Optimal Technology and Development

Hernan Moscoso Boedo

University of Virginia

September 2006

Optimal Technology and Development*

Hernan J. Moscoso Boedo†

University of Virginia

September 22nd 2006

Abstract

Skill intensive technologies seem to be adopted by rich countries rather than poor ones. Related to that observation, the ratio of wages of skilled to unskilled workers - the skill premium - shows two important features over time and across countries. In the US the skill premium decreased during the first half of the 20th century and it increased after 1950, evolving according to a U shaped pattern. On the other hand, the same measure across countries around 1990 is hump shaped when countries are ordered by GDP per worker.

By modeling the decisions for factor accumulation and technology adoption, this paper gives a systematic explanation as to why we see ever more skill intensive technologies being adopted both over time in the US and across countries. The model developed here endogenously generates predictions for the skill premium that are consistent with both the US and international observations under the same set of parameter values.

Journal of Economic Literature Classification Numbers: E25, J24, N32, O33 and O57

*Po Box 400182, Charlottesville VA 22904-4182. Email: hmoscoso@virginia.edu

†I am grateful to Rody Manuelli, Ananth Seshadri, John Kennan and Yongseok Shin for their valuable comments and support. I received useful comments from Tom Sargent, Chris Otrok and the participants at the Midwest Macroeconomics Meetings 2005. I also thank Santiago Oliveros and Luciana Moscoso Boedo for very productive discussions. All errors are, of course, mine

1. Introduction

In order to understand why some countries are rich while others remain poor, recent work has concluded that differences in production technologies are as important or even more important than differences in factors of production such as physical and human capital. Therefore the question is: why don't poor countries adopt more advanced technologies when they are available? One strand of recent work points towards differences in the skill intensity of the production function along the development spectrum, with skill intensive technologies being adopted as countries become richer. Optimal technological adoption decisions are made observing the price of the different production inputs, such as skilled workers, unskilled workers and physical capital. Therefore, the skill premium is intimately tied to the technology adoption decision. As a consequence a successful model for technical adoption should also be capable of capturing the evolution of the skill premium over time and across countries.

A large literature has emerged to understand how differences in production technologies over time and across countries may affect output. This literature ranges from exogenous barriers to the transfer of new technologies to a literature on "Appropriate Technology"[1]. However, recent research on technological differences primarily focuses on skilled biased technological change. This literature shows potential in explaining seemingly puzzling observations in terms of skill premium both over time and across countries. This work focused initially on exogenous skilled bias technological change, offering little explanation as to why the technologies seemed to be relatively more intensive in the use of skilled workers in developed economies than in developing ones.

This paper develops a systematic explanation as to why it is that we see ever more skill intensive technologies being adopted both in the time series for the US and across countries. In doing so I provide a unified reason why the skill premium in the US decreased until 1950

[1] The New Palgrave Dictionary of Economics lists under "Appropriate technology" a non homogeneous set of ideas that varied over time. The idea was to induce adoption of technologies that maximized output per worker, growth rate of output, employment or even maximize the use of locally available resources.

and then increased, displaying a U shape pattern together with an ever growing stock of skilled workers. Across countries, the model explains how the technology adoption decision is related to the stage of development of each country.

To this end I construct and calibrate a general equilibrium dynamic model with endogenous decisions for both factor accumulation and technology adoption. The factor accumulation decision is over the stocks of skilled workers and with physical capital. The technology adoption decision focuses on the optimal level of skill bias in the production function in the presence of a convex technology adoption cost in terms of stocks of physical capital and skilled workers. This cost can be interpreted as an accelerated obsolescence in the stocks of skilled workers and physical capital due to technological change. When deciding which technology to adopt, the agents take into account the accelerated obsolescence on their stocks of production inputs. It is important to stress that the model is calibrated to the US around 1990 and, using the same set of parameter values, it is applied internationally.

The paper is organized as follows. Section 2 presents a literature review focused on the work on skill biased technological change and technology adoption. Section 3 is devoted to presenting the theoretical model. Section 4 calibrates the model to the US around 1990. This calibration is used both for the time series for the US and for the international comparison. Sections 5 and 6 present the experiments on the US time series and across countries respectively. Section 7 concludes.

