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Human Capital, Technology Adoption and Development*

A. Kerem Cosar

Abstract

This paper presents a model of development in which skilled labor is an input in technology adoption. The model combines Nelson and Phelps (1966) type technology dynamics with a growth model in which intermediate goods are used to produce a final good. The intermediate good producers hire skilled labor to increase their productivity by adopting techniques from an exogenously evolving stock of world knowledge. I solve for the stationary equilibrium and derive analytic expressions for steady state income level and wage premium. In a quantitative exercise, I calibrate the model and compare its predictions with data. The model successfully accounts for cross-country income differences and within-country wage premia on skilled labor. These results strengthen the idea that different types of human capital perform separate tasks and should not be aggregated into a single stock of human capital in development accounting exercises. The availability of skilled labor is potentially much more important for development than such aggregative exercises have so far suggested.

KEYWORDS: productivity, human capital, technology adoption

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1 Introduction

As it is well-known in growth literature, productivity differences explain a significant part of the variation observed in cross-country income distribution.[1] A major determinant of productivity is the set of technologies available to firms in a country. The model presented here demonstrates that productivity differences may arise as a result of differences in skilled labor endowments which facilitate the adoption of technologies from an exogenously available set.

The idea that a link exists between technology adoption and human capital is not new. The line of thought initiated by Nelson and Phelps (1966) suggests that the role of human capital in development may go beyond its role as a mere factor of production. In this approach, human capital, in general, and education, in particular, help people to perceive, evaluate and implement new production techniques and inputs.

Empirical literature supports this approach. Using aggregate data, Benhabib and Spiegel (1997, 2005) as well as Papageorgiou (2003) find that specifying human capital as a determinant of productivity level, instead of using it as an input in the production function, gives better results in growth regressions. On a micro-level, Doms et al. (1997) show that plants with a higher share of workers in skilled occupational categories or with higher educational levels use a greater number of advanced technologies. Foster and Rosenzweig (1995) document that in the wake of the “Green Revolution” period in India, the profitability of adopting new high-yield seed varieties and chemical fertilizers is increasing in the education level of farmers.

Human capital may affect technological diffusion through various channels.[2] One channel is international trade which makes the transfer of embodied technology possible. Caselli and Coleman (2001), and Caselli and Wilson (2004) demonstrate that the amount of embodied technology in imported capital goods is positively related to the level of educational attainment. Another avenue is foreign direct investment. Xu (2000) demonstrates that the level of human capital is a key factor in explaining the level of technology diffusion from multinational companies to their host countries. Trade in ideas, as reflected by international patenting and licensing, constitutes yet another channel through which technology flows across borders. Using patenting data of OECD countries, Eaton and Kortum (1999) estimate a model of bilateral diffusion of knowledge. According to their findings, human capital of the receiving country, measured as average years of schooling,

[1] Notable papers documenting the sources of income differences are Klenow and Rodríguez-Clare (1997), Hall and Jones (1997) and Caselli (2005).

[2] For a survey of international technology diffusion, see Keller (2004).

has a significant positive impact on patenting after controlling for the degree of intellectual property protection, cost of patenting and research intensity.

The theoretical contribution of the paper is to embed the Nelson and Phelps (1966) idea into a general equilibrium model. A homogeneous final good is produced competitively by combining unskilled labor with intermediate goods. The producers of intermediate varieties operate with a constant returns to scale technology employing capital only. The productivity of an intermediate variety is a product characteristic that affects its contribution to the production of the final good. A technology adoption function describes how skilled labor helps firms to augment their productivity levels by adopting techniques from an exogenously growing world knowledge stock. The demand for a variety is increasing in its productivity in the final good production. Hence, intermediate good producers have an incentive to hire skilled labor by paying them out of the positive operating profits. Skilled labor share of the workforce is the key exogenous variable in my model.

I show the existence of a stationary equilibrium and derive analytical expressions for the steady state income level and wage premium. I calibrate the model and undertake a quantitative exercise to evaluate its success in explaining cross- and within-country income differences. The key parameter of the technology adoption function, the curvature of skilled labor, is calibrated to the US wage premium. Using these parameters, I predict income levels and wage premia for a group of countries.

As a theory of development, the model does a good job in replicating patterns of cross-country income levels by generating large productivity differences. The model simultaneously generates within-country income differences in the form of a wage premium for skilled labor. For a subset of countries with available data, the model performs reasonably well in fitting the wage premia data as well. The main quantitative contribution of the paper is the ability to simultaneously account for cross- and within country income differences.

This paper does not address the endogenous formation of skills. The question I am trying to answer is simply how far we can go in explaining income dispersion through observed skilled labor endowments. Models of endogenous skill formation include Manuelli and Seshadri (2007), and Erosa et al. (2010). A related recent paper by Stokey (2010) endogenizes human capital accumulation in a growth model with similar Nelson-Phelps type technology adoption dynamics.

Relation to the Literature This paper contributes to the literature that seeks to explain how countries benefit from an ever expanding technology frontier. Griffith et al. (2004), Howitt (2000), Klenow and Rodríguez-Clare (2005), and Parente and Prescott (1994), among others, are contributions in this line. All these papers emphasize the role of physical investment and formal research and development (R&D) expenditures in augmenting firm-level productivity. The model presented here takes a different approach. It argues that whereas many R&D activities are geared towards product innovation, certain process innovations on the factory floor or the introduction of new inputs to the production process do not necessarily involve formal R&D activities. To quote R.J. Gordon who is reporting on anecdotal evidence from his visits to six U.S. plants in various industries,

> Clearly, much of the effort directed at productivity improvement we witnessed was not being achieved within any kind of formal R&D activity, but could be classified under the general rubric of "incremental tinkering.", Gordon (2000).

It is conceivable that the knowledge needed to undertake such "incremental tinkering" on the factory floor is based on basic engineering and operations research principles. As a result, R&D intensity data misses a wide range of technology adoption efforts undertaken at firm level. This mismeasurement especially applies to developing countries which, according to UNESCO (1975), only perform 16% of global R&D expenditures in 1996. Firms in developing countries have means other than formal R&D to benefit from the evolution of the frontier. Hence, I argue that many "incremental tinkering" activities are missed by the existing R&D measures.[3]

This last point is also made by Klenow and Rodríguez-Clare (2005) who build a model of technology diffusion where R&D is needed to adopt technologies. Using data on R&D investment rates, their model delivers the results that poor countries have R&D investment rates that are too low to explain their income levels. They conclude that the true research intensities must be higher than the measured ones and call for further research to measure "research". The quantitative application of my model contributes to the literature by proposing an alternative measure of a country's true research effort through its entire stock of skilled labor defined as scientists and engineers.

Another contribution of the paper is to explain cross-country income differences consistently with returns to skills within countries. Growth-accounting exercises based on the Nelson and Phelphs framework, such as Benhabib and Spiegel (1997, 2005) and Papageorgiou (2003), can not take stock of the skill premium implications of particular functional forms. I construct a general equilibrium model

[3]In a related paper, Hashmi (2008) attributes part of the TFP dispersion to intangible capital which includes capitalized R&D. Such expenditures plausibly add to "technology capital", but are not properly measured in national income accounts. He also considers human capital as an input in accumulating intangible capital and calibrates the production function of intangible capital to U.S. data. He then backs out the cross-country TFPs. My approach is to use the observed cross-country variation in skilled workforce and then confront the data on income and wage premia.

and I am thus able to discipline the adoption technology by the evidence on wage premium.

The remainder of the paper is structured as follows: Section two introduces the economic environment, describes the equilibrium concept, and presents analytic steady state solutions. Section three presents the quantitative exercise, pins down parameter values through calibration and compares model predictions with data. Section four concludes.

2 Model Economy

At time t, the economy is composed of a continuum of identical households of measure one, intermediate goods producers with a mass of M_t, a representative firm producing a final good and a government.

Each household consists of workers with measure L_t. Population grows by the rate g_ℓ,

$$\dot{L}_t = g_\ell L_t.$$

There are two types of workers in the economy: skilled and unskilled. A fraction $s \in (0,1)$ of each household is skilled and the rest is unskilled. Each unskilled worker is endowed with u units of efficiency labor and one unit of time. Aggregate endowment of skilled and unskilled labor are sL_t and $u(1-s)L_t$ respectively.

Besides the labor market, there are capital and financial markets in operation where intermediate good producers rent capital from households, and households can trade one-period bonds and the shares of these firms among each other. Now I turn to the description of production technologies.

2.1 Production

The structure of production is similar to Howitt (2000). There is a final good and a continuum of intermediate goods indexed by i. The final good can be consumed or employed as capital in the production of intermediate goods. It is produced competitively by a representative firm using intermediate goods and unskilled labor:

$$Y_t \;=\; L_{u,t}^{1-\alpha}\left[M_t^{-(1-\alpha)}\int_0^{M_t} A_t(i)\frac{x_t(i)^\alpha}{\alpha(1-\alpha)}\,di\right], \tag{2.1}$$

where $x_t(i)$ is the quantity of intermediate good used and $A_t(i)$ is its productivity. The normalization with respect to M_t eliminates the growth effect of expanding intermediate good varieties.[4] The final good producer takes the unskilled wage $w_{u,t}$ and intermediate good prices $p_t(i)$ and productivity levels $A_t(i)$ as given, and solves the static problem of maximizing (2.1) by optimally choosing $L_{u,t}$ and $x_t(i)$ every period.

The marginal product of each variety is independent of other varieties used in production. Each variety i is a distinct product and its producer has a monopoly right over its supply.[5] The marginal product of each variety goes to infinity as its quantity goes to zero. This implies that, for any price level, the representative final good firm demands a positive amount of each available variety.

The number of varieties grows proportionally to the size of the population,

$$\dot{M}_t \; = \; \varphi L_t.$$

This assumption eliminates scale effects. The ratio of the population to varieties monotonically converges to the constant given by:

$$\lim_{t \to \infty} \frac{L_t}{M_t} \; = \; \frac{g_\ell}{\varphi},$$

which I assume is equal to one by setting $\varphi = g_\ell$.[6] The number of unskilled production workers per variety converges to a constant as well:

$$\ell_u \; = \; \frac{L_{u,t}}{M_t} \; = \; \frac{L_{u,t}}{L_t}\frac{L_t}{M_t} \; = \; u(1-s). \tag{2.2}$$

The last equality holds in equilibrium where unskilled labor demand $L_{u,t}$ is equal to its supply $u(1-s)L_t$. I also assume that the two types of labor cannot be substituted with each other.

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[4]This channel is well understood through the contribution of endogenous growth models in the style of Romer (1990). In the context of technology diffusion, Barro and Sala-i Martin (1997) study the effects of increasing product varieties through imitation by the South. I abstract from this source of growth since my focus here is on the evolution of what one can call process efficiency, and not TFP gains through expanding product variety.

