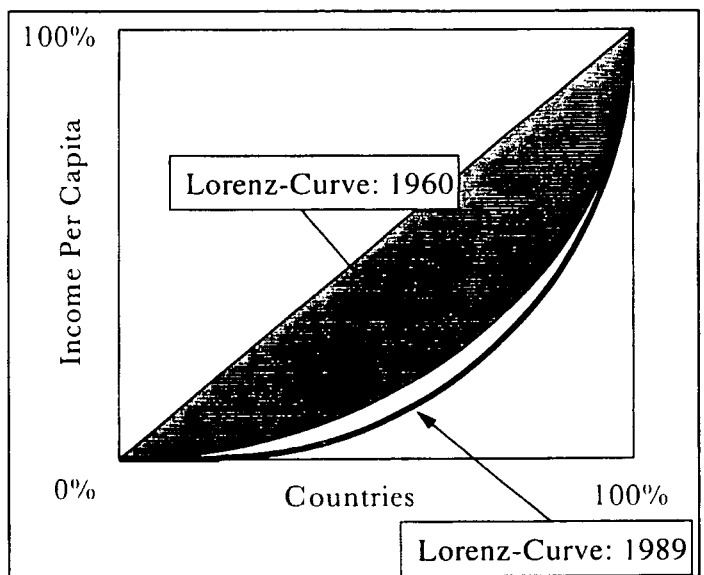

Figure 4b: Rising world income (per capita) inequality. The figure is based on per capita income data for 114 countries from Penn World Tables, Mark 5.6. The dark area corresponds to the Gini-Coefficient in 1960.

that the return to investing in stagnating underdeveloped countries is low because barriers to technology transfer translate into less human and physical capital intensive production methods and that underdeveloped countries can catch up fast if they adopt economic policies similar to the policies of developed countries. There are many other important papers with related ideas which will be easier to discuss later.

3 Description of the Model

The model consists of many partially open economies. The final goods of each economy are traded internationally. Firms producing final goods employ labor and a variety of capital goods. Labor is immobile. But capital goods are traded internationally. They are produced and supplied by capital goods firms. These firms decide in which economies to produce their goods, in which economies to supply their goods, and what prices to charge. To begin supplying capital goods in any particular economy they need to make an initial fixed investment. This investment results in a fixed cost which I attribute to technology transfer.

Fixed Costs of Technology Transfer

Fixed costs of technology transfer—interpreted broadly—include R&D expenditures required to adapt capital goods to the infrastructure, labor force, laws, regulations, customs, and particular demand and supply conditions of the economy, as well as fixed costs of setting up a marketing and distribution network. The slow diffusion of hybrid corns across the US can—for example—be explained by fixed costs of marketing, distributing, and especially adapting hybrid corns to specific regions (Griliches (1957)). American and European producers of blueprints, machinery, and equipment used in the production of palm oil, paper, matches, cement, particle boards, jute, and bricks and tiles

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$\partial F(cQ)/\partial Q = c^{-(1-\theta)}\partial F(Q)/\partial Q$ for all $Q \in \Re_+^N$, $c \geq 0$ is equivalent to $F(cQ) = c^\theta F(Q)$ for all $Q \in \Re_+^N$, $c \geq 0$. Interpreting Q as a vector of accumulable production factors and $F(\circ)$ as a production function, "aggregate returns to scale to accumulable factors" are equal to θ (I assume $0 \leq \theta \leq 1$). The "strength of complementarities" is captured by $1 - \theta$: $1 - \theta$ is the increase (in percent) of the marginal product of any single accumulable production factor if all accumulable factors decrease by 1 percent. The smaller $1 - \theta$, the "stronger the complementarities" among accumulable factors: Complementarities among accumulable factors are strongest if there are constant aggregate returns to scale to accumulable factors.

customize their products to the available raw materials; to do so they first study the materials and perform tests (Manual of Industrial Project Analysis (1972)). The first glazing machines used in the Italian Ceramic Tile Industry were adapted by German producers from equipment originally designed for the food industry; later, the firing equipment was adapted to work with the relatively cheap red clay available locally (Porter (1990)). The need for adaptation is especially evident for computer hardware and software. For hardware companies to sell their products in the Ukraine—for example—they must adapt keyboards and drivers to the Cyrillic alphabet; software companies need to translate handbooks and programs into Ukrainian; spreadsheet suppliers must additionally face the substantial costs of changing decimal points to decimal commas; and suppliers of financial packages need to further add the costs of incorporating the available financial options, the prevalent accounting practices, and the latest financial regulations and tax laws. This is one reason why many software and hardware companies set up subsidiaries in different countries. In Spain, Fujitsu España adapts and provides services for Japanese Fujitsu computers and Microsoft Iberica adapts, markets, and distributes American Microsoft software. Additional fixed costs stem from having to set up services which must often be provided by equipment producers: design, installation, maintenance, repair, replacement, training of personnel, and temporary support. In many countries the fixed cost of technology transfer includes taxes, permits, bribes, or some other similar costs of doing business; see De Soto (1989) for estimates of such costs in Peru and Ekpo (1979) for Sub-Saharan Africa.

Capital and Final Goods Production

Capital goods firms finance fixed costs of technology transfer by issuing shares in international capital markets. Denoting the total value of outstanding shares with v and operating profits with π, arbitrage ensures that the real rate of return to holding shares is equal to the real interest rate in international capital markets r',

$$(\pi + \dot{v}) / v = r'. \tag{1}$$

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All prices and profits are in terms of final goods. Share prices and profits refer to the operations of a particular firm in a particular economy: IBM de Mexico for example; but indices for different firms and different economies will generally be suppressed. Capital goods firms produce and adapt capital goods using final goods only. The fixed initial investment consists of F units of final goods; the production of one unit of any capital good requires u units of final goods.

Final goods firms use a variety of different capital goods and qualities of labor for production. Any variety $M \equiv [0, M]$ of capital goods employed yields a flow of productive services according to

$$k = \left(\frac{1}{\Lambda} \int_M \kappa_i^{1/\mu} \, di \right)^{\mu}, \tag{2}$$

where $\{\kappa_i | i \in M\}$ denotes the quantities of different specialized capital goods employed; Λ denotes an index of exogenous technology; and $-\mu / (\mu - 1)$ the elasticity of substitution between any pair of capital goods. I assume that capital goods are imperfect substitutes $\mu > 1$. It is well understood by now that imperfect substitutability among capital goods in (2) will lead to endogenous total factor productivity growth because growth accounting generally identifies the resale value of the capital stock but not the host of different specialized capital goods employed (Romer (1987)). The endogenous supply of specialized capital goods in each economy will therefore become the source of endogenous differences in total factor productivity.

Capital goods firms adapt and supply different capital goods to different economies. Final goods firms employ only those capital goods which have been adapted and are supplied to the economy where they produce. This is because final goods producers cannot recoup fixed costs of technology transfer in competitive international final goods markets. The assumption that no single final goods producer can recoup the costs of having a software package translated, adapting equipment to the locally available raw materials, setting up a parts distribution network, or hiring a full time consultant from their supplier to integrate machinery into the production process appears reasonable in many cases. No

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single Alabaman farmer paid for the development of Alabaman hybrid corn, and equipment for the production of palm oil or ceramic tiles is sold to a large number of small competitive firms in West Africa and Italy (Porter (1990)). It is the capital goods suppliers who judge the profitability of the market and make a decision on whether to incur the fixed cost necessary to transfer their particular equipment. This may be because the capital good is covered by an enforceable patent or because the cost of adaptation is lower for capital goods producers who already know about the underlying design and production process. Capital goods producers may also have a better understanding of the potential applications of the equipment across different firms and industries or be in a better position to diversify the risk from failed adaptations.

Final goods firms may also use different qualities of labor. The quality of labor is summarized by an index H which takes values in $\mathbf{H} \equiv [0, \infty]$. It will often be convenient to measure the quality of labor relative to the index of exogenous technology $h \equiv H / \Lambda$. Different qualities of labor and capital goods translate into output according to the production technology

$$y = \int_H \left(\Lambda h^A k(h)^B l(h)^{1-B} \right) n(h) dH ; \qquad (3)$$

where y denotes the total amount of final goods produced, $l(h)$ hours per worker by workers with human capital h, $k(h)$ services from capital goods $\{\kappa_i(h) | i \in M\}$ employed with each worker with human capital h, and $n(h)$ the number of workers with human capital h. This formulation implies constant returns to capital and hours and constant returns to the size of the work force. I also assume decreasing returns to capital $A + B < 1$ and that final goods firms may differ in A and B, i.e. the intensity with which they use human capital and physical capital at the same factor prices.

Each capital good is produced by a different firm. Producers of capital goods set their rental prices R_i in each economy to maximize operating profits given the prices set by their competitors R_{-i}, $-i \equiv M / \{i\}$ and the distribution of human capital in the labor force $N(H)$. They finance production in international capital markets. Denoting the rate of

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depreciation of final goods used in production with δ and the tax on operating profits in the particular economy with τ_π, after-tax operating profits are

$$\pi_i = (1 - \tau_\pi)((R_i - (r' + \delta)u)\,\kappa_i(R_i, R_{-i}, N(H))); \tag{4}$$

where $r' + \delta$ is the user cost of capital and $\kappa_i(R_i, R_{-i}, N(H))$ describes aggregate demand for capital goods as a function of capital goods prices and the distribution of human capital in the economy. Because of the constant elasticity of substitution between capital goods in (2), the price elasticity of aggregate demand is independent of the prices set by competitors and the distribution of human capital in the economy. Combined with the constant marginal cost of production, this implies that profit maximizing rental prices are equal to a constant markup over the marginal cost of production $R_i = \mu(r' + \delta)u$. I will set $u = 1 / \mu$. This implies that the rental price of any capital good is equal to capital goods producers' user cost of capital $R_i = r' + \delta$ and discounted rental income equal to unity $P_i = 1$. I assume that capital goods firms require final goods firms to pay $P_i = 1$ upfront and that final goods firms finance capital goods in national capital markets.[13]

Capital goods firms adapt and supply their blueprints, machinery, and equipment to a particular economy only if they expect discounted profits v to exceed the fixed cost of technology transfer. They are price takers in the labor markets and therefore make their entry decisions taking current and future human capital/wage schedules $\{w(H,t)\,|\,H \geq 0,\ t \geq 0\}$ as given—but they may contract to coordinate entry with suppliers of other capital goods. Because I assume free entry of international capital goods producers into national markets, competition will drive pure profits to zero, $v = F$.

Human Capital and Capital Markets

The population of each economy consists of a large number of infinitely long lived families. Families supply one unit of labor inelastically. They decide how much of their current income to consume and how much of it to invest into national capital markets or

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13. An alternative formulation would be that final goods firms purchase capital goods and capital goods firms guarantee to repurchase (used) capital goods at the same relative price.

human capital. A family with human capital H investing an amount of final output I into improving skills or education accumulates human capital according to

$$\dot{H} = vI - \delta H;$$ (5)

where v can be interpreted as the efficiency of the education system or the cost of human capital relative to the final output; δ denotes the rate of depreciation of human capital. (Dotted variables denote derivatives with respect to time). I assume that families in the same economy start with the same level of human capital and that they cannot borrow to invest in human capital. Subject to these constraints, families maximize dynastic welfare $\int_0^\infty e^{-\rho t} U(C(t))dt$ where C denotes consumption of final goods and $U(C)$ is a constant elasticity of intertemporal substitution utility function $U(C) = (C^{1-1/\sigma} - 1)/(1 - 1/\sigma)$ with $\sigma \geq 0$.