2. Literature review

This paper builds upon two distinct but related bodies of literature. The first is the literature on technology adoption. This literature can be divided into two different categories. The first are the papers that base their findings on irreversible decisions of different agents, such as Chari and Hopenhayn (1991), Greenwood and Yorokoglu (1997) and Jovanovic (1998). They base their findings in terms of the dynamic effects of technological change and adoption decisions to acquire skills or invest in technology specific embedded capital goods. The second category follows papers such as Jovanovic and Nyarko (1996) and argues that the central mechanism is one of learning by doing where changes in technologies induce an informational cost. This cost lowers productivity temporarily as the technology is introduced into production.

The second literature is on skilled biased technological change. This literature claims that as economies develop, the intensity in the use of the different production inputs shifts towards the use of the skilled labor. Work on this area includes Heckman, Lochner and Taber (1998), and Krusell, Ohanian, Rios-Rull and Violante (2000). In both of these cases technical change is taken as exogenous. On the other hand Caselli and Coleman (2006) introduce a choice of the production function. In their work, the economy adopts the technology that is optimal given the stocks of physical capital, skilled workers and unskilled workers. A partial equilibrium is considered, with no investment either in physical capital or human capital, and given those stocks, the optimal technology is chosen.

Exogenous skilled bias technological change has been suggested as an explanation to the puzzling observation that the skill premium grew together with the stock of skilled workers in the US since 1950. Previous to that date, the skill premium had been declining as observed by Goldin and Katz (1999), accompanied with a growing number of skilled workers. Goldin and Katz (1999) argue that no satisfactory and unified explanation covers both the decreasing and increasing phases in the skill premium evolution along with an ever growing number of skilled workers.

Across countries, skill bias technological change has also been suggested to explain differences in the prices and number of skilled workers. Caselli and Coleman (2006) argue that the most developed countries tend to use technologies that are more intensive in the use of skilled labor. The findings in terms of skill premium across countries are very different to the US time series. Instead of observing an increasing skill premium as countries develop as one would suspect from the evidence in the second half of the 20th century in the US time series, the evidence points towards a hump shape relationship between skill premium and development.

In their recent paper, Funk and Vogel (2004), show that technological change does not have to be skill biased and conclude that instead of being assumed, the skill bias technical change can be an equilibrium result. The same feature can be found in Acemoglu (2002), where he describes technological change bias as a function of both prices and stocks of skills, with opposed results in terms of technological change. The price effect inducing innovation towards the scarce factor, the stock effect induces innovations towards the abundant one. Both Funk and Vogel (2004) and Acemoglu (2002), point out that technological change is not per se skill biased and give as an example the unskilled biased technical change that took place in the late 18th and early 19th century, where mass production replaced the artisan.

3. The Model Economy

3.1. Planner's problem

Time is discrete and there is no uncertainty. The utility function of the infinitely lived representative consumer is given by

$$\sum_{t=0}^{\infty} \beta^t u\left(C_t\right) \tag{3.1}$$

The planner in this economy maximizes (3.1), subject to the following budget constraint

$$C_t + I_t \leq F\left(b_t, K_{p_t}, S_{p_t}, U_{p_t}\right) \tag{3.2}$$

where C_t denotes consumption in period t, I_t denotes investment in physical capital in period t, and $F()$ denotes the production function of final goods. $F()$ is a function of b_t, which indexes the technology adopted in period t and belongs to the unit interval. In addition to the technology parameter, the amount produced is a function of the stock of physical capital K_{p_t}, and both the skilled and unskilled labor devoted to the production of final goods, S_{p_t}, and U_{p_t} respectively.

The stocks of skilled labor, unskilled labor and physical capital, are divided as follows:

$$U_{p_t} + U_{e_t} + S_{p_t} + S_{e_t} \leq 1 \tag{3.3}$$

$$K_{p_t} + K_{e_t} \leq K_t \tag{3.4}$$

$$U_{p_t} \geq 0,\ U_{e_t} \geq 0,\ S_{p_t} \geq 0,\ S_{e_t} \geq 0 \tag{3.5}$$

A variable with a subscript p denotes that that variable is being used in the production of final goods, and a variable with an e subscript denotes a variable that is being used in the production of skilled workers (interpreted as the educational sector). Variables without p or e subscript denote aggregates of physical capital or skilled labor.

Technological change is costly. The function $G(b_t, b_{t+1})$ in equations (3.6) and (3.7) below maps changes in the production function into costs of adjustment, with the following properties: $G(b_t, b_t) = 0$, $G(b_t, b_{t+1}) > 0$ for $b_t \neq b_{t+1}$ and $G(b_t, b_{t+1}) = G(b_{t+1}, b_t)$. These costs of adjustment can be understood as accelerated depreciation of the stocks of physical capital and skilled labor or obsolescence due to technological change of those stocks. The cost function can be interpreted as capturing the fact that some skills and physical capital may not be appropriate under every technology. For example, the transition from steam to diesel locomotives, meant that some skills were not used anymore, whereas others remain perfectly suitable for the new technology. The technology transfer cost function can be thought of as capturing an average cost of transition from one technology to other.