[5]This assumption is not crucial for the argument here. One can write a CES composite of differentiated intermediate goods, such as

$$Y_t \; = \; L_{u,t}^{1-\alpha} \left[M_t^{-(1-\gamma)} \int_0^{M_t} A_t(i) \frac{x_t(i)^\gamma}{\gamma(1-\gamma)} \, di \right]^{\frac{\alpha}{\gamma}},$$

and derive the same results. The analysis here corresponds to the case $\gamma = \alpha$.

[6]This assumption is not innocuous when one compares income levels across countries unless one also assumes identical population growth rates. This is what I implicitly do in the quantitative section.

Using these results in (2.1), I can restate the production function of the representative final good producer as

$$Y_t = \int_0^{M_t} A_t(i)\ \frac{x_t(i)^{\alpha}\ell_u^{1-\alpha}}{\alpha(1-\alpha)}di. \tag{2.3}$$

The demand for an intermediate good is given by the inverse demand function:[7]

$$p_t(i) = \frac{A_t(i)}{1-\alpha}x_t(i)^{\alpha-1}\ell_u^{1-\alpha},$$

which yields total revenues as

$$Revenue[x_t(i)] = \frac{A_t(i)}{1-\alpha}x_t(i)^{\alpha}\ell_u^{1-\alpha}.$$

Now I introduce the technology for producing intermediate goods. Capital is the only input and the production function is given by:

$$x_t(i) = \frac{k_t(i)}{A_t(i)}, \tag{2.4}$$

which has the feature that more productive varieties also require a more capital intensive production technology. Intermediate goods producers rent capital at a cost of R_t. The associated cost function is given by:

$$Cost[x_t(i)] = R_t A_t(i) x_t(i).$$

The demand for capital is determined by setting marginal cost equal to marginal revenue which yields

$$R_t = \frac{\alpha}{1-\alpha}\left(\frac{x_t(i)}{\ell_u}\right)^{\alpha-1}. \tag{2.5}$$

Note that nothing in (2.5) depends on firm characteristics. All firms supply the same quantity of intermediate good, i.e.,

$$x_t(i) = x_t.$$

[7] This is derived by the solution to the problem

$$\max_{\{x_t(i)\},\ell_{u,t}} \int_0^{M_t} A_t(i)\frac{x_t(i)^{\alpha}\ell_u^{1-\alpha}}{\alpha(1-\alpha)}di - \int_0^{M_t} p_t(i)x_t(i)di - \ell_{u,t}M_t w_{u,t}.$$

Static operating profits after rental payment is given by:

$$\pi_t(i) = A_t(i) x_t^{\alpha} \ell_u^{1-\alpha}.$$

Since the profit for a variety is increasing in its efficiency in the production of the final good, intermediate good producers have an incentive to invest in the augmentation of $A_t(i)$. In the following subsection, I describe the evolution of the productivity term $A_t(i)$ as a function of skilled labor employed in the process.

2.2 Technology Dynamics

The evolution of the technology motivated by the technology adoption model of Nelson and Phelps (1966). At each period, there is a world stock of ideas of size T_t.[8] This stock exogenously grows at a constant rate $\lambda > 0$,

$$\dot{T}_t \; = \; \lambda \, T_t. \tag{2.6}$$

For each firm, however, the growth rate of $A_t(i)$ depends on the number of skilled labor employed and the current distance to T_t. When the firm hires $\ell_{s,t}(i)$ measure of skilled labor, its technology evolves according to

$$\dot{A}_t(i) \; = \; \ell_{s,t}^{\beta}(i) \left(\frac{T_t}{A_t(i)} \right)^{\eta} A_t(i). \tag{2.7}$$

The functional form reflects the two mechanisms affecting the evolution of productivity. The first mechanism is automatic diffusion from the frontier given by the term T/A. The bigger the gap to the frontier, the higher is the speed of the productivity increase. The second mechanism is the employment of skilled labor by a firm. The following restrictions on the two technology adoption parameters (β, η) guarantee that the firm problem of optimal skilled labor choice has a solution:

$$\begin{aligned} \beta \; &\in \; (0,1), \\ \eta \; &\in \; [\beta, 1]. \end{aligned}$$

For the rest of the analysis, I restrict attention to the symmetric case where a representative firm with average productivity A_t is given by:

$$A_t = \frac{1}{M_t} \int_0^{M_t} A_t(i) \, di.$$

[8]Nelson and Phelps refer to T_t as ‘theoretical level of technology’ and to A_t as ‘technology in practice’.

By symmetry, the representative firm employs skilled labor of measure

$$\ell_{s,t} \;=\; \frac{sL_t}{M_t} \;=\; s. \tag{2.8}$$

Using (2.2) and (2.8) in (2.7), the law of motion for technology is given by the function

$$\dot{A}_t \;=\; s^{\beta}\left(\frac{T_t}{A_t}\right)^{\eta} A_t, \tag{2.9}$$

which has the limit property

$$\lim_{t\to\infty}\frac{A_t}{T_t} \;=\; \left(\frac{s^{\beta}}{\lambda}\right)^{\frac{1}{\eta}}. \tag{2.10}$$

The share of skilled labor in employment, s, has a level effect on the distance to the frontier and on output.

Having introduced the static profit maximization and the adoption technology, I can now define the firms' dynamic problem. The discount rate used by the firm is equal to the interest rate r_t in the bond market. Let $w_{s,t}$ be the wage rate for skilled labor. Firms rent capital and hire skilled labor by rationally anticipating the future path $\{R_t, w_{s,t}, r_t\}_{t=0}^{\infty}$ of factor prices and the interest rate. Since they face a downward-sloping demand curve, they earn strictly positive rents given by $\pi_t = A_t x_t^{\alpha}\ell_u^{1-\alpha}$. Skilled labor is paid out of this rent and the expenditure $w_{s,t}\ell_{s,t}$ can be considered as a technology adoption investment. The net profit after all factor payments is distributed as dividends and is given by:

$$\Pi_t \;=\; A_t x_t^{\alpha}\ell_u^{1-\alpha} - w_{s,t}\ell_{s,t}.$$

Starting with an initial technology level A_0, representative firm's problem is to choose factor demands $\{k_t, \ell_{s,t}\}_{t=0}^{\infty}$ in order to maximize the discounted sum of dividends,

$$V(A_0) \;=\; \max\int_{t=0}^{\infty} e^{-\bar{r}(t)\cdot t}\,\Pi_t\,dt, \tag{2.11}$$

subject (2.4), (2.6), (2.7), (2.9) and the average interest rate between times 0 and t is defined as $\bar{r}(t) = (1/t)\cdot\int_0^t r_v\,dv$. As discussed in the Appendix, dividends are positive in steady state. Total dividends, $D_t = M_t\Pi_t$, are collected by the households who own the firms. Next, I turn to the description of the household problem.

2.3 Households

The representative household is composed of two types of members: skilled and unskilled. I assume that the fraction of skilled members, s, is exogenously given. The representative household is endowed with $(1-s)uL_t$ units of efficiency units of unskilled labor and sL_t units of skilled labor. Both types of labor are supplied inelastically.

The representative household owns physical capital K_t which depreciates by a rate of δ. It accumulates capital by investing $(1+\theta)\mathrm{N_t}$ out of its budget. The term θ is the time-invariant tax/subsidy rate that the government implements on purchases of investment goods. Households' capital stock evolves according to

$$\dot{K}_t \;=\; \mathrm{N_t} - \delta K_t. \tag{2.12}$$

Households are also endowed with equal shares of the representative intermediate good producer denoted by a_t. These shares can be traded any period at post-dividend share prices given by q_t. There is a market for bonds with one period maturity where households can borrow and lend by the market interest rate r_t. Bond holdings are given by b_t.

Let C_t denote the total consumption of the household. The budget constraint is given by

$$C_t+(1+\theta)\mathrm{N_t}+q_tS_t+B_t = w_{s,t}sL_t+w_{u,t}(1-s)uL_t+R_tK_t+D_ta_t+(1+r_t)b_t+Z_t, \tag{2.13}$$

where S_t is purchase of new shares, B_t is purchase of new bonds, Z_t is tax rebates (or lump-sum taxation) and a_t is fraction of intermediate firm equity owned by the household. The law of motion for a_t and b_t are given by

$$\dot{a}_t \;=\; S_t, \tag{2.14}$$

$$\dot{b}_t \;=\; B_t. \tag{2.15}$$

Household members only value consumption. Members equally split the total consumption C_t. Momentary utility of a member is given by $\ln(C_t/L_t)$. The future path of dividends and tax rebates, $\{D_t, Z_t\}_{t=0}^{\infty}$, as well as that of prices, $\{q_t, R_t, w_{u,t}, w_{s,t}\}_{t=0}^{\infty}$, are taken as given by the household. The problem faced by the representative household with initial endowments (a_0, b_0, K_0) is then to make consumption and investment decisions $\{C_t, \mathrm{N_t}\}_{t=0}^{\infty}$, and asset trades $\{S_t, B_t\}_{t=0}^{\infty}$ to maximize the discounted sum of utility,

$$U(a_0, b_0, K_0) \ = \ \max \int_0^{\infty} e^{-(\rho - g_\ell)t} \ \ln(C_t/L_t) \ dt. \qquad (2.16)$$

subject to the constraints (2.12), (2.13), (2.14) and (2.15) under the assumption $\rho > g_\ell$.

2.4 Equilibrium

An equilibrium for this economy is a tax rate θ and sequence of government rebates $\{Z_t\}_{t=0}^{\infty}$, a set of prices $\{p_t, w_{s,t}, w_{u,t}, R_t, r_t, q_t\}_{t=0}^{\infty}$, a final good producer with factor demands $\{L_{u,t}, x_t\}_{t=0}^{\infty}$, intermediate good producers of measure M_t with factor demands $\{k_t, \ell_{s,t}\}_{t=0}^{\infty}$, identical households of measure one who own capital stock $\{K_t\}_{t=0}^{\infty}$, labor endowments $\{sL_t, (1-s)uL_t\}_{t=0}^{\infty}$ and undertake sequences of asset trades $\{S_t, B_t\}_{t=0}^{\infty}$, consumption and investment decisions $\{C_t, \mathrm{N_t}\}_{t=0}^{\infty}$, such that

1. given $\{w_{u,t}, p_t\}_{t=0}^{\infty}$, the representative final good producer demands the input bundle $\{L_{u,t}, x_t\}_{t=0}^{\infty}$ that minimizes its costs,

2. given $\{w_{s,t}, R_t, r_t\}_{t=0}^{\infty}$, factor demands $\{k_t, \ell_{s,t}\}_{t=0}^{\infty}$ solve the representative intermediate good producer's problem,

3. given $\{D_t, Z_t, q_t, R_t, r_t, w_{u,t}, w_{s,t}\}_{t=0}^{\infty}$, consumption, investment, and asset trade decisions $\{C_t, \mathrm{N_t}, S_t, B_t\}_{t=0}^{\infty}$ solve the representative household problem, yielding a capital supply of $\{K_t\}_{t=0}^{\infty}$,

4. capital market clears: for all t, $k_t M_t = K_t$,

5. labor markets clear: for all t, $\ell_{s,t} M_t = sL_t$ and $\ell_{u,t} M_t = (1-s)uL_t$,

6. asset and bond markets clear with no trade since all households are identical: for all t we have $S(t) = 0$ and $B(t) = 0$,

7. the intermediate goods market clears: the demand for x_t by the final good producers is met by its supply,

8. the final good market clears: for all t, we have $Y_t = C_t + \mathrm{N_t}$,

9. government's budget is balanced: for all t, we have $\theta \mathrm{N_t} = Z_t$.