National capital markets are perfectly competitive. Banks borrow from households and lend to final goods firms at real interest rate r. I assume that the banks of some economies can refinance in international capital markets at the real interest rate r' while other national capital markets are closed. Arbitrage between the international capital market and economies with open capital markets implies $r' = r$.

4 Rapid Catch-Up and Persistent Underdevelopment

Can high barriers to technology transfer explain persistent underdevelopment, and can falling barriers to technology transfer explain rapid catch-up? To answer these questions I reduce the rather complicated (disaggregate) model in section 3 to a simple (aggregate) neoclassical growth model with endogenous technology. I use the "reduced model" to determine the long run income distribution and to identify and estimate aggregate returns to scale to capital. My findings suggest strong decreasing aggregate returns to scale to capital. Strong decreasing aggregate returns to capital imply fast convergence of actual income to long run income: The average annual rate of convergence is approximately 6 percent. This confirms that growth miracles may be accounted for by fast convergence to long run income levels between 50 and 100 percent of US long run income. But strong

decreasing aggregate returns to capital also imply small long run income effects of large reductions in barriers to technology transfer: Only very high barriers to technology transfer can explain persistent underdevelopment, and only very large cuts in barriers to technology transfer can explain the large increase in long run income levels necessary to account for growth miracles. This is because the reduced model cannot capture structural changes towards sectors which are more human and physical capital intensive at all factor prices. To explain fast convergence and large long run income effects of relatively minor differences in barriers to technology transfer, I extend the reduced model to two sectors—one more human and physical capital intensive at all factor prices than the other. Finally, I test for differences in the capital intensity at all factor prices and find that countries with more capital per worker use capital more intensively at all factor prices.

Endogemous Technology im a Neoclassical Growth Model

The main virtue of the disaggregate model described in the section 3 is that it readily reduces to a simple aggregate neoclassical growth model with endogenous technology. In particular, the structure of production implies that output per worker Y can be written as a function of the worker's human capital H, the value of capital goods employed $K = PM\kappa$, and a residual Θ which can be interpreted as the aggregate level of technology

$$Y = (Hl)^A K^B (\Theta l)^{1-A-B}. \tag{6}$$

The efficiency of hours l is determined by two factors: the individual level of human capital—which depends on the family's past investment decisions—and the aggregate level of technology—which depends on the exogenous index of technology Λ and the endogenous variety of capital goods M supplied in the economy

$$\Theta = M^{B'} \Lambda^{1-B'}, \tag{7}$$

with $B' \equiv (\mu - 1)B / (1 - A - B)$. The exogenous index of technology Λ captures technological improvements which are not embodied in capital or labor and spread rapidly across economies: I assume that Λ grows at the same rate λ across all economies. The variety of capital goods supplied in the economy M is endogenous and depends on the

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technology transfer decisions of capital goods firms. In particular, foreign firms using foreign resources can increase the aggregate level of technology available in any economy by adapting and supplying capital goods. Capital goods firms with R&D facilities in Europe—for example—develop and adapt equipment for West African palm oil producers (Manual of Industrial Project Analysis (1972)). They also raise capital in international markets to set up distribution networks or transfer consulting staff to branch offices. Many European, Japanese, and US companies in steel making, chemical, pharmaceutical, and petroleum refining industries have made technology transfer their main business (Robock and Simmonds (1989)).

4.A Technology Transfer, Income, and Fast Convergence

The most intuitive way to think about the reduced model is by splitting it into factors which determine the human and physical capital intensity—conditional on the aggregate level of technology in (7), and factors which determine the aggregate level of technology. The first part reduces to a neoclassical growth model. The aggregate level of technology is determined by the technology transfer decisions of capital goods firms.

A Neoclassical Growth Model

Final goods firms in the reduced model can be thought of as taking the aggregate level of technology Θ as given and demand capital K and labor of different qualities H until the net marginal product of capital has fallen to the national real interest rate,[14]

$$r + \delta = \beta (H / \Theta)^A (K / \Theta l)^{B-1} \tag{8}$$

and the marginal product of labor $\omega(H, l)$ has fallen to the market wage $w(H)$,

$$\omega(H, l) \equiv (1 - B)\Theta(H / \Theta)^A (K / \Theta l)^B \leq w(H) \tag{9}$$

with strict equality if the amount of labor demanded l is strictly positive. Households decide about human capital investment today by looking at the implied future increase in

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14. This follows from the demand for individual capital goods, taking into account that final goods firms demand the same quantity of all available capital goods and using the definitions of K and Θ.

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wages. They realize that final goods firms will employ more capital with better skilled and educated workers—the capital demand equation is

$$K / l = x^{1/B} H^{A''} \Theta^{1-A''},$$ (10)

where $A'' \equiv A / (1 - B)$ and x is some constant—and look at future wages as a function of the human capital and the aggregate level of technology only

$$w(H) = x(1 - B) H^{A''} \Theta^{1-A''}.$$ (11)

Households also realize that their individual human capital investment decisions will not affect the aggregate level of technology: The net private return to human capital investment is $v w_H(H, \Theta) - \delta = x v A (H / \Theta)^{-(1-A'')} - \delta$, which they set equal to the return they can earn on their savings rate r

$$v w_H(H, \Theta) = x v A (H / \Theta)^{-(1-A'')} = r + \delta.$$ (12)

Equations (8) to (12) summarize the neoclassical implications of the model.

Endogenous Technology

The level of technology Θ is determined by the technology transfer decisions of capital goods suppliers. Free entry of suppliers into national markets implies that the discounted value of profits will be equal to the fixed cost of entry in equilibrium $v = F$: At any time the latest supplier of new specialized capital goods expects to just break even given the current and future level of skills and education and the rate at which other capital goods suppliers enter. This free entry condition can be combined with arbitrage between debt and equity in (1) in order to obtain the quantity κ^* of each capital good supplied in the balanced growth equilibrium as a function of the fixed costs of entry, the taxes on profits, and the real interest rate r^*

$$\kappa^* = \mu F r^* / ((1 - \tau_\pi)(\mu - 1)(r^* + \delta)).$$ (13)

Determining the variety of capital goods supplied in the balanced growth equilibrium is now straightforward: Intuitively, the variety of capital goods available in an economy increases with the average level of skills and education of its labor force H_m (m for mean); a labor force which is better skilled and educated on average makes better use of capital goods, shifting aggregate demand for capital goods outwards and making it more

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profitable for producers to adapt and supply capital goods. This can be seen formally by substituting (7) and (13) into (8) and solving for the variety of capital goods supplied in the balanced growth equilibrium

$$M^* = sH_m^{A'} \Lambda^{1-A'},\tag{14}$$

where $A' \equiv A/(1-\mu B)$ and s is some constant. The implied aggregate level of technology Θ^* follows from substituting the balanced growth variety of capital goods in (14) into the definition of the aggregate level of technology in (7)

$$\Theta^* = qH_m^{A^*} \Lambda^{1-A^*},\tag{15}$$

where $A^* \equiv A'B'$ and q is some constant; (15) with $A^* > 0$ and (6) capture a mutually reinforcing relationship between technological progress and human capital accumulation which results in interdependencies between the individual and the average level of human capital.[15] More importantly, $A^* > 0$ also implies that aggregate returns to scale to capital $A + B + (1 - A - B)A^*$ exceed returns to scale to capital at the firm level $A + B$. In contrast to the endogenous growth literature (Lucas, Rebelo, and Romer for example), I assume throughout that there are decreasing returns to capital—not only at the firm level $A + B < 1$ but also at the aggregate level $A + B + (1 - A - B)A^* < 1$: I will explain large differences in income by differences in the sectoral structure of production—not by constant aggregate returns to capital.

Equilibrium

The balanced growth equilibrium can now be determined by combining the endogenous aggregate level of technology with the determinants of capital accumulation. Accounting for the endogenous aggregate level of technology in (12), and setting the return to human capital equal to $r^* + \delta$, yields the equilibrium level of human capital H^*

$$vw_H = evA(H^*/\Lambda)^{-(1-A')}(\kappa^*)^{-(1-A')B'/(1-B')} = r^* + \delta,\tag{16}$$

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15. Abramowitz (1970) and Nelson and Phelps (1966) emphasize the mutually reinforcing relationship between human capital accumulation and technological progress and Lucas (1988) the interdependencies between the individual and average level of human capital in the economy.

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where e is some constant.[16] Aggregate decreasing returns to capital lead to aggregate decreasing returns to human capital $A' < 1$ and hence to a unique solution for $h^* \equiv H^* / \Lambda$. This implies that the amount of human capital, the variety of capital goods supplied in (14), the aggregate level of technology in (15), the amount of physical capital in (10), and gross domestic product in (6) all increase at the same rate λ across all economies.

Equilibrium Income Distribution

It will be useful to start with the long run income distribution predicted by the neoclassical part of the reduced model:

$$Y^* = \Theta^* \left(\frac{vi_H}{\lambda + \delta} \right)^{\frac{A}{1-A-B}} \left(\frac{i_K}{\lambda + \delta} \right)^{\frac{B}{1-A-B}} , \tag{17}$$

determined as usual, where i_H and i_K denote the human and physical capital investment/gross domestic product ratios in the balanced growth equilibrium. This captures the neoclassical determinants of income—investment in human and physical capital. Accounting for endogenous technology Θ^* yields[17]

$$Y^* = \Lambda \left(\frac{F}{(1-\tau_\pi)} \right)^{\frac{-(\mu-1)B}{1-A-\mu B}} \left(\frac{vi_H}{\lambda + \delta} \right)^{\frac{A}{1-A-\mu B}} \left(\frac{i_K}{\lambda + \delta} \right)^{\frac{\mu B}{1-A-\mu B}} . \tag{18}$$

An endogenous aggregate level of technology implies that $AB(\mu - 1) > 0$. This changes the income distribution relative to (17) in two ways: First, the interplay between technological progress and capital accumulation increases the elasticity of output with respect to human and physical capital investment. Second and more importantly, fixed costs of technology transfer and taxes affect the balanced growth income distribution through the aggregate level of technology. This decreases income in countries with high fixed costs and taxes and raises income in countries with low fixed costs and taxes.

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16. The real interest rate in the balanced growth equilibrium is equal to $r^* = \rho + \lambda / \sigma$ which follows from the optimality condition for the consumption profile $\dot{C} / C = \sigma(r^* - \rho)$ and the fact that the rate of consumption growth is equal to λ in the balanced growth equilibrium.

17. Formally, the aggregate level of technology is related to taxes, investment rates, and average labor productivity by $\Theta^* = Y^{A^*} \Lambda^{1-A^*} ((i_K / (\lambda + \delta))((\theta i_H / (\lambda + \delta))^A ((1 - \tau_\pi) / F)^{(1-B)})^{A^*/A}$; (18) follows from solving this equation simultaneously with (17).

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Barriers to Technology Transfer, Returns to Scale, and Development

The natural next step would be to use data on the cost of technology transfer and taxes on operating profits together with data on investment rates and income in (18) to see whether barriers to technology transfer can explain large differences in income. But there is no such data. I therefore ask the opposite question: How large would barriers to technology transfer have to be to explain underdevelopment? To answer this question it is necessary to estimate aggregate returns to scale to capital $A + \mu B \equiv \Gamma$ in (18). This is because the elasticity of long run income with respect to barriers to technology transfer $F / (1 - \tau_\pi)$ is smaller than $-\Gamma / (1 - \Gamma)$: Estimating aggregate returns to scale Γ allows me to infer the largest possible long run income effect of differences in barriers to technology transfer.