The production of skilled labor is given by a function $H(K_{e_t}, S_{e_t}, U_{e_t})$. Where the function $H(K_{e_t}, S_{e_t}, U_{e_t})$ is the output of the educational sector. Therefore S_{e_t}denotes the skilled workers in the educational sector, or teachers, U_{e_t} denotes the number of students and K_{e_t} the physical capital in the educational sector.

The law of motion for the stocks of physical capital and skilled workers are as follows:

$$S_{t+1} \leq S_t\left[1-\delta_s - G(b_t, b_{t+1})\right] + H(K_{e_t}, S_{e_t}, U_{e_t}) \tag{3.6}$$

$$K_{t+1} \leq K_t\left[1-\delta_k - G(b_t, b_{t+1})\right] + I_t \tag{3.7}$$

Combining (3.2) and (3.7) we get the resource constraint for the economy

$$C_t + K_{t+1} \leq F(b_t, K_{p_t}, S_{p_t}, U_{p_t}) + K_t\left[1-\delta_k - G(b_t, b_{t+1})\right] \tag{3.8}$$

The problem can be written as the maximization of (3.1), subject to (3.3), (3.4), (3.5), (3.6), and (3.8). I denote the Lagrange multipliers associated with this optimization as τ_t, ϕ_t, η_{i_t}, θ_t and λ_t respectively.

Other than the choice of the technological parameter b_{t+1}, the first order conditions are standard. The first order condition with respect b_{t+1} is

$$\begin{aligned}\frac{\partial G(b_t, b_{t+1})}{\partial b_{t+1}}(-\lambda_t K_t - \theta_t S_t) + \beta\lambda_{t+1} F_{b_{t+1}}\left(b_{t+1}, K_{p_{t+1}}, S_{p_{t+1}}, U_{p_{t+1}}\right) + \\ +\beta\frac{\partial G(b_{t+1}, b_{t+2})}{\partial b_{t+1}}(-\lambda_{t+1}K_{t+1} - \theta_{t+1}S_{t+1}) = 0\end{aligned} \tag{3.9}$$

The first term captures the cost of choosing b_{t+1} in terms of accelerated obsolescence for both K_t and S_t, and the second and third terms reflect the benefits. The benefits are divided into two terms. The second term of the equation captures the increased production due to the change in technology and the last term captures the benefit in terms of technology adoption at $t+1$. This last term captures the benefit when transiting to b_{t+2} for having moved to b_{t+1}. This captures the change in cost incurred due to technical change from having chosen b_{t+1}as a stepping stone in the transition from b_t to b_{t+2}.

The steady state satisfies:

$$\frac{1-\beta}{\beta} + \delta_k = F_{K_p}\left(b, K_p, S_p, U_p\right) \tag{3.10}$$

$$\frac{1-\beta}{\beta} + \delta_s = H_{S_e}\left(K_e, S_e, U_e\right) - H_{U_e}\left(K_e, S_e, U_e\right) \tag{3.11}$$

$$\frac{H_{U_e}\left(K_e, S_e, U_e\right)}{F_{U_p}\left(b, K_p, S_p, U_p\right)} = \frac{H_{S_e}\left(K_e, S_e, U_e\right)}{F_{S_p}\left(b, K_p, S_p, U_p\right)} = \frac{H_{K_e}\left(K_e, S_e, U_e\right)}{F_{K_p}\left(b, K_p, S_p, U_p\right)} \tag{3.12}$$

$$F_b\left(b, K_p, S_p, U_p\right) = 0 \tag{3.13}$$

Where equation (3.10) is the standard first order condition with respect to capital and equation (3.11) is the first order condition with respect to skilled workers which is also standard once we take into account that when the stock of skilled workers grows, the stock of unskilled workers shrinks. Equation (3.12) is determining the optimal levels of skilled workers, unskilled workers and physical capital across sectors. Finally equation (3.13) shows that in steady state no more improvements can be made by shifting the technology away from b. This is the case since the function $G\left(b_t, b_{t+1}\right)$ is symmetric and therefore $\frac{\partial G(b_t,b_{t+1})}{\partial b_t} = \frac{\partial G(b_t,b_{t+1})}{\partial b_{t+1}}$. Note that in steady state the function $G(b,b)$ does not play a role, since it only affects the transition across technologies.