2.5 Aggregation and the Steady State

I first aggregate the variables of interest generated by the model and then analyze their steady state properties. The existence of a steady state equilibrium is shown at the Appendix.

I have shown that all intermediate good producers supply an equal amount of x_t. The final good producer employs ℓ_u unskilled workers per intermediate good. Letting $x_t(i) = x_t$ in (2.3), aggregate output is equal to:

$$Y_t = \frac{x_t^{\alpha}\ell_u^{1-\alpha}}{\alpha(1-\alpha)} \int_0^{M_t} A_t(i)\, di. \tag{2.17}$$

Aggregating the capital demand $k_t(i) = A_t(i)x_t$ over i, and using the capital market clearance condition $\int_0^{M_t} k_t(i)\, di = K_t$, one obtains:

$$x_t = \frac{K_t}{M_t A_t}. \tag{2.18}$$

And by labor market clearance, we have

$$\ell_u = (1-s)u\frac{L_t}{M_t} = (1-s)u.$$

Using these expressions in (2.17), and recognizing that $\int_0^{M_t} A_t(i)\ di = M_t A_t$, aggregate output is:

$$Y_t = \nu[(1-s)u]^{1-\alpha} K_t^{\alpha}(A_t L_t)^{1-\alpha}. \tag{2.19}$$

where $\nu = \frac{1}{\alpha(1-\alpha)}$ is a re-scaling constant which I drop for the remainder of the paper. The aggregate output of this economy displays constant returns to scale with labor-augmenting technological change.

Capital-output ratio in steady state is constant and it is a function of taste, technology and distortion parameters. As expected, it is decreasing in the level of distortions:

$$\frac{K}{Y} = \frac{\alpha^2}{(r_{ss}+\delta)(1+\theta)}. \tag{2.20}$$

In order to analyze the implications of the model on per-capita income, I transform variables into their stationary counterparts. I start with the TFP term. Revoking (2.10), the steady state limiting gap between the frontier and a country's productivity is a function of its skilled labor fraction. With a little abuse of notation in skipping the limit expression, this gap is given by:

$$g(s) \;=\; \frac{A}{T} \;=\; \lambda^{-\frac{1}{\eta}}\; s^{\frac{\beta}{\eta}}.$$

Comparative statics with respect to (s, λ) are intuitive. Relative technology is increasing in s since a higher skilled labor supply facilitates technology adoption form the frontier. It is decreasing in the growth rate λ since a rapidly expanding frontier makes catch-up harder.

Let $\tilde{y}$ denote normalized aggregate output per capita $Y_t/(L_t T_t)$. Substituting (2.20) into (2.17) and re-arranging terms, per-capita stationary income is equal to:

$$\tilde{y}_{ss} = g(s)(1-s)u\left[\frac{\alpha^2}{(r_{ss}+\delta)(1+\theta)}\right]^{\frac{\alpha}{1-\alpha}}. \tag{2.21}$$

The non-substitutability of the two types of labor causes per-capita income to display an inverse-U shaped relationship with s. Although $g(s)$ is increasing, it is bounded by one. As s increases, there are not enough unskilled workers to undertake production tasks and this leads to a decline after a certain level of s^* where $\tilde{y}_{ss}$ is maximized. Alternatively, as u increases, the range of s over which per-capita income is decreasing narrows. In other words, an economy with an increasing share of skilled labor in the workforce can escape a decline in per-capita income by increasing the efficiency of its unskilled labor. Finally, note that the model is silent on whether the optimum s^* will be attained in equilibrium since it is treated as exogenous.

In steady state, technology level A_t grows at a stationary rate equal to λ, which is also the growth rate of per-capita quantities. Interest rate and rental rate of capital are constant:

$$r_{ss} = \rho + \lambda, \tag{2.22}$$

$$R_{ss} = (r_{ss}+\delta)(1+\theta). \tag{2.23}$$

The rental rate of capital is increasing in investment distortions which tend to make capital more costly.

Finally, I present the wage premium of the skilled over efficiency units of unskilled labor,

$$\frac{\tilde{w}_s}{\tilde{w}_u} = \frac{\alpha\beta\lambda}{\eta\lambda+\rho}\;\frac{(1-s)}{s}\;u. \tag{2.24}$$

As expected, the wage premium is decreasing in s and increasing in u. A faster rate of growth in the frontier, reflected by a higher λ, leads to an increase in the wage premium, a similar result to Greenwood and Yorukoglu (1997). This result is quite intuitive. If the frontier expands at a faster rate, there is a greater stock of knowledge to adopt and the marginal product of skilled labor increases. A higher discount rate ρ, on the other hand, increases the interest rate which depresses the wage premium since hiring skilled labor is like an investment in technology.

The model generates predictions for the income level and the wage premium in equations (2.21) and (2.24) respectively. Next, I undertake a quantitative exercise to evaluate whether the model can simultaneously account for cross-country and within-country income differences.

3 Quantitative Implications of the Model

In order to bring the model to data, I measure skilled labor as scientists and engineers (S&E) with a college degree. This choice is motivated by micro evidence. Doms et al. (1997) find that the positive association between technology use in U.S. manufacturing plants and the share of skilled workers in their workforce is primarily due to a higher share of scientists and engineers. Another reason for restricting attention to S&E degree holders among college graduates is that not all university majors are equally relevant for technology adoption activities. Murphy et al. (1991) report a positive relationship between the share of engineering majors in university enrollment and growth performance of countries. Enrollment in law, on the other hand, has a negative impact on growth.[9]

Although the stock of S&E degree holders is a reasonable proxy for the kind of skills that matter for technology adoption, it is limited on two fronts. First, some scientists and engineers innovate new technologies rather than adopt existing ones. This group, however, does not constitute the majority. In the U.S., only 30.2% of S&E degree holders have R&D as a major work activity.[10] This fraction is plausibly much lower in developing countries. Second, differences in education systems matter. In some countries, technical and vocational secondary schools play an important role in training skilled workers. I will further discuss this measurement problem in Section 3.2 when I present the results.

I choose 1985 as the year of analysis because the college enrollment in the U.S. was relatively stationary around 25% between 1965-1980.[11]

[9] Murphy et al. (1991) consider engineering and law majors as proxies for entrepreneurship versus rent-seeking. For the purpose of this paper, their empirical evidence shows that not all college degrees are the same from a growth perspective.

[10] http://www.nsf.gov/statistics/seind10/c3/tt03-06.htm

[11] Data from Current Population Survey, Historical Tables A-5a. Available in http://www.census.gov/population/www/socdemo/school.html

3.1 Calibration

I calibrate the set of parameters $(\alpha, \delta, \lambda, \rho, \beta, \eta)$ by matching some key statistics of the U.S. data to the steady state characteristics of the model and the evidence on the rate of convergence to the steady state.

The growth rate of per worker output in the model, λ, is set equal to 0.02 to match the average growth rate of real GDP per equivalent adult in the U.S. between 1950-1985. Using this value, I set $\rho = 0.02$ to match an average real interest rate of $r_{ss} = 4\%$ in (2.22).

The depreciation rate δ and the production function parameter α are calibrated to the U.S. investment rate N/Y and the capital-output ratio K/Y. The law of motion for capital implies that $\delta = N/K - \lambda$. The investment rate and capital-output ratio (based on yearly output) in the U.S. are roughly 0.2 and 2.5 respectively. This implies $N/K = 0.2/2.5 = 0.08$, and $\delta = 0.06$. Finally, α is calibrated to match the capital-output ratio, given by expression (2.20), to its U.S. value of 2.5 which yields $\alpha = 0.5$.

The parameters of the technology adoption function, (β, η), are pinned down by the implied rate of convergence to the steady state and the wage premium. In the Appendix, I show that the rate of convergence is equal to $\eta\lambda$. I set η equal to 1, the upper bound of permissible values for this parameter, to be consistent with the evidence of a rate convergence rate around 0.02 reported by Barro and Sala-i Martin (2004).[12] Finally, I use the wage premium expression (2.24) and the U.S. values for (s, u, θ) to pin down β. Scientist and engineers as a share of total U.S. labor force is computed as 3.7% in 1985. According to Heston et al. (2006), the average relative price level of investment over that of consumption in U.S. between 1950-1985 is one. In the one-sector model presented here, this ratio corresponds to $1 + \theta_{us}$ which yields $\theta_{us} = 0$. Details about the computation of u and s can be found in the Appendix. Table 1 summarizes the parameter values.

How does the assumption of no substitutability between the two types of human capital affect the calibration of β? It is more likely that skilled workers can substitute the unskilled but not the other way. In such a case, the equilibrium wages of both types will be equal if there are skilled workers in unskilled jobs. As long as all skilled workers are employed at technology adoption tasks, both types will be paid their marginal contribution and the wage premium expression above will hold. Also, given the measured (u, s) levels, all countries fall into the range where where per-capita income is increasing is increasing in s.

[12] There is a knife-edge case in calibrating η: in order skilled labor demand to be finite, we need $\eta \leq 1$. Given $\lambda = 0.02$, we cannot target a convergence rate higher than 0.02 while being consistent with this restriction. In other words, the model is not compatible with convergence rates higher than the value of λ.