There is a second reason why estimating aggregate returns to scale is crucial for the theory proposed in this paper. I have argued in the introduction that fast convergence is crucial for explaining rapid growth. It is straightforward to check that the "rate of convergence" in (♣) is equal to $(1 - \Gamma)(\lambda + \delta)$ in the reduced model,

$$\text{Rate of Convergence} = (1 - \Gamma)(\lambda + \delta):^{18}$$

Estimating aggregate returns to scale to capital allows me to infer the average rate of convergence to the long run equilibrium distribution and hence the growth effects of lower barriers to technology transfer.

Estimating Aggregate Returns to Scale to Capital

A simple theoretical restriction of the neoclassical growth model yields a consistent estimator of aggregate returns to scale to capital.[19] The idea is easiest to explain in the

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18. In the neoclassical model: Rate of Convergence $= (1 - \Gamma)(\lambda + \delta + n)$ where n denotes the rate of population growth, see Mankiw, Romer, and Weil for a derivation. The derivation is exactly identical for the reduced model presented at the beginning of section 4, with the only difference that there is no population growth.

19. Mankiw, Romer, and Weil use data on physical and human capital investment rates to estimate aggregate returns to scale assuming that income distribution in 1985 is close to the long run income distribution in (17). This estimator will overstate aggregate returns to scale (understate the rate of convergence) if technology is endogenous, i.e. $\mu > 1$. This is easily seen from (18): Suppose—for example—that all tax rates are the same: $\tau_K = \tau_L = \tau_\pi = \tau$ in each economy but that tax rates differ across

reduced framework. Suppose that all economies with open capital markets are in their balanced growth equilibrium and that households optimally allocate their savings between human and physical capital. This implies that human and physical capital grow at the same rate in all economies, whether they have open or closed capital markets, $g_H = g_K$ using (8) and (12), and that the growth rate of average labor productivity is linked to the growth rate of physical capital per worker by $(g_Y - \lambda) = \Gamma(g_K - \lambda)$, using (7) in (6). The theory identifies the growth rate of exogenous total factor productivity λ with the growth rate of average labor productivity of a country in the balanced growth equilibrium—which I take to be the US—and the Penn World Tables contain data on output and capital per worker for approximately 62 countries between 1965 and 1989. This allows me to identify aggregate returns to capital by comparing growth of output per worker, adjusted for exogenous total factor productivity growth, $g_Y - \lambda$ with growth of capital per worker, also worker adjusted for total factor productivity growth, $g_K - \lambda$.

This approach can be extended to a stochastic environment with longer gestation lags for human than for physical capital. To see this, suppose that exogenous productivity growth is equal to λ plus a country specific, stationary productivity shock η with $E\eta = 0$. Longer gestation lags for human than for physical capital imply that human and physical capital do no longer grow at the same rate. Instead, $g_K = g_H + \iota$ where ι —which may capture fluctuation of physical capital investment over the business cycle—satisfies $E\iota = 0$ because of rational expectations.[20] Proceeding analogously to the non-stochastic case I

economies. In this case, neoclassical growth theory predicts that long run investment rates in physical and human capital are $i_K = (1-\tau)B(\lambda + \delta)/(r^* + \delta)$ and $i_H = (1-\tau)A(\lambda + \delta)/(r^* + \delta)$ respectively. The bias $\hat{\Gamma}_{ols} - \Gamma$ of the ordinary least squares estimator which controls for differences in investment rates—but not in endogenous technology—can then be calculated as $(\mu - 1)B(1 + \Gamma)/(1 - (\mu - 1)B) > 0$. This bias arises because high taxes depress capital investment rates and technology; not controlling for technology forces the estimator to attribute all the variation in income to investment rates, overstating aggregate returns to scale to capital. Suppose that the true value of aggregate returns to capital is 45 percent, that the share of capital is 25 percent, and that capital goods firms set a markup of 33 percent above marginal cost; then the ordinary least squares estimate of aggregate returns to scale is 60 percent, the value estimated by Mankiw, Romer and Weil. This problem carries over to the estimates of aggregate returns to capital obtained from the rate of convergence to the balanced growth income distribution.

20. See appendix A.3 for a more formal argument.

now get that the growth rate of average labor productivity is linked to the growth rate of physical capital per worker by:

$$(g_Y - \lambda) = \Gamma(g_K - \lambda) + \varepsilon,^{21} \tag{19}$$

where $E\varepsilon = AE\iota + (1 - \Gamma)E\eta = 0$. This equation allows me to estimate aggregate returns to scale to capital by comparing average growth of output per worker, adjusted for exogenous total factor productivity growth, $g_Y - \lambda$ with average growth of capital per worker, also adjusted for exogenous total factor productivity growth, $g_K - \lambda$. The actual estimator used is generalized instrumental variables—the variance of the disturbance in (19) most likely varies across countries—using the constant as an instrument. Not surprisingly, this estimator remains consistent in the presence of measurement error in both the rate of growth of output (left-hand side variable) and the rate of growth of capital per worker (right-hand side variable, even if the measurement error in capital per worker and ε are correlated): The estimator will be consistent as long as physical and human capital accumulation reflect long run growth trends in the economy in a similar way.

The instrumental variable estimate of aggregate returns to scale to capital Γ in (19) is 40 percent with a standard error of 5 percent.[22] This estimate is precise and much lower

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21. The estimator is analogous to the estimator used to infer long run total factor productivity growth in growth accounting. There, the theoretical restriction is on the elasticity of output with respect to capital and the parameter estimated is long run total factor productivity growth. My estimator reverses these roles.

22. This estimate is rather small, considering that the share of physical capital alone is estimated to be above 40 percent in many underdeveloped economies. But these estimates most likely overstate the elasticity of production with respect to physical capital. This is for two reasons. First, the share of physical capital generally includes payments to the owners of residential capital: But residential capital is not a factor of production. Second, it also includes payments to land. Land is a factor of production but cannot be accumulated. To see whether these two factors can help my low estimates, I examine data on the Spanish economy in the 1950s—most likely the best available data on the functional distribution of income in "poor" economies—using data from Banco de Bilbao's Renta Nacional de España contained in different issues starting in 1955: They estimate the "capital share" at 17 percent, the "labor share" at 46 percent, and classify 33 percent of income as "mixed rents"—a category which is essentially the income of the self-employed, professionals, entrepreneurs, and mostly farmers. Splitting "mixed rents" between labor and capital using the ratio of the "labor share" to the "capital share," I obtain that 36 percent of income are payments to capital; 4 percent of which are payments to residential capital. The share of agriculture in production during this period was approximately 33 percent, and 22 percent of income in agriculture was paid to labor. Assuming

than estimates in Barro and Sala-i-Martin and Mankiw, Romer, and Weil for example.[23,24] The estimate suggests that the estimators in Barro and Sala-i-Martin and Mankiw, Romer, and Weil do not adequately control for initial differences in the aggregate level of technology; this forces their estimators to attribute all differences in growth rates to differences in human and physical capital per worker.[25]

Implications of Decreasing Aggregate Returns to Capital

With $\lambda + \delta$ around 10 percent, strong decreasing returns to capital translate into an average rate of convergence of 6 percent annually: Countries converge very rapidly to their long run income. Strong decreasing aggregate returns to capital also translate into a small elasticity of long run income with respect to barriers to technology transfer. The elasticity of long run income with respect to barriers to technology transfer is between 0 and $-2/3$: Only very large differences in barriers to technology transfer could explain

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that one third of the remaining income accrues to capital and two thirds to land, I find that 20 percent of income are payments to physical capital used in production. This estimate is probably still too large: the Direction Generale des Affaires Economiques et Financieres of the European Community estimates that the average share of physical capital in Greece, Ireland, Portugal, and Spain in 1960 was 20 percent, without correcting for the share of land in agriculture.

23. The difference between my estimates and the estimates in Mankiw, Romer, and Weil mentioned in footnote 20 could also be due to the fact that the sample of 62 countries for which capital stock data is available differs systematically from the overall sample used in Mankiw, Romer, and Weil or the fact that they infer human capital investment from schooling rates. To check against this possibility I reproduce their estimation procedure with the 62 countries in my sample, inferring—as they do—physical capital stocks from average investment rates and—as I do—human capital stocks from physical capital stocks. The results I obtain are virtually identical to their results in Table II. In particular I estimate returns to scale capital to be 60 percent with a standard error of 4 percent and an R^2 of about 65 percent.

24. It turns out that this estimate is insensitive to changes in the rate of growth of exogenous total factor productivity λ, and that the estimate would decrease if the rate of growth of exogenous total factor productivity in poor countries was smaller than the rate of growth of income in the US. To put it differently: The estimate is an upper bound for aggregate returns to scale to capital.

25. See footnote 7. Canova and Marcet (1995), among others (see their references), also obtain fast convergence using a bayesian panel data approach: when they allow countries to differ in their aggregate level of technology they get strong decreasing returns to capital; but when they restrict the aggregate level of technology to be the same they obtain the weak decreasing returns to capital estimated in Barro and Sala-i-Martin and Mankiw, Romer, and Weil.

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large differences in long run income.[26] The next section shows that this is because of the unrealistic and empirically rejected (implicit) assumption that all countries use capital with the same intensity at all factor prices.

4.B Technology Transfer, Income, and Structural Change

The model in the previous section cannot explain large long run income effects of small changes in barriers to technology transfer. This is because it cannot capture that lower barriers to technology transfer and higher rates of technology transfer may switch production into sectors which use complementary production factors—human and physical capital in the neoclassical growth model—relatively more intensively at all factor prices.

This idea is easiest to illustrate in a model where final goods can be produced in two sectors which use human and physical capital with different intensities, i.e. differ in (A, B).[27] Final goods firms in the first sector have access to a technology denoted by (a, b), while firms in the second sector have access to a technology (α, β), where I assume $\alpha \geq a$ and $\beta \geq b$, and that $\alpha'' \equiv \alpha / (1 - \beta) > a / (1 - b) \equiv a''$.[28] Firms in the two sectors may also use different capital goods. A simple way to deal with this is by assuming that a fraction q of capital goods supplied specifically to final goods firms in the more capital intensive sector (less capital intensive sector) are also productive in the less capital intensive sector (more capital intensive sector).

Sectoral differences in capital intensities at the same factor prices extend the neoclassical model in two crucial ways: They induce sectoral differences in the demand for human capital and sectoral differences in the incidence of endogenous technological change.

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26. With a capital share of 30 percent and a markup over marginal cost of 33 percent, the elasticity of long run income with respect to barriers to technology transfer would be $-1/6$. A tenfold increase of barriers to technology transfer would lower long run income by 30 percent.

27. I assume that there are two technologies to produce the same good. In some cases, it may be more useful to think of two different goods which can be sold at a fixed relative price determined in international goods markets. This is the reason why I use "production methods" in some cases and "sectors" in others. In any case, the formulation can also be seen as a simple way to capture a more complex technology where the share of capital rises as the relative price of capital falls.

28. This specification follows Ciccone (1993 and 1994).

Sectoral Differences in the Demand for Human Capital

Final goods firms in the two sectors will differ in the qualities of labor they demand. Firms in the α -sector will only demand labor qualities above some threshold. They find that the cost per efficiency unit of labor skilled and educated below this threshold is below its marginal productivity. Similarly, final goods firms in the a -sector only demand labor qualities below some threshold because the cost per efficiency unit of higher labor qualities exceeds their marginal productivity. To see this, notice that (8), (9) and $\alpha'' > a''$ imply a threshold value of human capital—which will be denoted by H^{ic}—such that all workers with a level of human capital above, $H \geq H^{ic}$, are more productive in the α -sector than in the a -sector

$$\omega_\alpha(H) \geq \omega_a(H),^{29} \qquad \qquad (20)$$

and all workers with a level of human capital below, $H < H^{ic}$, are more productive in the a -sector than in the α -sector (subscripts refer to the sector of production). Perfect competition in labor markets and labor market clearing imply that the equilibrium wage/human capital schedule satisfies $w^*(H) = \max(\omega_a(H), \omega_\alpha(H))$: Wages of a worker with human capital H are equal to the marginal product of labor in whichever sector the worker is more productive. Hence, firms in the α -sector do not demand labor of a quality strictly below H^{ic} because wages exceed marginal productivity. Firms in the a -sector do not demand labor of quality above H^{ic} for the same reason.

Technological Change and the Human Capital/Wage Premium

Endogenous technological change will not raise the human capital/wage premium in each sector.[30] But endogenous technological change will raise the productivity schedule relatively more in the relatively more capital intensive sector, i.e. increase $\omega_\alpha(H)/\omega_a(H)$.

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29. The precise definitions are:

$$\omega_\alpha(H) \equiv x_\alpha(1-\beta)\Theta_\alpha^{1-\alpha''}H^{\alpha''} \text{ and } \omega_a(H) \equiv x_a(1-b)\Theta_a^{1-a''}H^{a''}. \qquad (21)$$

30. Hick-neutral technological change implies that technological change in a neoclassical growth model with human capital would always leave the human capital/wage premium unaffected.

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Cutting barriers to technology transfer will therefore increase the (intersectoral) human capital/wage premium.[31]

Existence of a Balanced Growth Equilibrium

Before discussing the implications of endogenous capital intensity at all factor prices for the long run income distribution it is necessary to verify whether a long run equilibrium exists. The two main conditions for existence are: First, workers must maximize life-time income by working in the less capital intensive sector (more capital intensive sector) given the aggregate level of technology and the rate of technological change; this implies that workers maximize current wages by working in the less capital intensive sector (more capital intensive sector) and do not find it worthwhile to invest more (less) into human capital accumulation in order to switch into the more (less) capital intensive sector. Second, firms supplying capital goods must maximize discounted profits given the rate of capital accumulation in the economy.

The existence of a long run equilibrium depends on the distribution of fixed costs and taxes on operating profits across countries. This is because of the non-convexity which arises when workers can be employed in two sectors which use their human capital with different intensities (see figure 2a for example). It can be shown, however, that the balanced growth equilibrium exists for any distribution if $q \le (b/(1-b))/(\beta/(1-\beta))$.[32] The sectoral structure of production can—in this case—be characterized by two decreasing functions of $F/(1-\tau_\pi)$ (barriers to technology transfer), denoted with h_a^*/h_c and h_a^*/h_c.[33] If fixed costs and taxes are so low that

$$h_a^*/h_c > 1 \text{ and } h_a^*/h_c > 1,$$

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31. To be more precise, endogenous technological change strictly increases the intersectoral human capital/wage premium if $\beta > b$; it always strictly increases the wage differential between workers in the more human capital sector with the optimal level of human capital and workers in the less human capital sector with the optimal level of human capital, see (21), (7) and (17).

32. The proof is in the appendix.

33. The precise definitions are:

$$h_\alpha^* \equiv z_\alpha (F/(1-\tau_\pi))^{-(\mu-1)\beta/(1-\alpha-\mu\beta)}, \quad h_a^* \equiv z_a (F/(1-\tau_\pi))^{-(\mu-1)b/(1-a-\mu b)}, \quad h^c \equiv z^c (F/(1-\tau_\pi))^\gamma \quad (22)$$

with $\gamma \equiv (\beta(\mu-1)/(1-\mu\beta)) - (b(\mu-1)/(1-\mu b))$; z_α, z_a, and z^c are some (unimportant) constants.

then the economy will have a level of human capital of Ah_α^* and will produce in the more capital intensive sector. If fixed costs and taxes are so high that $h_\alpha^* / h_c < 1$ and $h_a^*/h_c < 1$, then the economy will have a level of human capital of Ah_a^* and produce in the less capital intensive sector.[34] For intermediate values of fixed costs where $h_\alpha^* / h_c \leq 1 \leq h_a^* / h_c$, the economy produces either in the more capital intensive sector or the less capital intensive sector. It is straightforward to check that countries producing in the more capital intensive sector have a higher level of human capital per worker than countries producing in the less capital intensive sector—as long as the latter do not have considerably larger exogenous level of technology.

Small and Large Effects of Cutting Barriers to Technology Transfer

Cutting barriers to technology transfer in an economy producing in the less capital intensive sector increases average labor productivity, see (18). This increase will be relatively minor as long as lower barriers do not translate into a sectoral shift. In particular, the increase will depend on the degree of decreasing returns to capital in the less capital intensive sector. The increase will be relatively large when barriers to technology transfer are so low that they induce a sectoral shift towards the more capital intensive sector: i.e. when they barriers are so low that $h_\alpha^* / h_c > 1$ and $h_a^*/h_c > 1$.[35] The relatively large effect of lower barriers to technology transfer combined with strong decreasing returns to capital in each sector will then translate into a high growth rate.[36]

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34. A related implication is that richer countries have higher physical and human capital investment rates than poorer countries if they use physical and human capital strictly more intensively at all factor prices.

35. In fact, countries in the model will separate into "almost" convergence clubs. Relatively large differences in barriers to technology transfer will result in relatively minor differences in long run income among countries adopting similar production methods: they will converge to similar levels of long run incomes. But there will be large differences in long run income among countries when differences in barriers to technology transfer translate into differences in production methods. See Azariadis and Drazen (1990), Baumol, Blackman, and Wolff (1989), and Durlauf and Johnson (1992) for evidence on convergence clubs.

36. Parente and Prescott (1994) and Romer (1994) also emphasize large long run income effects of relatively minor differences in barriers to technology transfer. But they argue that this is because of weak aggregate decreasing returns to capital. The weaker the aggregate decreasing returns to capital, the larger the elasticity of long run income in (18) with respect to barriers to technology transfer.

Equilibrium Income Distribution: a Step Further

The relatively large long run income effect of lower barriers to technology transfer arises because the two sectors use capital with different intensities at all factor prices. This can be seen in (18). Consider two economies which are identical, except that one economy uses capital more intensively at all factor prices: $\alpha > a$ and $\beta > b$. Lower barriers to technology transfer increase long run income in both economies, see (18). But the increase in income is relatively larger in the economy which uses capital more intensively at all factor prices. This is because of stronger complementarities between capital and the aggregate level of technology in the more capital intensive sector.

Combined with the effect of barriers to technology transfer on the production structure, the following explanation for large persistent income differences emerges: Endogenous differences in the structure of production follow from differences in barriers to technology transfer. Relatively large differences in income per capita follow from relatively low barriers to technology transfer. They are consistent with small differences in the productivity of investment across economies because barriers to technology transfer affect income per capita through the aggregate level of technology, not the capital/output ratio.[37]

Testing for Differences in Aggregate Returns to Capital

The explanation for large differences in income relies on cross-country differences in the capital intensity of production methods. In particular, the theory implies that countries with lower barriers to technology transfer should have a higher level of capital per worker and use capital more intensively at all factor prices.[38] To test whether more capital per

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37. Both the endogeneity of the aggregate level of technology and the endogeneity of the production structure (capital intensity at all factor prices) are crucial for this argument. Exogenous aggregate technology $\mu = 1$ implies that fixed costs of technology transfer and taxes on operating profits are irrelevant for the balanced growth equilibrium level of income. If countries could not differ in production methods, then fixed costs of technology transfer and taxes on operating profits would affect the aggregate level of technology in all countries in the same way.

38. To be more specific, consider two economies—one with low barriers to technology transfer and another with high barriers to technology transfer. For large enough differences in barriers to technology transfer, the economy with low barriers will have a relatively lower level of human and physical capital per worker and use human and physical capital relatively less intensively at all factor prices in the balanced growth

workers translates into production methods which are more capital intensive at all factor prices, I re-estimate (19), grouping the data according to capital per worker available at the beginning of the year (in which I measure the growth rates for estimating (19)). Table 1a shows that aggregate returns to scale to capital $\Gamma \equiv A + \mu B$ are larger when more capital per worker is available. Table 1b presents the results of formal hypothesis testing. The hypothesis that aggregate returns to scale increase at a capital stock per worker of 1000 US\$, 2500 US\$, 5000 US\$, 7500 US\$ and 9000 US\$ (which is not in table 1b but splits the sample exactly in half) cannot be rejected at the 10 percent significance level.[39]

5 Accelerating Growth and Increasing Investment Rates

Many of the economic success stories, like Hong Kong, Singapore, South Korea, Taiwan, and more recently Indonesia and Malaysia, have experienced accelerating growth rates and increasing investment rates (Chari, Kehoe, and McGratten (1995) and Chen (1978)). Explaining these experiences with the neoclassical model is challenging. The neoclassical model predicts that economic policies which increase long run income result in higher growth rates, but that growth rates decrease over time. It has also been difficult to identify differences in economic fundamentals (economic policies, initial level of human capital) that are large enough to have triggered rapid catch-up: Apparently similar economies have gone through dramatically different growth experiences (Lucas (1993), Chari, Kehoe, and McGratten). The challenge translates into two related questions: What could have magnified the long run income effects of initial differences in economic fundamentals, and

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equilibrium. This follows from proposition explained in the main text just above. This remains true out of the balanced growth equilibrium—as long as the economies are close to their balanced growth equilibrium. (See figures 2c–2d for example. Countries with low barriers (in figure 2d) use more capital intensive production methods as long as $H \geq H^{IC}$. Countries with high barriers (in figure 2c) use less capital intensive methods as long as $H < H^{IC}$.)

39. Durlauf and Johnson (1992) also estimate the differences in technology, relating them to literacy and income per capita. Following the estimation strategy in Mankiw, Romer, and Weil they find—broadly speaking—that the elasticity of output with respect to human and physical capital increases with literacy and income per capita.

Table 1a. Estimating Aggregate Returns To Scale				
Capital Per Worker			Returns To Scale	Standard Error	Observations Between
Between	0 and	2,500 US$	23 percent	11 percent	287
Between	2,500 and	5,000 US$	35 percent	13 percent	192
Between	5,000 and	7,500 US$	45 percent	17 percent	141
Between	7,500 and	10,000 US$	55 percent	18 percent	124
Above		10,000 US$	59 percent	6 percent	644

Notes: "Capital Per Worker" in 1985 US$; "Returns To Scale" is the estimated value of Γ in (19) using all the observations between the thresholds given in the leftmost column; "Standard Error" is the (heteroskedasticity adjusted) standard error of the estimated Γ; "Observations Between" is the number of observations between the thresholds given in the leftmost column. The data is for all countries for which capital stock per worker is available in the Penn World Tables, Mark 5.6, with the following exclusions: The OPEC countries for their dependence on oil, Iceland because it is very small and completely dependent on fishing, and New Zealand. I have excluded New Zealand because it appears to be a very influential outlier: With the 24 observations for New Zealand, estimated returns to scale for the 668 observations with capital per worker above 10,000 US$ falls to 56 percent with a standard error of 6 percent. Other estimates are unaffected.