Parameter	Target	Value
α	Capital-output ratio	0.5
δ	Investment rate/capital-output ratio	0.06
λ	U.S. per worker growth rate	0.02
ρ	Real interest rate $(= \rho + \lambda)$	0.02
η	Speed of convergence to steady state $(= \eta\lambda)$	1
β	U.S. wage premium	0.30

Table 1 – Calibrated Parameters

A discussion of the calibrated value of $\alpha = 0.5$ is in order. This figure is higher than the commonly used value of $1/3$. The comparison, however, is misleading. Note that although the model delivers the same aggregate production function (2.17) as the neoclassical model, its micro-foundations are quite different. The marginal revenue product of capital in the neoclassical model is $\alpha K^{\alpha}(AL)^{1-\alpha}$, whereas it is $\alpha^2 K^{\alpha}(AL)^{1-\alpha}$ in this paper (ignoring the normalization with respect to $\alpha(1-\alpha)$ in equation (2.1)). In that sense, α^2 is qualitatively comparable to α in the benchmark model. Quantitatively, calibrating α around $0.5 - 0.6$ puts α^2 into the ballpark of the benchmark figure of $1/3$. A look at the share of total wage bill in output confirms this point. In the model, α determines the share of payments to (unskilled) production workers only. Total wage bill is higher when we account for wages paid to skilled labor. With this calibration, 62.3% of total output is labor compensation which is in line with the U.S. data: the average share of employee compensation in gross domestic product over 1970-1985 is 59% (calculated from OECD.Stat Extracts database).

3.2 Cross-Country Income Differences

In this section, I investigate whether the model can account for the cross-country income differences seen in the data.[13] I assume that the parameter values for $(\alpha, \delta, \lambda, \rho, \beta, \eta)$ are common across economies. I use the steady state income expression (2.21) and the observed variation in (s, u, θ) to derive the cross-country relative income predicted by the model. The U.S. is the benchmark country and model-generated relative income is

$$\frac{\tilde{y}_i}{\tilde{y}_{us}} = \frac{1-s_i}{1-s_{us}}\left(\frac{s_i}{s_{us}}\right)^{\frac{\beta}{\eta}}\frac{u_i}{u_{us}}\left(\frac{1+\theta_{us}}{1+\theta_i}\right)^{\frac{\alpha}{1-\alpha}}. \tag{3.1}$$

[13] Caselli (2005) provides a survey of the success of various models in that regard.

		Models						
Statistic	Data	Benchmark	s only	u only	θ only	(u,θ) only	(u,s) only	(s,θ) only
Mean	0.432	0.354	0.647	0.539	0.950	0.520	0.361	0.626
St. Dev.	0.281	0.225	0.163	0.153	0.377	0.261	0.172	0.307
Median	0.345	0.323	0.651	0.492	0.976	0.476	0.339	0.640
Minimum	0.040	0.085	0.351	0.334	0.230	0.134	0.134	0.155

Table 2 – Key Development Accounting Statistics

Data about relative price of investment and income are from Heston et al. (2006). The former is the relative price of investment over that of consumption averaged over all available data points between the years 1950-1985. Observed income is real GDP per worker in 1985. I have a sample of 58 market economies countries with complete data.

Figure 1 and Tables 2, 3 and 4 summarize the results. In all tables, *benchmark model* refers to the predictions of equation (3.1) where all three components, (s, u, θ) vary across countries. Figure 1 plots relative income data against the benchmark model. In order to assess the contribution of each channel to output dispersion, I report the results separately by holding various components fixed while varying the others, i.e. the column "*s only*" means that (u, θ) are held constant across countries in equation (3.1).

As evident from Table 2, the benchmark model does a good job in matching the median of world income distribution. None of the components in isolation can capture this key statistic. Especially poor is the performance of the model with relative price differences. It predicts mean and median income levels close to 1. Differences in unskilled human capital do better ("u only" model) but still overpredict income levels. Adding s differences improves the performance considerably ("*(u,s) only*" model). None of the models correctly predict the mean income, but the benchmark and "*(u,s) only*" models are closer to it than others. Ghana has the lowest per-capita income level both in the data (4% of the U.S. level) and in the model (8.5% of the U.S. level).

To check whether some of these moments are correctly captured for the right countries, Table 2 provides product-moment and rank correlations between model outcomes and data. All correlation statistics suggest that the mechanism proposed here is much better in capturing income ranking across countries than other components.

Finally, Table 4 reports income levels at various percentiles. The benchmark and "*(u,s) only*" models capture the variation up to the $80th$ percentile quite well. On the other hand, the model with differences in unskilled human capital and relative price of capital ("*(u, θ) only*" model) is better in fitting the data for the $80th$ and $90th$ percentiles. This suggests that the main impediment to development may vary with stages of development: for very poor countries, skill shortages seem to play a big role, whereas for countries closer to the frontier, barriers to capital accumulation matter more.

Coming back to the benchmark model, the interpretation of the failure to explain higher income percentiles is that according to the model, developed countries in general have too few scientists and engineers in the workforce to explain their relative income levels vis-$\grave{a}$-vis the U.S. This point relates to the literature in the following way. Klenow and Rodríguez-Clare (2005) construct and calibrate a similar model with international diffusion and externalities. They measure technology adoption effort through R&D investment. Quantitatively, they obtain the opposite results. Productivity (and thus income) levels of rich countries are accurately predicted but poor countries have too little R&D investment to be consistent with their levels of development. They suggest that the 'true' research intensities are higher than the observed ones, and that informal research could be potentially important in non-OECD countries.[14] The contribution of my paper is to capture this unobserved technology adoption effort through the measurement of the type of workers who are likely to be engaged in technology related activities regardless of whether they are employed in a formal R&D department or not. Of course, human capital is not the only input into the technology adoption process. Real resources such as labs and equipment are used as well. The model, however, does not take them into account and is thus unable to explain higher income levels. A more elaborate model which includes both types of inputs is likely to explain the data better.

Another explanation for why the model fails to capture the income levels at $80th$ and $90th$ percentiles lies in the international differences in education systems. A closer look at the lower right quadrant of Figure 1 reveals that the model underpredicts the income level of many European countries. In these countries, vocational and technical secondary education plays an important role. Consequently, defining technology-adoption relevant skills by a S&E degree at the tertiary level undermeasures the skilled workforce for them.[15] An ideal measure of technology-adoption relevant skills would have to capture the variation in educational systems across countries. This remains an important avenue for future research.

	Models						
Statistic	Benchmark	s only	u only	θ only	(u,θ) only	(u,s) only	(s,θ) only
Pearson's r	0.598	0.613	0.337	0.394	0.471	0.532	0.615
Spearman's rho	0.649	0.602	0.433	0.497	0.539	0.564	0.679
Kendall's tau	0.464	0.437	0.312	0.321	0.364	0.410	0.475

Table 3 – Correlations of Predicted Incomes with the Data

[14]Córdoba and Ripoll (2007) obtain a similar result using an alternative model.

[15]To substantiate this claim, I obtained data on vocational and technical enrollment

		Models						
Percentile	Data	Benchmark	s only	u only	θ only	(u,θ) only	(u,s) only	(s,θ) only
$10th$	0.120	0.095	0.432	0.384	0.481	0.189	0.176	0.235
$20th$	0.186	0.152	0.487	0.430	0.641	0.286	0.211	0.363
$40th$	0.302	0.227	0.626	0.483	0.855	0.437	0.316	0.472
$60th$	0.427	0.396	0.694	0.536	1.013	0.544	0.365	0.725
$80th$	0.756	0.513	0.78	0.619	1.202	0.765	0.464	0.889
$90th$	0.836	0.702	0.846	0.724	1.443	0.861	0.597	1

Table 4 – Relative Incomes at Various Percentiles

3.3 Within-Country Income Differences

I have disciplined the parameters of the model to be consistent with the U.S. wage premium on skilled labor and used these values in the development accounting exercise above. In this section, I investigate the ability of the model to account for within-country income difference between S&E degree holders and the rest of the workforce.

Empirical wage premia are obtained using the cross-country rates of return education reported by Psacharopoulos (1994). The measurement of the wage premium is not based on a Mincerian approach because the rental rate of the two types of human capital are different. In the Mincer approach, human capital is measured in efficiency units and more educated workers are simply more efficient in performing the same task. In my model, the two types of human capital perform separate tasks and are paid different rental rates. I employ the method described in Psacharopoulos (1995) to back out the wage premia using the reported rates of return to education. Detailed description of the data is provided in the Appendix.

I report all wage premia in logs. The sub-sample for which data is available consists of 43 countries. The sample mean and standard deviation are 2.99 and 1.53 respectively. The U.S. value used in calibration is 1.84. Using expression (2.24), I generate wage premia predictions for the sub-sample of countries. How independent is this wage premium from Mincer returns? Looking at equation (2.24), one could ask whether u is the primary source of variation in skill premium. Let's define $\phi(s) = (1-s)/s$, and write the variance of log wage premium as

$$var[log(w_p)] = var[log(\phi(s)] + var[log(u)] + 2cov[log(\phi(s), log(u)].$$

(VTE) in upper-secondary education (see UNESCO Institute for Statistics, Table 5 in http://stats.uis.unesco.org). Data is available for 55 of the 58 countries in the original sample. Model's income prediction (relative income predicted by the model over that in the data) systematically varies by VTE. The correlation is -0.267: incomes of countries with above average VTE are indeed underpredicted.

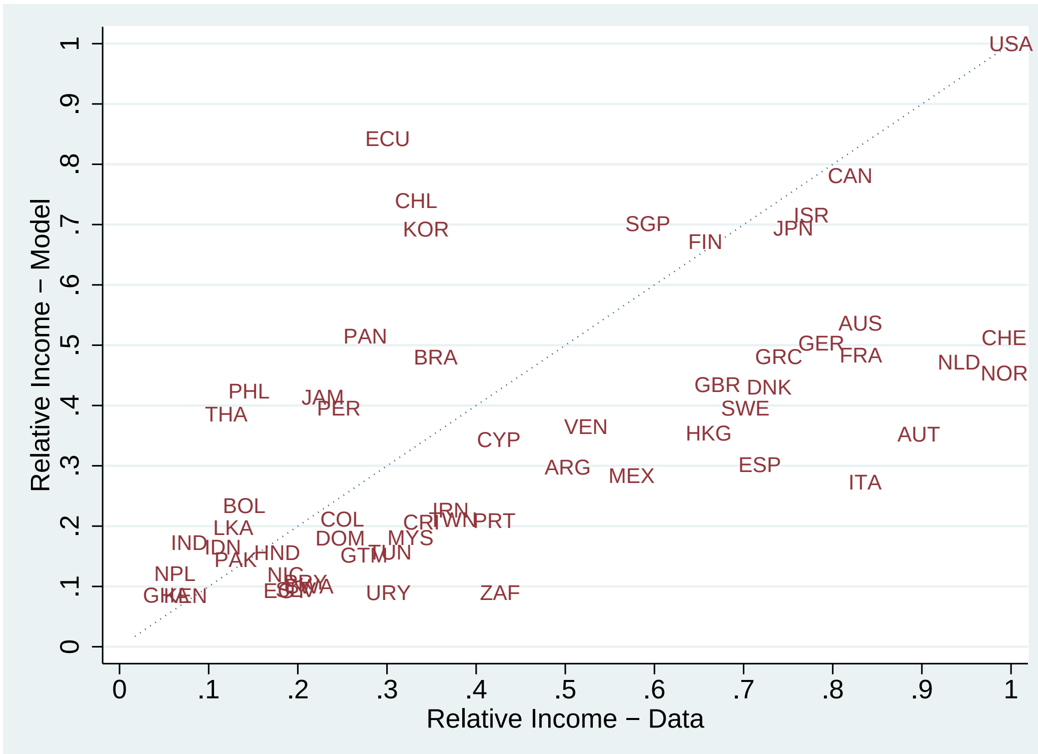

Figure 1 – Relative Incomes, Benchmark Model vs. Data

Using the data provided in Table 6, these magnitudes are $var[log(\phi(s)] = 0.167$, $var[log(u)] = 0.012$, and $cov[log(\phi(s), log(u)] = -0.023$. So the variation in predicted wages is primarily driven by the variation in s.