Table 1b. Testing for Differences				
Capital Per Worker	Returns To Scale	Standard Error	P-Value	Observations Below
Below 1,000 US$	16 percent	11 percent	1 percent	9 percent
Below 2,500 US$	22 percent	12 percent	2 percent	20 percent
Below 5,000 US$	27 percent	9 percent	3 percent	34 percent
Below 7,500 US$	29 percent	8 percent	3 percent	45 percent
Below 10,000 US$	35 percent	7 percent	12 percent	54 percent

Notes: "Capital Per Worker" in 1985 US$; "Returns To Scale" is the estimated value of Γ in (19) using all observations below the threshold in the leftmost column; "Standard Error" is the (heteroskedasticity adjusted) standard error of the estimated Γ; "P-Value" is the P-Value of the hypothesis test that returns to scale above the threshold in the leftmost column are larger than below the threshold; "Observations Below" is the fraction of the sample below the threshold in the leftmost column. The data are the same as in Table 1b.

what accounts for the dynamic response of growth and investment rates? I approach both questions through induced shifts in the production structure.[40]

The idea is easiest to explain in a simple variant of the two sector model introduced in section 4B. Production can take place in two different sectors, one more capital intensive than the other. In this section, I assume that human capital is unproductive in the less capital intensive sector $a = 0$ while the share of human capital in the more capital intensive sector is $\alpha = 1 - \mu\beta$ and therefore permits endogenous growth—though I maintain the assumption of decreasing returns at the firm level $\mu > 1$. The most important difference with the framework in the previous sections is that I focus exclusively on households' decisions to accumulate human capital: All physical capital is owned by foreigners and all physical capital investment is by foreigners. Less important differences are that an increase in the variety of capital goods supplied specifically to the less capital intensive sector (more capital intensive sector) translates into a less than proportional increase in the variety of capital goods productive in the more capital intensive sector (less capital intensive sector); that physical and human capital do not depreciate; and that the less capital intensive sector and the more capital intensive sector use physical capital with the same intensity $b = \beta > 0$ at the same factor prices.

Consider two economies that are identical in all respects but one: The first economy has a high average level of human capital $H > H^c$—where $H^c = Ah^c$ is defined in (22)—and produces in the more human capital intensive sector. The second economy has a low average level of human capital $H \leq H^c$ and produces in the less human capital intensive sector. Can the economy which starts by producing in the less human capital intensive sector make a transition into the more human capital intensive sector? Is the transition characterized by accelerating growth rates and increasing investment rates? And can relatively small changes in economic policy trigger such a transition? The answers are

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40. For a similar model see Ciccone (1993). And see footnote 9 for evidence of such shifts.

illustrated in figures 5a–5b. Both figures assume that barriers to technology transfer are low enough to guarantee endogenous growth.[41]

Endogenous Growth Path

Economies that start with a high average level of human capital and produce in the more human capital intensive sector have higher growth rates and higher investment rates than economies with a low average level of human capital that produce in the less human capital intensive sector. This is because of strong complementarities in the more human capital intensive sector and low barriers to technology transfer. Strong complementarities and low barriers to technology transfer translate into a real return to human capital that is persistently higher than the return in international capital markets.

Transition Path

Whether a transition into the more human capital intensive sector is possible depends on the initial average level of human capital in the economy and on households' expectations about the rate of endogenous technological change. If the initial average level of human capital is relatively high—above Λh^L—and households expect new specialized capital goods to be supplied, then the economy will embark on the transition depicted in figure 5a: The growth rate of consumption will be lower than the rate of exogenous technological change and households will invest in human capital in order to use the new specialized capital goods more effectively. The increase in the average level of human capital makes it profitable for capital goods producers to supply new specialized goods in the economy; the intersectoral human capital/wage premium increases and workers switch into the more human capital intensive sector. This translates into accelerating growth rates and increasing investment rates as illustrated in figure 5b.

Stagnation Path

If households expect technological stagnation, they will not invest in human capital and continue to work in the less human capital intensive sector. Capital goods suppliers will not

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41. All results hold for a small rate of exogenous technological change. The proof is in appendix A.2.

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Figure 5a: Equilibria with a strictly positive rate of exogenous technological change. All variables are relative to the exogenous index of technology. Economies which start with a level of human capital below H^L produce in the less human capital intensive sector—they embark upon the stagnation path. Economies above H^L but below H^C may make it onto the transition path, depending on households' expectations about endogenous technological change. Above H^C the endogenous growth path is the unique equilibrium.
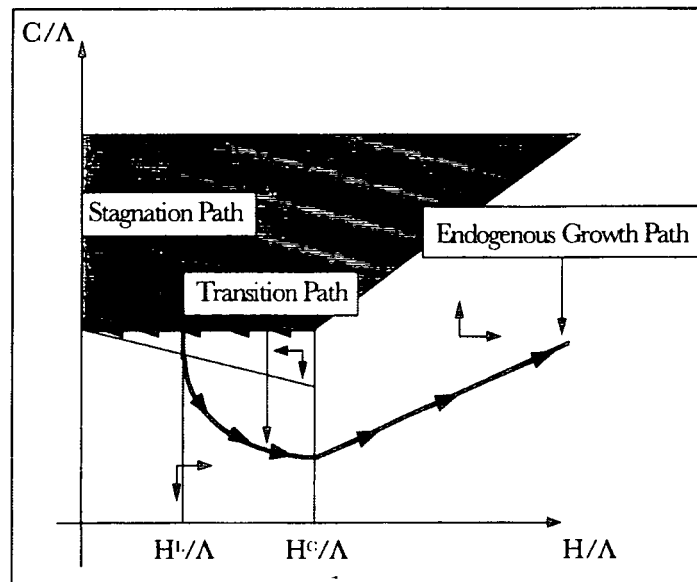
Figure 5b: The transition is characterized by increasing physical and human capital investment rates and accelerating income and total factor productivity growth rates. The average level of human capital increases faster than the exogenous index of technology in the transition, which is why the arrows point to the right. The jumps arise because I assume that human capital is unproductive in the less human capital intensive sector and because physical capital is financed by capital inflows.
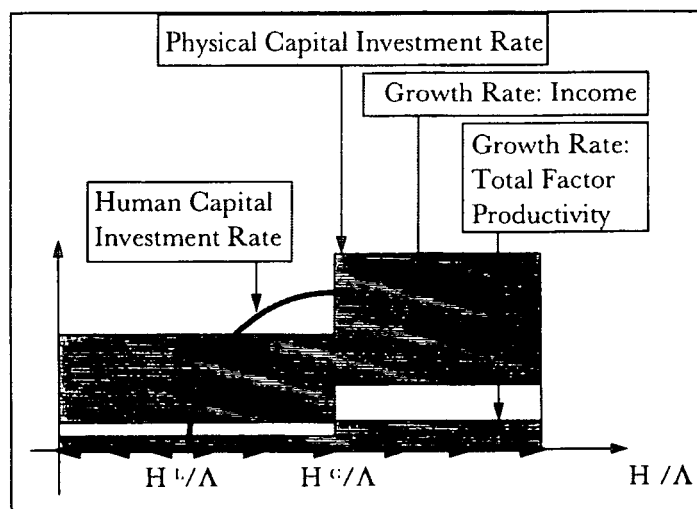
supply new specialized goods because they could not break even. Eventually, the average level of human capital in the economy will fall below the lower threshold Ah^L, locking the economy permanently into the less human capital intensive sector.

Economies starting with levels of human capital below Ah^L can never make a transition into the more human capital intensive sector. They start with so little human capital that it is never worthwhile for workers to invest in human capital to switch into the more human capital intensive sector. These economies keep producing in the less human capital intensive sector.[42] Growth rates are constant and equal to the rate of exogenous technological change. There is no investment in human capital.[43]

Economic Policy, Investment, and Income

The lower collective threshold Ah^L in figure 5a decreases with barriers to technology transfer.[44] Lower barriers to technology transfer increase workers' incentives to invest into human capital in order to switch into the more human capital intensive sector; relatively minor cuts in barriers to technology transfer will trigger a transition into the more human capital intensive sector in economies with an average level of human capital close to the lower collective threshold. The dynamic response to such cuts matches the stylized response of the economic success stories: The industrial structure switches towards more human capital intensive sectors, growth rates accelerate, and investment rates increase.

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42. If they start with a level of human capital well below Ah^L this will be Pareto-efficient, see appendix A.2.

43. Threshold effects at Ah^L are not limited to growth and investment: there are threshold effects in welfare. The interdependencies between human capital accumulation and technological change imply that welfare jumps up at the lower collective threshold if the economy makes a transition. Without interdependencies between human capital accumulation and technological change, $(\mu - 1)\beta = 0$, the dynamic market equilibrium is Pareto-efficient and there are no threshold effects in welfare. See Azariadis and Drazen (1989) for other reasons for threshold effects in growth.

44. For a small rate of growth of exogenous technology, the threshold is close to

$$h^C - (f(c_\alpha) - f(1)); \tag{23}$$

where $c_\alpha = 1 - \sigma\alpha(1 - \rho / v\omega_{\alpha\prime}) / (1 - \beta)$ denotes the workers' average propensity to consume out of income in the balanced growth equilibrium in the endogenous growth path; $\omega_{\alpha\prime}$ is the marginal product of human capital in the more human capital intensive sector; h^C is the upper collective threshold defined in (22); and $f(c) \equiv v(1 - b)x_\alpha(c - \log c) / \rho\sigma$. The result follows from (23) and the definition of c_α.

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6 Conclusions

This paper makes two simple points, one theoretical and one empirical. The theoretical point is that relatively minor differences in barriers to technology transfer can translate into large differences in long run income—despite strong decreasing aggregate returns to capital in each sector of the economy. This is because high barriers to technology transfer shift production towards less human and physical capital intensive sectors. Similarly, low barriers to technology transfer shift production towards more human and physical capital intensive sectors. The empirical point is that a simple long run restriction of neoclassical growth theory can be used to identify aggregate returns to scale to capital. Consistent estimates of aggregate returns to capital suggest strong decreasing aggregate returns in each sector. They also suggest that more developed countries shift to a structure of production which uses human and physical capital more intensively at all factor prices.

Based on these two points I propose the following explanation of rapid catch-up and persistent underdevelopment. Low barriers to technology transfer have shifted the production structure in rapidly growing underdeveloped countries towards sectors and production methods which are more human and physical capital intensive at all factor prices. This has brought long run income levels in rapidly growing countries closer to the US level: Fast convergence to higher long run income levels explains their rapid growth. High barriers to technology transfer in stagnating underdeveloped countries lock their production structure into sectors and production methods which are less human and physical capital intensive at all factor prices: This depresses the returns to human and physical capital investment and to technology transfer in stagnating underdeveloped countries in spite of their inferior technologies and in spite of their lack of human and physical capital.

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Appendix

In this appendix I sketch the proof of the proposition in section 4.B (in A.1) and the characterization of the transition equilibrium in section 5 (in A.2). I also illustrate why the estimator of aggregate returns to scale to accumulable factors developed in section 4.A remains consistent in the presence of uncertainty about future returns and longer gestation lags for human than for physical capital (in A.3).