Figure 2 plots model generated wage premia against the data. The model does not systematically under- or overestimate the wage premia across countries except two outliers (Botswana and Puerto Rico). Given that the values are in logs, there is a non-negligible absolute error for some countries such as Jamaica, Kenya, Pakistan and Taiwan. Most of the countries, however, are aligned around the 45^o degree line. 8 out of 43 countries are predicted within a 10% error margin, and 22 countries are within a 20% error margin. Pearson's product-moment correlation and Spearman's rank correlation coefficients between data and model predicted wage premia are 0.52 and 0.439 respectively. The model mean is 2.843 compared to the data mean of 2.99. On overall, the model captures the pattern in the data.

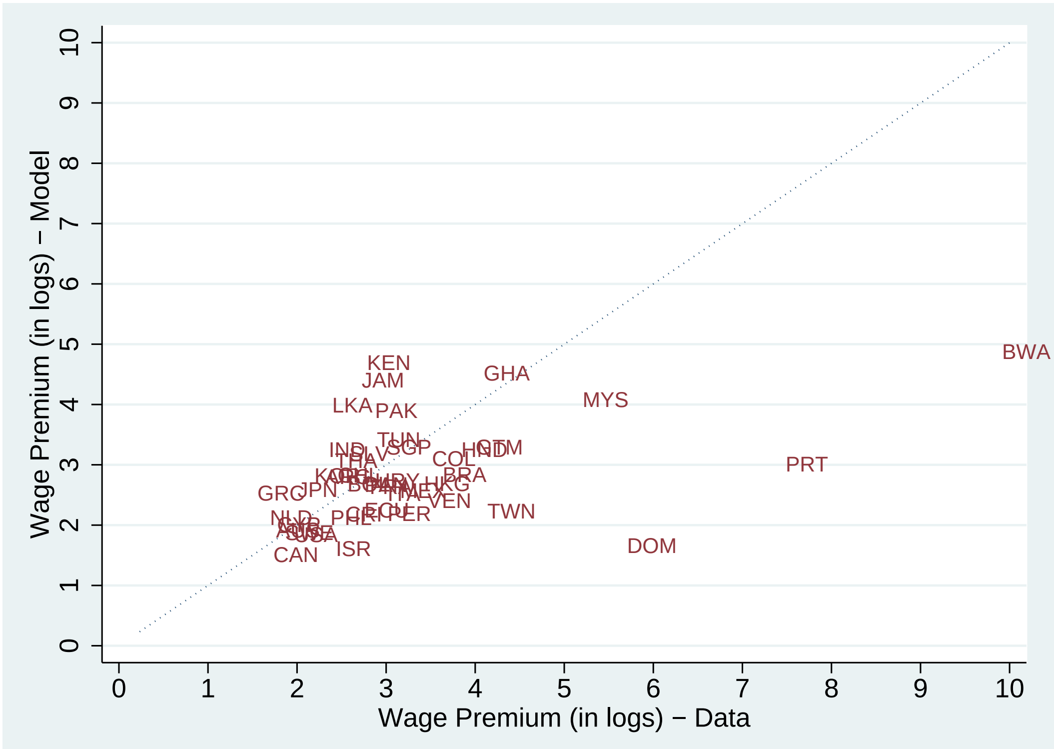

Figure 2 – Wage Premia, Model vs. Data (in logs)

In a recent contribution, Caselli and Coleman (2006) use country-specific wage premia to pin down unobserved productivity levels of skilled and unskilled labor and analyze whether these 'calibrated' productivity differences can explain income differences. The quantitative approach here differs from theirs in that it uses one observation (U.S. wage premium) to discipline the relevant structural parameter, and resorts to observable variables only to generate predictions on cross- and within-country income differences.

4 Sensitivity Analysis

The two non-standard parameters of the model are β and η. This section investigates the sensitivity of the results with respect to these parameters. Note that what matters for international income differences is the ratio of β/η in equation (3.1). A higher ratio amplifies the importance of skill differences across countries. It thus makes sense to consider the case when β/η is lower than its calibrated value. Furthermore, note that η is already calibrated to its maximum permissible value of 1. The only variation left to look at is when β has a value less than 0.3.

Statistic	Data	Benchmark $\beta = 0.3$	Full model with $\beta = 0.25$	Full model with $\beta = 0.2$
Mean	0.432	0.354	0.377	0.403
St. Dev.	0.281	0.225	0.229	0.234
Median	0.345	0.323	0.343	0.364
Minimum	0.040	0.085	0.097	0.104

Table 5 – Sensitivity of Income Statistics With Respect To β

I calibrated β to match a skill premium of 6.13 in the U.S. It is possible that the procedure used to map the model wage premium to the data suffers from measurement errors (see Appendix B). For instance, I used the minimum wage rate as the opportunity cost of higher education in calculating the empirical wage premium. Many unskilled workers, however, earn more than the minimum wage.[16] This overstatement of wage premium leads to an upward bias in calibrating β.

In Table 5, I report cross-country income statistics for $\beta = 0.25$ and $\beta = 0.2$. These values correspond to a wage premium of 5.22 and 4.18, respectively.

As expected, predicted relative income levels are decreasing in β. Still, mean and median income levels are not overly sensitive to variation in β: a 17% decrease in this parameter, corresponding to a wage premium that is 15% lower than its benchmark value, increases mean income by 6.5% (from 0.354 to 0.377). When we target a wage premium of 4.18 (i.e. $\beta = 0.2$) instead of 6.13, mean income increases by around 14% from its benchmark value (from 0.354 to 0.403). In fact, the full model does a better job in capturing the median income level for β values around 0.25. On the other hand, as β decreases, the predicted income level of the poorest country diverges from its data value. The benchmark model with $\beta = 0.3$ already overshoots minimum income by some margin (0.085 in the model vs. 0.04 in the data). For $\beta = 0.2$, this discrepancy is even larger (0.104 vs. 0.04).

5 Conclusion

What is the exact role of human capital in development? To answer that question, I propose a growth model in which firms employ skilled workers in order to augment their productivity by adopting technologies from a freely available stock of knowledge in the frontier. The variation in the skilled labor share leads to income differences between countries. The idea that human capital facilitates technology

[16] I thank the anonymous referee for pointing this out.

adoption goes back to Nelson and Phelps (1966). The first contribution I make is to build a general equilibrium model around it.

In the quantitative part, I calibrate model parameters to match some key statistics of the U.S. data and measure skilled labor as scientist and engineers. The second contribution of the model is in that it successfully accounts for cross-country income differences, especially at the lower end of the sample. The main departure from the related quantitative literature is the idea that technology diffusion not only takes place through formal R&D, but through the employment of skilled labor in general. Quantitatively, this channel seems to be relevant for countries up to the $60th$ percentile of the global income distribution. Previous research by Klenow and Rodríguez-Clare (2005) suggests that measured differences in formal R&D expenditures across countries is able to explain top two income quantiles in a similar model with technology diffusion. A synthesis of the two models can potentially fit the whole distribution more satisfactorily.

The model also predicts within-country income differences between skilled and unskilled workers. When confronted with data, it fits the wage premia of a subset of countries with some success. The third contribution of the model is that both cross- and within country income differences can be simultaneously accounted for using the same calibrated parameter values and variation in observable variables. Since the model departs from the standard Mincerian human capital specification by assuming that production and non-production workforces are not substitutable, I use a technique proposed by Psacharopoulos (1995) to measure the rental rate of skilled labor as defined in the model. Sensitivity analysis shows that the ability of the model to account for large international income inequalities is robust to using more conservative values for the parameter governing returns to skilled labor.

The analysis has some limitations that further research could improve upon. First, the model restricts the range of a key parameter that governs the rate of convergence towards steady state. As a result, it cannot be calibrated to convergence rates higher than 2% per annum. Although this figure is widely used in empirical exercises, an alternative estimation approach by Caselli et al. (1996) suggests that the true value of the convergence rate might be higher. The model, however, cannot quantitatively account for higher rates. This limitation is a result of the particular functional form used to capture technology adoption dynamics. Generalizing the model with a more flexible form that retains some desirable properties yet enables us to consider a wider range of parameter values would be a contribution. The other limitation of the analysis is the definition of skills considered to be relevant for technology adoption. I defined skilled labor as college educated scientists and engineers. Other types of skilled and semi-skilled labor could plausibly play a role, too. In fact, the model underpredicts income levels of a group of developed countries with high quality vocational and technical secondary education. Further research should seek alternative ways to define and measure the types of skills that facilitate the implementation of new technologies.

The implications of the results are twofold. First, the notion put forward by Nelson and Phelps (1966), that human capital contributes to the production process in a different way than direct inputs by being a facilitator of technology adoption seems to be quantitatively relevant. Second, some types of human capital which we denote as 'skilled' are more suitable to perform the technology adoption activities than others. Given the difference in tasks, it is a misspecification to aggregate all types of human capital into one single stock as it is done in most development accounting exercises. Models with disaggregated human capital, where the specific role played by each type is carefully considered (beyond simple capital-skills complementarity), could substantially improve our understanding of development.

Appendix A Steady State Equilibrium

In this section, I show the existence of an equilibrium along a balanced growth path (BGP). There are two dynamic decisions in this economy: capital accumulation undertaken by households and skilled labor employment decision given by intermediate good producers. I solve these problems to characterize the equilibrium interest rate, rental price of capital and the wage premium along the BGP. To find the equilibrium quantities and prices, I impose equilibrium conditions to the first order necessary conditions of these problems and check the sufficiency conditions. I derive the necessary parameter restrictions to ensure the existence of a BGP. Stability conditions are trivial since the technology adoption function approaches its steady state level monotonically, and capital accumulation dynamics are the same as in the neoclassical growth model.