A.1. Main Proposition

Definition of the Balanced Growth Equilibrium

In the balanced growth equilibrium, production and consumption of final goods grow at the same constant rate in all economies. For the usual reasons—technological change is labor augmenting, see (6)—this implies that the real interest rate in capital markets is constant and equal to $r^* = \lambda / \sigma + \rho$. The balanced growth equilibrium consists of sequences for human capital $\{H^*(t): t \geq 0\}$, financial assets $\{A^*(t): t \geq 0\}$, human capital investment $\{I^*(t): t \geq 0\}$, and consumption $\{C^*(t): t \geq 0\}$ for each household; for the variety of capital goods productive in the less human capital intensive sector $\{M_a^*(t): t \geq 0\}$ and the more human capital intensive sector $\{M_\alpha^*(t): t \geq 0\}$; for production plans and input demands in the less human capital intensive sector $\{Y_a^*(t): t \geq 0\}$, $\{n_a^*(H,t), H \geq 0, t \geq 0; l_a^*(H,t): H \geq 0, t \geq 0; k_a^*(i,H,t): i \in M_a^*(t), H \geq 0, t \geq 0\}$ and the more human capital intensive sector for each final output firm; for the wage/human capital profile $\{w^*(H,t): H \geq 0, t \geq 0\}$; and for rental prices for capital goods productive in the less human capital intensive sector $\{R_i^*(i,t): i \in M_a^*(t), t \geq 0\}$ and the more human capital intensive sector in each country, such that households maximize intertemporal welfare subject to the asset and human capital accumulation constraint; capital and final goods firms maximize profits; there is no group of capital goods firms which could enter and make strictly positive profits; and all markets clear.

Balanced Growth Equilibrium

I focus on sufficient conditions for a balanced growth equilibrium with production in the less capital intensive sector, but the balanced growth equilibrium with production in the more capital intensive sector can be dealt with analogously: **(i)** In the balanced growth equilibrium, the private return to human capital must be equal to $r^* + \delta$, $v w_H^*(H^*(t), t) = r^* + \delta$. Production in the less capital intensive sector implies that wages are $w^*(H^*(t), t) = \omega_a(A(t), M_a^*(t), H^*(t))$ and that the return to human capital is $v w_H^*(H^*(t), t) = v \omega_{aH}(A(t), M_a^*(t), H^*(t)) = r^* + \delta$, where $\omega_a(A, M_a, H)$ denotes the marginal product of a worker with human capital H in the less capital intensive sector if the exogenous level of technology is A, a variety of M_a capital goods are available in the less capital intensive sector, and the return to physical capital is equal to r^* (corresponding to (7) and (10) in (9)); the subscript H denotes the partial derivative with respect to H. Making use of the zero profit variety as a function of the average level of human capital in the economy (in (14), I will suppress the fact that the variety also depends on the exogenous level of technology A directly), the last equality yields the implicit definition of $h_a^* \equiv H_a^* / A$,

$$v \omega_{aH}(A(t), M_a(A(t) h_a^*), A(t) h_a^*) = e_a v A(h_a^*)^{-(1-a')}(\kappa^*)^{-(1-a')b'/(1-b')} = r^* + \delta; \tag{A1}$$

the last equality could alternatively be derived from (16) directly; **(ii)** in a balanced growth equilibrium with production in the less capital intensive sector, final goods firms maximize profits. Hence the equilibrium wage/human capital schedule must satisfy

$$w^*(H^*(t), t) = \omega_a(A(t), M_a^*(t), H^*(t)) \geq \omega_\alpha(A(t), \tilde{M}_\alpha^*(t), H^*(t)), \tag{A2}$$

where $\tilde{M}_\alpha^*$ denotes the variety of capital goods productive in the more capital intensive sector in an economy which produces in the less capital intensive sector (in the main text I have simply assumed that $\tilde{M}_\alpha^* = qM_a^*$ with $0 \le q \le 1$) and $\omega_a(\Lambda,M,H)$ is defined analogously to $\omega_a(\Lambda,M,H)$. If the inequality in (A2) would not hold, then there would be excess demand for workers with human capital $H^*(t)$ as their marginal product in the more capital intensive sector would exceed their wages; **(iii)** but in a balanced growth equilibrium with production in the less capital intensive sector it must also be the case that it does not pay for households to individually accumulate human capital in order to switch into the more human capital intensive sector. A simple sufficient condition for this is

$$v\omega_{\alpha H}(\Lambda,\tilde{M}_\alpha(H_a^*),\tilde{H}^C) = v\omega_{\alpha H}(1,\tilde{m}_\alpha(h_a^*),\tilde{h}^C) \le r^* + \delta, \qquad (A3)$$

where the first equality makes use of the fact that $\omega_a(\Lambda,M_a,H)$ is linear homogenous, $\omega_a(\Lambda,M_a,H) = \Lambda\omega_a(1,m_a,h)$; $m \equiv M/\Lambda$, $\tilde{m} \equiv \tilde{M}/\Lambda$, and $m(h), \tilde{m}(h)$ denote $M/\Lambda, \tilde{M}/\Lambda$ as a function of H/Λ (see (14) in the main text); $\tilde{h}^C \equiv \tilde{H}^C/\Lambda$ where $\tilde{H}^C$ is defined by the equality in (20) (see also (21)) taking into account that in an economy in a balanced growth equilibrium with production in the less human capital intensive sector the aggregate level of technology in the two sectors are $\Theta_\alpha = \tilde{M}_\alpha^{\beta'}\Lambda^{1-\beta'}$ and $\Theta_a = M_a^{b'}\Lambda^{1-b'}$ (see (7)) respectively. Intuitively, the condition in (A3) states that the individual return to human capital is always below the return to physical capital; as a result, no worker in an economy in a balanced growth equilibrium with production in the less capital intensive sector will find it worthwhile to accumulate human capital to eventually switch into the more capital intensive sector (of course, if all workers would accumulate human capital, then the variety of capital goods supplied would change and human capital investment may become worthwhile). There is another condition which must be satisfied: No group of capital goods firms can enter and make strictly positive profits. This condition **(iv)** is characterized next.

Capital Goods Firms Cannot Enter and Make a Profit

In the balanced growth equilibrium, no group of capital goods firms should be able to enter and make strictly positive profits. It is straightforward to show that this will be the case if

$$\omega_a(\Lambda,M_a(\Lambda h_a^*),\Lambda h_a^*) \ge \omega_\alpha(\Lambda,M_\alpha(\Lambda h_a^*),\Lambda h_a^*). \qquad (A4)$$

This condition is quite intuitive. Because of decreasing returns to capital goods, no group of capital goods firms supplying goods for the less capital intensive sector can enter and make a positive profit; this is simply because in a balanced growth equilibrium there are already $\Lambda m_a(h_a^*)$ firms supplying capital goods for the less capital intensive sector and they make a zero profit by definition (in (14)). The remaining question is whether capital goods firms supplying capital goods for the more capital intensive sector can enter and make a strictly positive profit. But that will also be impossible because—and this is what the inequality in (A4) states—workers would be less productive in the more capital intensive sector at the "zero profit variety of capital goods productive in the more capital intensive sector" $\Lambda m_\alpha(h_a^*)$ as defined in (14)—I have put the quotation marks because $\Lambda m_\alpha(h_a^*)$ is the zero profit variety only if all workers work in the more capital intensive sector, which will <u>not</u> happen. This implies that at the "zero profit variety of capital goods productive in the more capital intensive sector," wages in the less capital intensive sector—equal to the left hand side of the inequality in (A4) —would still exceed marginal labor productivity in the more capital intensive sector: Nobody would work in the more capital intensive sector as a result, and the entering capital goods firms would make a loss. Hence more than "the zero profit variety of firms $\Lambda m_\alpha(h_a^*)$ supplying capital goods for the more capital intensive sector" would have to enter for workers to find it worthwhile to work in the more capital intensive sector. But, because of decreasing returns to varieties in the more capital intensive

sector, this would imply that capital goods firms make a loss—this follows directly from the definition of "zero profit variety" in (14).

The following reverse implication can also be established: (A4) must hold in a balanced growth equilibrium with production in the less capital intensive sector. Intuitively this is because if (A4) would not hold, then workers would actually be better off by all working in the more capital intensive sector (they have the skills and education) if only the "zero profit variety of capital goods productive in the more capital intensive sector" was available. The reason why they would be working in the less capital intensive sector is that they happen to have coordinated on the less capital intensive sector; as a result, the economy got a variety of capital goods which made it worthwhile for each worker individually to work in the less capital intensive sector (this is not only because the type of capital goods used in the two sectors may differ—what I capture with q—but also because the number of capital goods supplied in the zero profit equilibrium in the two sectors differ. To put it differently, this argument will apply even if $q = 1$). But in this case, a group of capital goods firms supplying capital goods for the more human capital sector could enter and make a strictly positive profit. This is because if (A4) would not hold, then, by continuity, workers would be more productive in the more capital intensive sector even if less than the "zero profit variety of capital goods productive in the more capital intensive sector" would be supplied. Capital goods producers which would enter to supply capital goods for the more capital intensive sector could therefore make a strictly positive profit—this follows directly from the definition of zero profit variety and decreasing returns to the variety of capital goods available in the more capital intensive sector. This yields the contradiction which establishes that the inequality in (A4) must hold in a balanced growth equilibrium with production in the less capital intensive sector.

Balanced Growth Equilibrium

A value of h_a^* satisfying (A1) to (A4) will be a balanced growth equilibrium with production in the less capital intensive sector. The balanced growth equilibrium with production in the more capital intensive sector is defined analogously. The existence of a balanced growth equilibrium (with production in the more capital intensive sector or the less capital intensive sector) depends on tax rates and fixed costs of technology transfer. Because of the non-convexity induced by the fact that workers can work in two different sectors, an equilibrium may not exist. But there is a simple sufficient condition which makes that a balanced growth equilibrium exists for all values of tax rates and fixed costs of technology transfer. This is what I prove next.

Proving the Main Proposition

I prove that if

$$q \leq (b/(1-b))/(\beta/(1-\beta)) \leq 1 \text{ and } \alpha/(1-\beta) > a/(1-b) \qquad (\blacklozenge)$$

then a balanced growth equilibrium with production in the less capital intensive sector or the more capital intensive sector exists for all values of tax rates on profits and fixed costs of technology transfer. The proof goes as follows: I first (1.1-1.4) establish that (A4)

$$\omega_a(\Lambda, M_a(\Lambda h_a^*), \Lambda h_a^*) \geq \omega_\alpha(\Lambda, M_\alpha(\Lambda h_a^*), \Lambda h_a^*) \text{ implies } \omega_a(\Lambda, M_a(\Lambda h_a^*), \Lambda h_a^*) \geq \omega_\alpha(\Lambda, \tilde{M}_\alpha(\Lambda h_a^*), \Lambda h_a^*)$$

(A2), and the analogue for the more capital intensive sector, given the assumption ($\blacklozenge$). Then (2) I establish that

$$\omega_a(\Lambda, M_a(\Lambda h_a^*), \Lambda h_a^*) \geq \omega_\alpha(\Lambda, M_\alpha(\Lambda h_a^*), \Lambda h_a^*) \text{ or } \omega_\alpha(\Lambda, M_\alpha(\Lambda h_\alpha^*), \Lambda h_\alpha^*) \geq \omega_a(\Lambda, M_a(\Lambda h_\alpha^*), \Lambda h_\alpha^*)$$

must hold, given the assumption in ($\blacklozenge$). This makes that a balanced growth equilibrium with production in one of the two sectors may only fail to exist if $\omega_\alpha(\Lambda, M_\alpha(\Lambda h_a^*), \Lambda h_a^*) < \omega_a(\Lambda, M_a(\Lambda h_a^*), \Lambda h_a^*)$ but—starting from

A3

h_a^* and production in the less capital intensive sector—it is worthwhile for households to accumulate human capital individually in order to switch into the more capital intensive sector, i.e. (A3) $v\omega_\alpha(\Lambda,\tilde{M}_\alpha(\Lambda h_a^*),\Lambda\tilde{h}^C)\le r^*+\delta$ does not hold. To complete the proof, I show (3) that this is not possible because if (A3) does not hold, then $\omega_a(\Lambda,M_a(\Lambda h_a^*),\Lambda h_a^*)\ge\omega_\alpha(\Lambda,M_a(\Lambda h_a^*),\Lambda h_a^*)$.

(1.1) It will be convenient to start the proof by defining the <u>collectively critical threshold</u> h^C by

$$\omega_a(\Lambda,M_a(\Lambda h^C),\Lambda h^C)=\omega_\alpha(\Lambda,M_a(\Lambda h^C),\Lambda h^C) \tag{A5}$$

and proving that $\omega_a(\Lambda,M_a(\Lambda h_a^*),\Lambda h_a^*)\ge\omega_\alpha(\Lambda,M_a(\Lambda h_a^*),\Lambda h_a^*)$ is equivalent to $h_a^*\le h^C$. Making use of (7) and (14) in (21) it follows that $\omega_a(\Lambda,M_a(\Lambda h_a^*),\Lambda h_a^*)=x_a(1-b)\Lambda(m_a(\Lambda h_a^*))^{(1-a'')b'}h_a^{a''}=x_a s_a^{b'(1-a'')}(1-b)\Lambda h_a^{a^*}h_a^{a''}$ (where s_a is some constant) and that $\omega_\alpha(\Lambda,M_a(\Lambda h_a^*),\Lambda h_a^*)=x_a s_\alpha^{\beta'(1-\alpha'')}(1-\beta)\Lambda h_a^{\alpha^*}h_a^{\alpha''}$ (where s_α is some constant); the equivalence follows because ($\diamond$) implies that $a^*<\alpha^*$.

(1.2) With these preliminaries, it is straightforward to prove that $\omega_a(\Lambda,M_a(\Lambda h_a^*),\Lambda h_a^*)\ge\omega_\alpha(\Lambda,M_\alpha(\Lambda h_a^*),\Lambda h_a^*)$ implies $\omega_a(\Lambda,M_a(\Lambda h_a^*),\Lambda h_a^*)\ge\omega_\alpha(\Lambda,\tilde{M}_a(\Lambda h_a^*),\Lambda h_a^*)$. First, notice that the following inequality holds

$$x_\alpha(1-\beta)\Lambda(m_a(h^C))^{(1-\alpha'')}\beta'(h^C)^{\alpha''}\le x_a(1-b)\Lambda(m_a(h^C))^{(1-a'')b'}(h^C)^{a''}. \tag{A6}$$

The left hand side is larger or equal to $\Lambda\omega_\alpha(1,\tilde{m}_a(h^C),h^C)$, the wage in the more capital intensive sector in an economy with production in the less capital intensive sector and a level of human capital equal to Λh^C: This is simply because the variety of capital goods productive in the more capital intensive sector cannot be larger than the variety of capital goods supplied. The inequality in (A6) must hold because

$$x_\alpha(1-\beta)\Lambda(m_a(h^C))^{(1-\alpha'')}\beta'(h^C)^{\alpha''}\le x_\alpha(1-\beta)\Lambda(m_\alpha(h^C))^{(1-\alpha'')}\beta'(h^C)^{\alpha''}=x_a(1-b)\Lambda(m_a(h^C))^{(1-a'')b'}(h^C)^{a''}.$$

The equality follows from the definition h^C. The inequality holds because it can be shown that $m_a(h^C)=(b/(1-b))/(\beta/(1-\beta))m_\alpha(h^C)$ and hence that ($\diamond$) implies that $m_a(h^C)\le m_\alpha(h^C)$.

(1.3) To see that this implies $\omega_a(1,m_a^*,h_a^*)\ge\omega_\alpha(1,\tilde{m}_a^*,h_a^*)$ define $\tilde{h}_a^C(m)$ as the level of human capital which equalizes a worker's productivity in the less capital intensive and the more capital intensive sector, assuming that a variety of capital goods m is productive in the less capital intensive sector and a variety qm in the more capital intensive sector; using (20 and 21) with equality, $\tilde{h}_a^C(m)$ is defined implicitly by $x_\alpha(1-\beta)\Lambda(qm)^{(1-\alpha'')}\beta'(\tilde{h}_a^C)^{\alpha''}=x_a(1-b)\Lambda(m)^{(1-a'')b'}(\tilde{h}_a^C)^{a''}$. Because of ($\diamond$), workers with $h\le\tilde{h}_a^C(m)$ will be more productive in the less capital intensive sector and workers with $h>\tilde{h}_a^C(m)$ will be more productive in the more capital intensive sector. Also, and again because of ($\diamond$), it can be shown that $\tilde{h}_a^C(m)$ is decreasing in m. With this definition, (A6) establishes that $\tilde{h}_a^C(m_a(h^C))\ge h^C$ while I am trying to prove that $\tilde{h}_a^C(m_a^*)\ge h_a^*$. But because the maintained assumption is that $h^C\ge h_a^*$ and because the fact that $\tilde{h}_a^C(m)$ is decreasing in m implies that $\tilde{h}_a^C(m_a^*)\ge\tilde{h}_a^C(m(h^C))\Leftrightarrow m_a^*\le m_a(h^C)$, the latter follows from the former.

(1.4) To establish the analogue for the more capital intensive sector, notice that

$$\tilde{m}_a(h^C)=qm_\alpha(h^C)=q((\beta/(1-\beta))/(b/(1-b)))m_a(h^C)\le m_a(h^C) \tag{A7}$$

because of ($\diamond$). This implies $\omega_a(1,m_\alpha(h^C),h^C)=\omega_a(1,m_a(h^C),h^C)\ge\omega_a(1,\tilde{m}_a(h^C),h^C)$: The first equality follows from the definition of h^C and the second inequality follows from (A7). This then establishes that $\tilde{h}_\alpha^C(m_a(h^C))\le h^C$, where $\tilde{h}_\alpha^C(m)$ is defined analogously to $\tilde{h}_a^C(m)$ with the only differences that m now refers to the variety of capital goods available in the more capital intensive sector (and therefore qm to the variety in the less capital intensive sector). Because $h^C\le h_\alpha^*$ and $\tilde{h}_\alpha^C(m_\alpha^*)\le\tilde{h}_\alpha^C(m_\alpha(h^C))$, it follows that $\tilde{h}_\alpha^C(m_\alpha(h_\alpha^*))\le h_\alpha^*$.

(2) To prove that

$$\omega_a(\Lambda,M_a(\Lambda h_a^*),\Lambda h_a^*)\ge\omega_\alpha(\Lambda,M_\alpha(\Lambda h_a^*),\Lambda h_a^*)\text{ or }\omega_\alpha(\Lambda,M_\alpha(\Lambda h_\alpha^*),\Lambda h_\alpha^*)\ge\omega_a(\Lambda,M_a(\Lambda h_\alpha^*),\Lambda h_\alpha^*)$$

A4

always holds, it is sufficient to observe that $\omega_{aH}(h^C) > \omega_{aH}(h^C) = (a/(1-b)/(\alpha/(1-\beta))\omega_{aH}(h^C)$ (I am suppressing most of the arguments) because of ($\blacklozenge$) and that the individual return to human capital increases as the average level of human capital falls (aggregate decreasing returns). This makes it impossible that neither the first nor the second inequality holds.

(3) Finally, it remains to prove that $v\omega_{aH}(\Lambda, \tilde{M}_a(\Lambda h_a^*), \Lambda \tilde{h}_a^C(m_a(h_a^*))) > r^* + \delta$ implies $h_\alpha^* \geq h^C$. The previous section established $\tilde{h}_a^C(m_a(h_a^*)) \geq h^C$, which can be used to get the following inequalities

$$\omega_{aH}(1, \tilde{m}_a(h_a^*), \tilde{h}_a^C(m_a(h_a^*))) \leq \omega_{aH}(1, m_a(h^C), \tilde{h}_a^C(m_a(h_a^*))) \leq \omega_{aH}(1, m_a(h^C), \tilde{h}_a^C(m_a(h_a^*))) \leq \omega_{aH}(1, m_a(h^C), h^C); \quad \text{(A8)}$$

the first inequality follows because $h_a^* \leq h^C$; the second inequality follows because $m_a(h^C) \leq m_a(h^C)$, which follows from $m_a(h^C) = (b/(1-b))/(\beta/(1-\beta))m_a(h^C)$. The last inequality follows from $\tilde{h}_a^C(m_a(h_a^*)) \geq h^C$. But the inequalities in (A8) would then imply that if $v\omega_{aH}(1, \tilde{m}_a(h_a^*), \tilde{h}^C) > r^* + \delta$ then $v\omega_{aH}(1, m_a(h^C), h^C) > r^* + \delta$ and hence $h_\alpha^* > h^C$.

Finally, the inequalities in the main proposition in the main text follow because (A4) must hold in a balanced growth equilibrium with production in the less capital intensive sector, see the argument on top of page A3, and because the argument in (1.1) on page A4 establishes that $\omega_a(\Lambda, M_a(\Lambda h_a^*), \Lambda h_a^*) \geq \omega_\alpha(\Lambda, M_a(\Lambda h_a^*), \Lambda h_a^*)$ is equivalent to $h_a^* \leq h^C$.

A.2. Characterizing the Transition

Balanced Growth Equilibrium in More/Less Human Capital Intensive Sector

First **(1)** I characterize the balanced growth equilibria of the economy with an average level of human capital $H > H^C$ ($h > h^C$) which produces in the more human capital intensive sector and **(2)** the economy with an average level of human capital $H \leq H^C$ ($h \leq h^C$) which produces in the less human capital intensive sector.

(1) The growth rate of output in the latter economy is λ, the growth rate of total factor productivity is $(1-b)\lambda$ from (15) and (6) in the main text. It is straightforward to check that physical capital investment over GDP is $\lambda b/r^*$ and that investment in human capital is nil.

(2) To characterize the second economy is less straightforward. The assumption that $1 - \alpha - \mu\beta = 0$ (endogenous growth possible) made in the main text amounts to $\alpha^* = \alpha' = \beta' = 1$. Substituting in (16) implies that the return to final goods invested in human capital is constant and equal to $e_a \alpha v(k^*)^{-\beta(\mu-1)/\alpha} = v\omega_{aH} \equiv r_H^*$. This implies that the (endogenous) balanced growth rate of consumption, output, human and physical capital is $g_{aY} \equiv \sigma(r_H^* - \rho) > \lambda$, where the inequality follows from the assumption $r_H^* > r^* \equiv \lambda/\sigma + \rho$ made in the main text (an assumption which will be satisfied for small F, for example, see (13) and the definition of r_H^* just above), and the growth rate of total factor productivity is $(1 - \alpha - \beta)g_{aY}$ from (15), (6) and the fact that $\alpha^* = 1$. Human capital investment over gross national product (GNP) is $I/w = ((vI)/H)(H/vw) = (\dot{H}/H)(H/vw) = g_{aY}(H/vw)$ where using (16)

$$v(w/H) = v w_H((1-\beta)/\alpha) = r_H^*((1-\beta)/\alpha)$$

and hence $i_{aH} = I/w = (\alpha/(1-\beta))g_{aY}/r_H^* = (\alpha/(1-\beta))\sigma(1-\rho/r_H^*)$. Physical capital investment rate over GNP is $\dot{K}/w = (\dot{K}/K)(K/w) = g_{aY}\beta/r^*(1-\beta)$ because the share of capital in output is β and hence $r^*K = \beta Y$. Human and physical capital investment relative to gross domestic product (GDP) is $\alpha\sigma(1-\rho/r_H^*)$ and $g_{aY}\beta/r^*$ respectively.