Household Problem

Since households are identical, there will be no trade in shares and bonds in equilibrium. I suppress the bond market and consider the investment decisions for physical capital and shares. By no-arbitrage condition, the interest rate r_t on bonds will be equal to the rate of return on shares. Since household members equally split total consumption, the objective is to maximize C_t. Household takes rental rate of capital R_t, dividends and share prices (D_t, q_t), total wages W_t and transfers Z_t as given and solves,

$$\max_{\{C_t\},\{\mathrm{N}_t\},\{S_t\}} \int_{t=0}^{\infty} e^{-(\rho-g_\ell)t} \ \ln(C_t/L_t) \ dt,$$

subject to K_0 and

$$\begin{aligned} C_t + (1+\theta)\mathrm{N}_t + q_t S_t &= W_t + R_t \mathrm{K}_t + D_t a_t + Z_t, \\ \dot{K}_t &= \mathrm{N}_t - \delta \mathrm{K}_t, \\ \dot{a}_t &= S_t. \end{aligned}$$

Along a BGP, household level variables $\{C_t, \mathrm{N}_t, W_t, \mathrm{K}_t, D_t, Z_t\}$ grow at the same rate λ as the output. By the absence of trade in shares in equilibrium, share prices should also increase at the same rate. Suppressing the time subscripts, the Hamiltonian is

$$J = \ e^{-(\rho - g_\ell)t} \ \ln(C) + \mu_{\mathrm{K}}(\mathrm{N} - \delta \mathrm{K}) + \mu_a S$$

Necessary and sufficient conditions for the optimum read as

$$\frac{\partial J}{\partial \mathrm{N}} = 0 \quad \Rightarrow \quad \mu_{\mathrm{K}} = e^{-(\rho - g_\ell)t} \ \frac{1+\theta}{C}, \tag{A.1}$$

$$\frac{\partial J}{\partial S} = 0 \quad \Rightarrow \quad \mu_a = e^{-(\rho - g_\ell)t} \ \frac{q}{C}, \tag{A.2}$$

$$\frac{\partial J}{\partial \mathrm{K}} + \dot{\mu}_{\mathrm{K}} = 0 \quad \Rightarrow \quad \dot{\mu}_{\mathrm{K}} = -e^{-(\rho - g_\ell)t} \ \frac{R}{C} + \delta \mu_{\mathrm{K}}, \tag{A.3}$$

$$\frac{\partial J}{\partial a} + \dot{\mu}_a = 0 \quad \Rightarrow \quad \dot{\mu}_a = -e^{-(\rho - g_\ell)t} \ \frac{D}{C}, \tag{A.4}$$

$$\lim_{t \to \infty} [\mu_{\mathrm{K}}(t) \mathrm{K}(t)] = 0. \tag{A.5}$$

$$\lim_{t \to \infty} [\mu_a(t) a(t)] = 0. \tag{A.6}$$

First divide (A.4) by (A.2) to get:

$$\frac{\dot{\mu}_a}{\mu_a} \ = \ -\frac{D}{q}.$$

Then I take the logarithm of (A.2) and differentiate the resulting expression with respect to t. In a BGP, total consumption C_t grows at a rate equal to $\lambda + g_\ell$. Using $\frac{\dot{C}}{C} = \lambda + g_\ell$,

$$\frac{\dot{\mu}_a}{\mu_a} \ = \ -(\rho + \lambda) + \frac{\dot{q}}{q},$$

which implies

$$\frac{D+\dot{q}}{q}=\rho+\lambda.$$

This is the net rate of return to shares which is the sum of dividend and capital gains. The rental rate of capital is obtained by differentiating (A.1) with respect to t:

$$\frac{\dot{\mu}_{\mathrm{K}}}{\mu_{\mathrm{K}}} \;=\; -(\rho+\lambda).$$

Dividing (A.3) by this expression, we get

$$R_{ss}=(\rho+\lambda+\delta)(1+\theta).$$

The net interest rate in the bond market is equal to the rate of return to shares by a no-arbitrage condition:

$$r_{ss}=\rho+\lambda.$$

Since μ_{K} is decreasing at a rate $\rho+\lambda$, and household capital stock K_t is growing by $\lambda+g_\ell$, the assumption $\rho>g_\ell$ makes sure that the transversality condition (A.5) is satisfied. Since μ_a is decreasing by a rate ρ, and a_t is constant, the second transversality condition (A.6) is also satisfied.

Intermediate Good Producer's Problem

Henceforth I will refer the representative intermediate good producer as "the firm". The firm enjoys monopoly rents. Hence its net profit after rental payments is positive. Skilled labor is paid out of this rent. Now I solve firm's dynamic problem of skilled labor demand. While doing that, I will characterize the parameter restrictions needed to ensure that the firm has enough rents to cover the decentralized wage rate along the proposed BGP.

Given $w_{s,t}$, when the firm employs a measure of $\ell_{s,t}$ skilled, its profit and resulting change in its technology are given by

$$\Pi_t=A_t x_t^{\alpha}\ell_u^{1-\alpha}-w_{s,t}\ell_{s,t}\ , \tag{A.7}$$

$$\dot{A}_t=\ \ell_{s,t}^{\beta}\left(\frac{T_t}{A_t}\right)^{\eta}A_t. \tag{A.8}$$

I restrict attention to the constant interest rate r_{ss} along the BGP. The firm with an initial technology level A_0 solves the following problem:

$$V(A_0) \;=\; \max_{\{\ell_{s,t}\}} \int_{t=0}^{\infty} e^{-r_{ss}t}\; \Pi_t \; dt, \tag{A.9}$$

subject to (A.7) and (A.8).

Note that $x_t = x = k_t/A_t$ is constant along the BGP. Since wages grow by λ, I normalize wages and productivity by T_t. Let $\tilde{w}$ denote the stationary wage level. As in the text, $g = A_t/T_t$ is the gap between a country's productivity and the frontier. The problem in (A.9) can be rewritten as

$$\begin{aligned} V(A_0) \;&=\; \max_{\{\ell_{s,t}\}} \int_{t=0}^{\infty} e^{-r_{ss}t}\; T_t\, \frac{\Pi_t}{T_t}\; dt \\ &=\; \max_{\{\ell_{s,t}\}} \int_{t=0}^{\infty} e^{-\rho t}[g_t\; x^{\alpha}\ell_u^{1-\alpha} - \tilde{w}_s \ell_s]\; dt, \end{aligned}$$

subject to

$$\dot{g}_t = \ell_s^{\beta}\; g_t^{1-\eta} - \lambda g_t.$$

I present the Hamiltonian and the first order necessary conditions. Imposing equilibrium properties, I derive the wage premium. Lastly, I check that the sufficiency condition and transversality condition are satisfied. Suppressing the time subscripts,

$$H(g, \ell_s,) \;=\; e^{-\rho t}[\; g\; x^{\alpha}\ell_u^{1-\alpha} - \tilde{w}_s \ell_s \;] + \mu[\; \ell_s^{\beta}\; g^{1-\eta} - \lambda g \;],$$

$$\frac{\partial H}{\partial \ell_s} = 0 \quad \Rightarrow \quad e^{-\rho t}\; \tilde{w}_s = \mu\; \beta\; \ell_s^{\beta-1} g^{1-\eta} \tag{A.10}$$

$$\frac{\partial H}{\partial g} + \dot{\mu} = 0 \quad \Rightarrow \quad \dot{\mu} \;=\; -e^{-\rho t} x^{\alpha} \ell_u^{1-\alpha} + \mu[\; \ell_s^{\beta}(\eta-1) g^{-\eta} + \lambda \;]. \tag{A.11}$$

Rearrange (A.10) to get

$$\mu = \frac{e^{-\rho t}\; \tilde{w}_s}{\beta \ell_s^{\beta-1} g^{1-\eta}}, \tag{A.12}$$

and divide (A.11) by (A.12),

$$\frac{\dot{\mu}}{\mu} \;=\; -\frac{x^{\alpha}\ell_u^{1-\alpha}}{\tilde{w}_s}\;\beta\;\ell_s^{\beta-1}g^{1-\eta}+\ell_s^{\beta}(\eta-1)g^{-\eta}+\lambda. \tag{A.13}$$

Taking the logarithm of (A.12) and differentiating with respect to t, and using the steady state condition $\dot{g}=0$, I get

$$\frac{\dot{\mu}}{\mu} \;=\; -\rho. \tag{A.14}$$

Letting (A.13) and (A.14) equal, I obtain an expression for skilled wages:

$$\tilde{w}_s \;=\; x^{\alpha}\ell_u^{1-\alpha}\;\frac{\beta\;\ell_s^{\beta-1}\;g^{1-\eta}}{\ell_s^{\beta}\;(\eta-1)\;g^{-\eta}+\lambda+\rho}.$$

Total payments to skilled labor are given by

$$\tilde{w}_s\ell_s \;=\; gx^{\alpha}\ell_u^{1-\alpha}\;\frac{\beta\;\ell_s^{\beta}\;g^{-\eta}}{\ell_s^{\beta}\;(\eta-1)\;g^{-\eta}+\lambda+\rho}. \tag{A.15}$$

Under some additional conditions, the sufficiency of necessary conditions is guaranteed by Arrow-Kurz sufficiency theorem for dynamic control. The maximized Hamiltonian $H^o(g)$ is obtained when one solves (A.10) for optimal $\ell_s(g)$ and inserts this back into $H(\ell_s,g)$. Arrow-Kurz's sufficiency condition is the concavity of H^o in g.[17] The maximized Hamiltonian of this problem is

$$H^o(g) \;=\; g^{\frac{1-\eta}{1-\beta}}\left(\beta^{\frac{\beta}{1-\beta}}-\beta^{\frac{1}{1-\beta}}\right).$$

One can check that $\frac{\partial^2 H^o}{\partial g^2}\leq 0$ is satisfied if either of the following restrictions hold:

i. $\beta\in\;(0,1)$ and $\eta\;\in[\beta,1]$, or

ii. $\beta\;>1,\quad\eta\;>\;0$ and $\eta\;\notin\;(1,\beta)$.

In the text, I assume that the former condition holds. The restriction on β ensures that demand for skilled human capital is finite. As to η, if this parameter is larger than 1, it is optimal for the firm to delay investment in technology adoption, to let T_t/A_t increase over time such that the returns to hiring skilled labor is infinite in an indefinite future period.

[17] The reader can refer to Barro and Sala-i Martin (2004), page 610.

The firm has enough rents to pay skilled labor if

$$gx^{\alpha}\ell_u^{1-\alpha} - \tilde{w}_s \; \ell_s \geq 0.$$

Substituting the steady state gap $g = \lambda^{-\eta}\ell_s^{\beta/\eta}$ in (A.15), one can check that this condition is satisfied for

$$\rho \; > \; (\beta - \eta)\lambda. \tag{A.16}$$

This parameter restriction is needed to assure that the firm has enough resources to support technology investment in form of skilled labor hiring in a decentralized economy. Note that (A.16) holds under the assumption $\eta \geq \beta$ already assumed above.

Lastly, the transversality condition is given by

$$\lim_{t\to\infty} \; \mu_t g_t = 0, \tag{A.17}$$

and it is satisfied since g is constant in steady state and μ, as one can see in (A.10), is declining at the rate ρ.

Capital-Output Ratio

To find the steady state capital-output ratio, start rearranging term in (2.5), the demand function for capital by intermediate good producers:

$$\left(\frac{x}{\ell_u}\right)^{1-\alpha} = \frac{\alpha}{1-\alpha}\;\frac{1}{R_{ss}}.$$

The contribution of each producer to nation output is given by: $y = A\frac{x^{\alpha}\ell_u^{1-\alpha}}{\alpha(1-\alpha)}$. Using the production function for $x = \frac{k}{A}$, I obtain:

$$\frac{k}{y} = \alpha(1-\alpha)\left(\frac{x}{\ell_u}\right)^{1-\alpha}.$$

Inserting $(x/\ell_u)^{1-\alpha}$ from above, the capital-output ratio for the representative intermediate good producer reads as

$$\frac{k}{y} = \frac{\alpha^2}{(r_{ss}+\delta)(1+\theta)}. \tag{A.18}$$

The aggregate capital-output ratio is the same since $K = kM$, and $Y = yM$.

Wage Premium

The final good producer pays unskilled labor according to its marginal contribution in production. Total payments to unskilled labor (in efficiency units) amount to

$$w_{u,t}L_{u,t} = \frac{A_t}{\alpha}\,(x_t M_t)^{\alpha} L_{u,t}^{1-\alpha}.$$

In order to derive the wage premium, I divide both sides of this expression by M_t, normalize by T_t and find the payment to unskilled labor per variety:

$$\tilde{w}_u \ell_u = \frac{g}{\alpha}\, x^{\alpha} \ell_u^{1-\alpha}. \tag{A.19}$$

Dividing (A.15) by (A.19),

$$\frac{\tilde{w}_s}{\tilde{w}_u} \;=\; \frac{\alpha\, \beta\, \ell_s^{\beta-1}\, g^{-\eta}}{\ell_s^{\beta}(\eta-1)g^{-\eta} + \lambda + \rho}\;\; \ell_u.$$

Substituting the steady state g, I get

$$\frac{\tilde{w}_s}{\tilde{w}_u} \;=\; \frac{\alpha\beta\lambda}{\eta\lambda+\rho}\,\frac{\ell_u}{\ell_s}. \tag{A.20}$$

In equilibrium, $\ell_u = (1-s)u$ and $\ell_s = s$ which yields (2.24) in the text.

Rate of Convergence

As it is standard in the literature, I will first write the system of differential equations governing the evolution of state variables and co-state variables. Linearizing this system around its steady state will allow me to find the convergence rate towards steady state as a function of the model parameters. In this section, all lower case variables are normalized with respect to $L_t T_t$.

Taking the log of $k_t = K_t/(L_t T_t)$ and differentiating it with respect to time t, the law of motion is

$$\frac{\dot{k}_t}{k_t} = \frac{n_t}{k_t} - \Delta,$$

where $\Delta = \lambda + g_l + \delta$. Using equation (2.21), normalized output is

$$\begin{aligned} y_t &= \frac{Y_t}{L_t T_t} = \frac{1}{\alpha(1-\alpha)} \frac{[(1-s)u]^{1-\alpha} K_t^{\alpha} A^{1-\alpha} L_t^{1-\alpha}}{L_t T_t}, \\ &= \frac{[(1-s)u]^{1-\alpha}}{\alpha(1-\alpha)} k_t^{\alpha} \left(\frac{A_t}{T_t}\right)^{1-\alpha} = \frac{[(1-s)u]^{1-\alpha}}{\alpha(1-\alpha)} k_t^{\alpha} g_t^{1-\alpha}. \end{aligned}$$

Dividing this expression by k_t, noting that $n_t = y_t - c_t$ and substituting back into the law of motion for capital, we get

$$\frac{\dot{k}_t}{k_t} = \frac{[(1-s)u]^{1-\alpha}}{\alpha(1-\alpha)} k_t^{\alpha-1} g_t^{1-\alpha} - \frac{c_t}{k_t} - \Delta,$$

The law of motion for the technology gap, $g_t = A_t/T_t$, is as given in the text:

$$\frac{\dot{g}_t}{g_t} = s^{\beta} g_t^{-\eta} - \lambda.$$

The law of motion for normalized consumption follows

$$\frac{\dot{c}_t}{c_t} = \frac{\dot{C}_t}{C_t} - (\lambda + g_l).$$

To find $\dot{C}_t/C_t$, start with the first order condition (A.1)

$$\mu_{Kt} = e^{-\rho t} \frac{1+\theta}{C_t}.$$

Taking the log and time differentiating yields

$$\frac{\dot{\mu}_{Kt}}{\mu_{Kt}} = -\rho - \frac{\dot{C}_t}{C_t}.$$

Finally, divide condition (A.3) in the paper by μ_{Kt} to get

$$\frac{\dot{\mu}_{Kt}}{\mu_{Kt}} = \frac{-e^{-\rho t}}{\mu_{Kt}} \frac{R_t}{C_t} + \delta = \frac{-e^{-\rho t}}{(e^{-\rho t}\frac{1+\theta}{C_t})} \frac{R_t}{C_t} + \delta = -\frac{R_t}{1+\theta} + \delta,$$

and using the last two equations

$$\frac{\dot{C}_t}{C_t} = \frac{R_t}{1+\theta} - \rho - \delta.$$

To simplify things, concentrate on the case $\theta = 0$. The rate of return to capital, R_t, is given by equation (2.5) in the paper. Using equation (2.4), and the symmetry between intermediate good producers, we get

$$x_t = \frac{K_t}{M_t A_t},$$

which can be plugged into (2.5) to get

$$R_t = \frac{\alpha}{1-\alpha}\left(\frac{K_t}{\ell_u M_t A_t}\right)^{\alpha-1} = \frac{\alpha}{1-\alpha}\left(\frac{K_t}{(1-s)uL_t T_t}\frac{T_t}{A_t}\right)^{\alpha-1},$$

where the letter equality follows from the labor market equilibrium condition $\ell_u M_t = (1-s)uL_t$. Rearranging terms

$$R_t = \frac{\alpha}{1-\alpha}[(1-s)u]_t^{1-\alpha} k_t^{\alpha-1} g_t^{1-\alpha}.$$

Using this expression in the law of motion of C_t, we get

$$\frac{\dot{c}_t}{c_t} = \frac{\alpha}{1-\alpha}[(1-s)u]^{1-\alpha} k_t^{\alpha-1} g_t^{1-\alpha} - \rho - \Delta.$$

We have a system of differential equations with two state variables (k_t and g_t), and one co-state variable (c_t):

$$\begin{aligned}
\frac{\dot{k}_t}{k_t} &= f^1(k_t, g_t, c_t) = \frac{[(1-s)u]^{1-\alpha}}{\alpha(1-\alpha)} k_t^{\alpha-1} g_t^{1-\alpha} - \frac{c_t}{k_t} - \Delta, \\
\frac{\dot{g}_t}{g_t} &= f^2(k_t, g_t, c_t) = s^\beta g_t^{-\eta} - \lambda, \\
\frac{\dot{c}_t}{c_t} &= f^3(k_t, g_t, c_t) = \frac{\alpha}{1-\alpha}[(1-s)u]^{1-\alpha} k_t^{\alpha-1} g_t^{1-\alpha} - \rho - \Delta.
\end{aligned}$$

Denote the steady state variables by (k_{ss}, g_{ss}, c_{ss}). Using $\dot{c}_t = 0$, we get

$$k_{ss}^{\alpha-1} g_{ss}^{1-\alpha} = \frac{1-\alpha}{\alpha[(1-s)u]^{1-\alpha}}(\rho+\Delta).$$

Plugging this into $\dot{k}_t/k_t = 0$,

$$\frac{c_{ss}}{k_{ss}} = \frac{\rho + (1-\alpha^2)\,\Delta}{\alpha^2}.$$

Using (2.21) and (2.20)

$$c_{ss} = \lambda^{-\frac{1}{\eta}} s^{\frac{\beta}{\eta}} (1-s) u \frac{\rho + (1-\alpha^2)\,\Delta}{\rho+\lambda+\delta} \left(\frac{\alpha^2}{\rho+\lambda+\delta}\right)^{\frac{\alpha}{1-\alpha}}.$$

I linearize equations $f^i(\cdot)$ around their steady state using $f^i(k_{ss}, g_{ss}, c_{ss}) = 0$ to get,

$$f^i(k_t, g_t, c_t) \approx f_k^i(k_{ss}, g_{ss}, c_{ss})(k_t - k_{ss}) + f_g^i(k_{ss}, g_{ss}, c_{ss})(g_t - g_{ss}) + f_c^i(k_{ss}, g_{ss}, c_{ss})(c_t - c_{ss}).$$

Using the approximation $\log(x) \approx x - 1$ for $x \approx 1$, we can write this as

$$\begin{aligned} f^i(k_t, g_t, c_t) \approx f_k^i(k_{ss}, g_{ss}, c_{ss}) k_{ss} \log(k_t/k_{ss}) + f_g^i(k_{ss}, g_{ss}, c_{ss}) g_{ss} \log(g_t/g_{ss}) \\ + f_c^i(k_{ss}, g_{ss}, c_{ss}) c_{ss} \log\left(c_t/c_{ss}\right). \end{aligned}$$

In matrix notation, we have

$$\begin{aligned} \begin{bmatrix} \dot{k}_t/k_t \\ \dot{g}_t/g_t \\ \dot{c}_t/c_t \end{bmatrix} &= \begin{bmatrix} f_k^1(k_{ss}, g_{ss}, c_{ss})k_{ss} & f_g^1(k_{ss}, g_{ss}, c_{ss})g_{ss} & f_c^1(k_{ss}, g_{ss}, c_{ss})c_{ss} \\ 0 & f_g^2(k_{ss}, g_{ss}, c_{ss})g_{ss} & 0 \\ f_k^3(k_{ss}, g_{ss}, c_{ss})k_{ss} & f_g^3(k_{ss}, g_{ss}, c_{ss}) & 0 \end{bmatrix} \begin{bmatrix} \log(k_t/k_{ss}) \\ \log(g_t/g_{ss}) \\ \log\left(c_t/c_{ss}\right) \end{bmatrix}, \\ &= \mathcal{F} \cdot \begin{bmatrix} \log(k_t/k_{ss}) \\ \log(g_t/g_{ss}) \\ \log\left(c_t/c_{ss}\right) \end{bmatrix}. \end{aligned}$$