The Transition

To describe the transition, I **(1)** first describe the households' optimization problem then **(2)** determine the symmetric transition path satisfying the necessary conditions for household optimization and finally **(3)** show that this transition path satisfies the sufficient conditions for household optimality.

(1) Households maximize intertemporal utility subject to $\dot{H} = vI$ and $\dot{H} \geq 0$ (irreversibility of human capital investment). The necessary conditions for the households' optimization problem are obtained from the Lagrangian $L = U(C) + (\theta + v)v(w(H,t) - C)$ as

$$U'(C) = v(\theta + v), \quad \theta\rho = w_H(H,t)v(\theta + v) + \dot{\theta}, \quad v \geq 0, \quad v(w(H,t) - C) = 0, \tag{A9}$$

and the transversality condition, where θ and v are the usual multipliers and $w(H,t)$ denotes the wage/human capital schedule at time t.

(2) The transition path can be determined from the households' optimization conditions, taking into account that the economy will be in an endogenous balanced growth equilibrium once all households have a level of human capital $H \geq H^c$ ($h \geq h^c$) and that in the endogenous balanced growth equilibrium $C = (1 - i_{aH})w$. Defining $s \equiv C / \Lambda$ it is straightforward to show that in a symmetric transition the necessary conditions of the households' optimization problem give rise to the following system of differential equations,

$$\dot{s} = (\sigma(w_H - \rho) - \lambda)s \text{ and } \dot{h} = v((\overline{w} / \Lambda) - s) - \lambda h; \tag{A10}$$

where $\overline{w}(\Lambda, H) \equiv \max(\omega_a(\Lambda, M_a(H), H), \omega_\alpha(\Lambda, M_\alpha(H), H))$ and where, with a slight abuse of notation, $\overline{w}_H$ denotes the <u>partial</u> derivative with respect to the individual level of human capital holding the variety of capital goods in both sectors constant,

$$\overline{w}_H(\Lambda, H) = \{\partial(\max(\omega_a(\Lambda, M_a, H), \omega_\alpha(\Lambda, M_\alpha, H))) / \partial H : M_a, M_\alpha\}.$$

(I should, at this point, clarify the assumptions regarding specific capital goods. I am assuming that there are capital good which are productive in the less/more human capital intensive sector only and capital goods which are productive in both sectors. The capital goods supplied in the transition will be those that are productive in both sectors—this is because suppliers of capital goods that are specific to one sector could not break even.)

The fact that the economy will reach an endogenous balanced growth equilibrium with production in the more human capital intensive sector once the average level of human capital is H^c translates into the side conditions $s(h^c) = (1 - i_{aH})\omega_a(1, m_a(h^c), h^c) = (1 - i_{aH})\overline{w}(1, h^c)$, where the last equality makes use of the linear homogeneity of $\overline{w}(\Lambda, H)$ and the fact that by definition $\omega_a(1, m_a(h^c), h^c) = \omega_\alpha(1, m_a(h^c), h^c)$; i_{aH} denotes the human capital investment to GNP ratio in the balanced growth equilibrium with production in the more human capital intensive sector. The system of differential equations can be integrated backwards (starting from the boundary condition $s(h^c) = (1 - i_{aH})\overline{w}(1, h^c)$) to yield the lower collective threshold as defined in the main text,

$$h^L = h^c - (f(1 - i_{aH}) - f(1)) \tag{A11}$$

for the case of $\lambda = 0$. It can also be shown that the lower collective threshold is continuous in λ which implies that for small positive λ the true lower collective threshold is close to the threshold as determined in (A11).

(3) But the households' optimization problem is not convex and the necessary conditions for optimization may not be sufficient. In particular, the household may not find it optimal to invest in human capital even if all other households do. Here I show that this may indeed happen for large λ; in this case, **(2)** does not identify an equilibrium. But, as long as λ is sufficienctly small, not investing in human capital when all

A6

others do invest is not optimal and **(2)** does identify the transition equilibrium. To prove this it suffices to show that the return to human capital investment for a household who decides not to invest in human capital becomes arbitrarily large if all other households do invest in human capital. To see this, notice that the household's marginal product in the less human capital intensive sector is $\omega_a(\Lambda, M_a, H) = x_a(1-b)\Lambda^{1-b'}M_a^{b'}$ while the household's marginal product in the more human capital intensive sector is $\omega_a(\Lambda, M_a, \overline{H}) = x_a(1-b)M_a^{\beta'}\overline{H}^{\alpha/(1-b)}$; $\overline{H}$ denotes the household's initial, constant level of human capital. Because I assume that the variety of capital goods productive in the less human capital intensive sector grows at a strictly slower rate than the variety of capital goods productive in the more human capital intensive sector once the economy produces in the more human capital intensive sector, the marginal product in the more human capital intensive sector will eventually grow faster than the marginal product in the less human capital intensive sector for small λ; the household will therefore eventually work in the more human capital intensive sector; and the result follows because the marginal product of human capital in the more human capital intensive sector goes to infinity as the variety of productive capital goods grows. A similar, but more difficult, argument can be made even if all capital goods productive in the more human capital intensive sector are also productive in the less human capital intensive sector (and the other way round) if the more human capital intensive sector uses physical capital more intensively than the less human capital intensive sector $\beta > b$.

Threshold Effects in Welfare and Pareto-Ranking Equilibria

I first **(1)** determine welfare for the balanced growth equilibrium with production in the less human capital intensive sector and then **(2)** welfare for the transition into the balanced growth equilibrium with production in the more human capital intensive sector, both for the case of $\lambda = 0$ and for an initial level of human capital $h_0 = h^L$ defined in (A11). Finally **(3)** I show that welfare in the balanced growth equilibrium with production in the less human capital intensive sector is strictly smaller than the welfare in the transition into the balanced growth equilibrium with production in the more human capital intensive sector if there are interdependencies between human capital accumulation and technological change $(\mu - 1)\beta > 0$. This proves the threshold effect in welfare. The Pareto-ranking result follows simply because the welfare in the transition into the balanced growth equilibrium with production in the more human capital intensive sector is increasing in the initial average level of human capital. All the results can be extended to the case of small positive λ.

(1) This is simple. Household consume their constant wages forever; welfare is $U(\omega_a)/\rho$ where $\omega_a = x_a s_a^{b'(1-a'')}(1-b)\Lambda_0$ using what has been established in (1.1) in (A.1).

(2) This is harder. But making use of the transition path as determined in equation (A.10), the welfare in the transition of an economy starting with $h_0 = h^L$ can be determined as

$$W(\vartheta(i_{aH})) = \vartheta(i_{aH})(U(\omega_a)/\rho) + (\vartheta(i_{aH}) - 1)(1/(\rho(1 - 1/\sigma)),$$

where $\vartheta(i) \equiv i/\sigma + (1-i)(1/(1-(1-1/\sigma)(g_{aY}/\rho)))$.

(3) To establish the result notice that $\vartheta(g_{aY}/(\rho + g_{aY}/\sigma)) = 1$, that $W(1) = U(\omega_a)/\rho$, and that $i_{aH} < g_{aY}/(\rho + g_{aY}/\sigma)$ because $(\alpha/(1-\beta)) < 1$. Consider the case $\sigma < 1$. In this case, $\vartheta'(i) > 0$ and $W'(\vartheta) < 0$. This implies $W(\vartheta(i_{aH})) > W(1)$ if $(\mu - 1)\beta > 0$, which is what I wanted to establish: The threshold effect arises only if there are interdependencies between human capital accumulation and technological change. All the results can be established along the same lines for $\sigma \geq 1$.

Pareto-Efficient Human Capital Accumulation

It can be established, along the lines of equations (A9), (A10), and (A11), that Pareto-efficiency would require households to make a transition into the balanced growth equilibrium with production in the less human capital intensive sector if the economy started with a level of human capital above

$$h^c - (f(1 - i_{kH}) - f(1)),$$

where $i_{kH} = \sigma((1-\beta)/\alpha)((1-\alpha)/\beta - \rho/r_H^*) > i_{aH}$ if $(\mu-1)\beta > 0$: The human capital investment rate will be lower than efficient if there are interdependencies between human capital accumulation and technological change. (If $(\mu-1)\beta = 0$ then the dynamic market equilibrium and the Pareto-efficient solution coincide. There would still be threshold effects in growth but <u>no</u> threshold effects in welfare). Because $f'(c) < 0$ for $c < 1$ (see the definition of $f(\circ)$ in the main text, after equation (23)) it follows that the efficient lower collective threshold is lower than the equilibrium lower collective threshold if there are interdependencies between human capital accumulation and technological change. It is straighforward to show that the efficient lower collective threshold can be strictly positive, which illustrates that it can be efficient to keep producing in the less human capital intensive sector if the economy starts with a very low level of human capital.

A.3. Gestation Lags and Investment under Uncertainty

In this section I want to illustrate that the estimator presented in section 4.A is consistent even if there is uncertainty at the household level and gestation lags are longer for human capital than for physical capital. I first prove that exact proportionality between human and physical capital $H_t = (vA / B)K_t$ remains true with uncertainty but equal gestation lags for human and physical capital; second, that proportionality holds in expectations $H_{t+2} = (vA / B)E_t K_{t+2}$ if gestation lags for human capital are longer.

To see the former, suppose that households maximize

$$E_t \sum_{i=0}^{\infty} \beta^{t+i} U(C_{t+i}),$$

subject to $H_t = H_{t-1} + I_{H, t-1}$ and $K_t = K_{t-1} + I_{K, t-1}$. Take the case where households have to decide about $I_{H, t+2}$ and $I_{K, t+2}$ in period $t+1$. Then the first-order necessary conditions imply $vE_{t+1}MRS_{t+2, t+1}MPH_{t+2} = 1$ and $E_{t+1}MRS_{t+2, t+1}MPK_{t+2} = 1$, where MRS denotes the marginal rate of substitution and MPH, MPK the marginal product of human and physical capital. Using that (6) implies $MPK = BY / K$ and $MPH = BY / H$, these necessary conditions imply $vAE_{t+1}MRS_{t+2, t+1}Y_{t+2} = H_{t+2}$ and $BE_{t+1}MRS_{t+2, t+1}Y_{t+2} = K_{t+2}$ and hence $H_{t+2} = (vA / B)K_{t+2}$. Now suppose that households have to decide how much to invest in human capital one period before they have to decide how much to invest in physical capital (they have to decide about about $I_{H, t+2}$ in period t and about $I_{K, t+2}$ in period $t+1$). The necessary conditions for optimality then imply

$$vE_t MRS_{t+2, t+1}MPH_{t+2} = 1 \text{ and } E_{t+1}MRS_{t+2, t+1}MPK_{t+2} = 1.$$

Hence, $H_{t+2} = vAE_t MRS_{t+2, t+1}Y_{t+2}$ and $K_{t+2} = BE_{t+1}MRS_{t+2, t+1}Y_{t+2}$, which by the law of iterative expectations yields $H_{t+2} = (vA / B)E_t K_{t+2}$.

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