The eigenvalues of the characteristic matrix $\mathcal{F}$ determine the rate of convergence. Evaluating the derivatives at the steady state values, this matrix is

$$\mathcal{F} = \begin{bmatrix} \mathcal{F}_{11} & \mathcal{F}_{12} & \mathcal{F}_{13} \\ 0 & \mathcal{F}_{22} & 0 \\ \mathcal{F}_{31} & \mathcal{F}_{32} & 0 \end{bmatrix} = \begin{bmatrix} \frac{(1-\alpha)\Delta+\rho}{\alpha} & \frac{(1-\alpha)(\Delta+\rho)}{\alpha^2} & \frac{(\alpha^2-1)\Delta-\rho}{\alpha^2} \\ 0 & -\eta\lambda & 0 \\ -(1-\alpha)(\Delta+\rho) & (1-\alpha)(\Delta+\rho) & 0 \end{bmatrix}.$$

Its eigenvalues are obtained by solving the characteristic polynomial

$$\det(F - \epsilon I) = 0,$$
$$\det \begin{bmatrix} F_{11} - \epsilon & F_{12} & F_{13} \\ 0 & F_{22} - \epsilon & 0 \\ F_{31} & F_{32} & -\epsilon \end{bmatrix} = 0.$$

Expanding the determinant by minors across the second row, we get

$$(F_{22} - \epsilon)\left[(F_{11} - \epsilon) + F_{13}F_{31}\right] = 0.$$

There are two negative and one positive root. One negative root is

$$\epsilon_1 = -\eta\lambda.$$

Other two roots are given by

$$\epsilon_{2,3} = \frac{1}{2}\left[F_{11} \pm \sqrt{F_{11}^2 + 4F_{13}F_{31}}\right].$$

Using the elements of the matrix from above, the negative root is

$$\epsilon_2 = \frac{(1-\alpha)\Delta + \rho - \sqrt{[(1-\alpha)\Delta + \rho]^2 + 4[(1-\alpha^2)\Delta + \rho](1-\alpha)(\Delta + \rho)}}{2\alpha}.$$

The smaller (in absolute value) of these two negative roots (ϵ_1 and ϵ_2) will be the dominant one driving the convergence rate. Using the calibrated parameter values, I find $\epsilon_2 = -0.0923$. This is much higher than the commonly obtained empirical estimates of the speed of convergence which are around 2% - see Barro and Sala-i Martin (2004) for a summary. So, ϵ_1 must be the smaller of the negative roots, and thus the rate of convergence.

Appendix B Data

Human Capital Stocks

I measure s by the share of scientists and engineers in workforce at year 1985. This is computed using two pieces of evidence. Barro-Lee (2001) data provides the college attainment levels of countries. UNESCO (1975) reports the share of majors in total enrollment.

The efficiency level of unskilled human capital is measured using the country-specific Mincerian returns in Psacharopoulos (1994) and average years of schooling in Barro-Lee (2001). Following the standard procedure in the literature, in a country in which the Mincerian return is r and average years of schooling is m, total stock of unskilled labor is equivalent to $\exp(rm)$ units of efficiency labor.

Measurement of the Wage Premium

I measure the wage premium in two steps. First, I obtain the relative earnings ratio of an average college graduate over a worker with no education (college premium). Next, I use the premium of an engineering major over the average college graduate. Grogger and Eide (1995) provide estimates of major-specific wage premia in the U.S. Their estimate of engineering premium is 1.2 (over earnings of an average college graduate). Psacharopoulos (1994) reports a similar measure for a limited group of countries. These estimates do not systematically vary with income levels. Thus, I use the US value for other countries in the sample as well.

The measurement of the college premium follows the private rate of return method proposed by Psacharopoulos (1995) and is based on returns to investment in education data in Psacharopoulos (1994) (Table 6). The Mincerian method, used to construct of the human capital stocks u, is based on the assumption that there is a rental price for efficiency units of labor and workers of different skill levels are substitutable in production. Education enables a worker to produce more of the same. This assumption is valid when u is imputed because efficiency units of human capital embedded in unskilled workers with different education levels are substitutable in the model. However, skilled and unskilled labor are not substitutable and paid different the rental rates. The private rate of return method is appropriate to back out the underlying wage premium based on the estimated rates of return.

Let P stand for life-expectancy in a country. Also, let D indicate the duration of finishing a particular level of education. After finishing the school, the worker earns w_s for the rest of her life whereas the uneducated worker earns w_u. Given a private rate of return r, the discounted life-time gain of obtaining a degree is equal to the opportunity cost plus the direct cost c:

$$\sum_{t=1}^{P-D} \frac{w_s - w_u}{(1+r)^t} = \sum_{t=1}^{D} (w_u + c)(1+r)^t.$$

From this equation, one can calculate w_s/w_u. We have country specific data on r for primary, secondary and tertiary education as well as life-expectancy P.[18] The direct cost c is taken as zero for all levels of education in all countries except college education in the US. The case for the calibration target, the US value, is discussed below. I calculate the wage ratio for each education level (college over secondary, secondary over primary and primary over no education.) The college premium is obtained by multiplying these three ratios.

Psacharopoulos (1994) reports only the social rate of return for the US. Most of the higher education expenses in the US are, however, privately financed. In the absence of externalities, the social return will be close to the private return. Thus, I use the 10% rate of return for secondary and 12% rate of return for higher education in the US. I also compute an estimate of the relative direct cost of higher education in terms of the unskilled wage level, c/w_u, in the US for 1975. According to the US Department Education, the total cost of a year of college education was \$2,275 in 1975 in current dollars.[19] In the same year, minimum wage was \$2.1. An unskilled laborer working for 8 hours a day, 5 days a week for 9 months of school time would earn \$3.275 on total. This yields an estimate of $c/w_u = 0.7$. Using this figure, and a life expectancy of $P = 71$ years, the US college wage premium is estimated as 5.1. Using the engineering premium of 1.2, the calibration target is $w_s/w_u = 6.13$.

[18]International Life expectancy data is from US Census Bureau at http://www.census.gov/ipc/www/idb/idbprint.html. I take the 1975 value whenever possible to capture the educational choice of the average workforce in 1985. For many countries, data in this year is available. Otherwise, I choose the date closest to 1975. The results are not sensitive to small changes in life expectancy.

[19]Data on college costs available in http://nces.ed.gov/programs/digest/d06/tables/dt06_319.asp

Country	**Code**	y_i/y_{us}	u_i	s_i	$1+\theta_i$	**log**$[(w_s/w_u)_i]$
Argentina	ARG	0.48	2.00	0.009	1.40	2.19
Australia	AUS	0.81	2.24	0.024	1.15	1.64
Austria	AUT	0.86	1.81	0.006	0.95	-
Bolivia	BOL	0.13	1.57	0.008	1.35	2.44
Botswana	BWA	0.18	1.76	0.001	1.89	9.79
Brazil	BRA	0.32	1.61	0.007	0.65	3.51
Canada	CAN	0.80	2.52	0.040	1.02	1.61
Chile	CHL	0.32	2.06	0.009	0.58	2.33
Colombia	COL	0.27	1.79	0.006	1.56	3.39
Costa Rica	CRI	0.34	1.56	0.013	1.75	2.42
Cyprus	CYP	0.45	1.51	0.015	1.06	1.65
Denmark	DNK	0.77	1.53	0.020	0.93	-
Dominican Republic	DOM	0.22	1.43	0.020	2.08	5.58
Ecuador	ECU	0.28	1.92	0.015	0.55	2.63
Egypt	EGY	0.17	1.16	0.005	2.18	-
El Salvador	SLV	0.21	1.30	0.004	2.25	2.46
Finland	FIN	0.69	1.92	0.015	0.69	-
France	FRA	0.86	2.08	0.011	0.95	2.69
Germany	GER	0.76	2.00	0.008	0.80	-
Ghana	GHA	0.04	1.23	0.001	1.55	3.97
Greece	GRC	0.58	1.70	0.010	0.76	1.43
Guatemala	GTM	0.21	1.44	0.004	1.56	3.88
Honduras	HND	0.14	1.39	0.004	1.46	3.72
Hong Kong	HKG	0.65	1.58	0.008	0.90	3.3
India	IND	0.07	1.39	0.004	1.32	2.23
Indonesia	IDN	0.11	1.29	0.001	0.85	-
Iran	IRN	0.35	1.36	0.001	0.65	-
Israel	ISR	0.77	1.78	0.026	0.70	2.31
Italy	ITA	0.83	1.17	0.007	0.83	2.89
Jamaica	JAM	0.16	3.29	0.003	1.2	2.60
Japan	JPN	0.70	3.08	0.017	1.11	1.88
Kenya	KEN	0.05	1.46	0.001	1.86	2.66
Korea (South)	KOR	0.29	2.96	0.013	0.99	2.07
Malaysia	MYS	0.29	1.58	0.002	1.17	5.08
Mexico	MEX	0.41	1.41	0.008	1	3.03
Nepal	NPL	0.04	1.08	0.002	1.19	-
Netherlands	NLD	0.86	1.70	0.015	0.87	1.57
Nicaragua	NIC	0.30	1.47	0.008	2.47	-
Norway	NOR	0.93	1.59	0.014	0.83	-
Pakistan	PAK	0.11	1.32	0.002	1.22	2.75
Panama	PAN	0.35	2.34	0.012	1.03	2.63
Paraguay	PRY	0.27	1.74	0.005		2.85
Peru	PER	0.27	1.57	0.013	0.92	2.89
Philippines	PHL	0.15	2.28	0.020	1.41	2.25
Portugal	PRT	0.42	1.36	0.005	1.14	7.36
Singapore	SGP	0.61	1.80	0.005	0.45	2.88
South Africa	ZAF	0.41	1.24	0.003	2.08	-
Spain	ESP	0.65	1.47	0.008	0.98	-
Sri Lanka	LKA	0.12	1.45	0.002	0.98	2.27
Sweden	SWE	0.76	1.59	0.018	1.02	1.74
Switzerland	CHE	0.99	2.10	0.013	0.95	-
Taiwan	TWN	0.36	1.51	0.012	1.62	4.01
Thailand	THA	0.12	1.73	0.006	0.83	2.3
Tunisia	TUN	0.28	1.22	0.003	1.17	2.77
United Kingdom	GBR	0.70	1.78	0.014	0.97	-
United States	USA	1.00	3.23	0.037	1	1.82
Uruguay	URY	0.33	1.88	0.009	4.34	2.75
Venezuela	VEN	0.43	1.65	0.011	1	3.34

Table 6 – Data

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