3.2. Market equilibrium

There are two types of agents in the market equilibrium that implement the planner's equilibrium shown above. Households own physical capital and make decisions about skills accumulation and technology choice. Firms are competitive and produce final output.

3.2.1. Firms

Firms producing final goods can be ordered according to the technology they operate b. Firms operate for one period. They rent unskilled labor, skilled labor and capital of type b from the household in order to maximize profits. In other words in every period there is demand for unskilled labor, skilled labor and capital of every type b, $0 < b < 1$. The market under which firms operate is perfectly competitive. The problem each firm of type b solves is:

$$\max_{S_{p_t}(b), U_{p_t}, K_{p_t}(b)} \quad p_t F\left(b, K_{p_t}(b), S_{p_t}(b), U_{p_t}\right) - w_{s_t}(b) S_{p_t}(b) - w_{u_t}(b) U_{p_t} - r_t(b) K_{p_t}(b)$$

The optimal conditions for each type b firm are:

$$\begin{aligned} \frac{w_{s_t}(b)}{p_t} &= F_{S_p}\left(b, K_{p_t}(b), S_{p_t}(b), U_{p_t}\right) \\ \frac{w_{u_t}(b)}{p_t} &= F_{U_p}\left(b, K_{p_t}(b), S_{p_t}(b), U_{p_t}\right) \\ \frac{r_t(b)}{p_t} &= F_{K_p}\left(b, K_{p_t}(b), S_{p_t}(b), U_{p_t}\right) \end{aligned} \tag{3.14}$$

Where $w_{s_t}(b)$ stands for wages for skilled workers offered by a firm operating technology b in period t, $w_{u_t}(b)$ stands for wages for unskilled workers offered by a firm operating technology b in period t and $r_t(b)$ represents the interest rate offered by firms operating technology b in period t. And p_t stands for the price of final goods, which is normalized to 1. So, for every b-type firm, their maximizing behavior determines wages and the interest rate under each technology. Therefore at every moment in time we have a function of wages and interest rate as function of the parameter b.

Firms can also be interpreted as freely choosing the any production parameter $b \in [0, 1]$, where it is necessary to hire K_p and S_p of that type in order to produce final goods.

3.2.2. Households

A set of atomistic representative households own capital and labor. Given prices, they rent capital, skilled labor and unskilled labor to the firm every period The capital and skilled labor they own is of type b and can only be used in production in a type b firm. They make investment and education decisions. Education is undertaken internally to the household[2]. This means that the household decides how much capital, skilled labor and unskilled labor to supply to the market given prices. The part of capital, skilled labor and unskilled labor that is not supplied is used to produce more skilled labor for the next period. Every period the type of physical capital and skills the household owns is given but can be changed for the future, so the household not only chooses the evolution of the quantity of physical capital and skilled labor but also its type for the future.

The problem of the representative consumer can be written as follows

$$\max_{C_t, I_t, S_{p_t}, U_{p_t}, K_{p_t}, S_{e_t}, U_{e_t}, K_{e_t}, b_{t+1}} \sum_{t=0}^{\infty} \beta^t u(C_t) \tag{3.15}$$

[2]This is not a key issue. Households could buy $H()$ in the market since it is a constant returns to scale technology the results would not change.

subject to

$$C_t + \int_0^1 K_{t+1}(b_{t+1})\, db_{t+1} - \int_0^1 \int_0^1 K_t(b_t)\left[1-\delta_k - G(b_t, b_{t+1})\right] db_t db_{t+1} \le \int_0^1 w_s(b_t) S_{p_t} db_t + \int_0^1 w_u(b_t) U_{p_t} db_t + \int_0^1 r(b_t) K_p db_t$$

$$\int_0^1 S_{p_t}(b_t)\, db_t + \int_0^1 S_{e_t}(b_t)\, db_t \le \int_0^1 S_t(b_t)\, db_t$$

$$U_{p_t} + U_{e_t} \le 1 - \int_0^1 S_t(b_t)\, db_t$$

$$\int_0^1 K_{p_t}(b_t)\, db_t + \int_0^1 K_{e_t}(b_t)\, db_t \le \int_0^1 K_t(b_t)\, db_t$$

$$\int_0^1 S_{t+1}(b_{t+1})\, db_{t+1} \le \int_0^1 \int_0^1 S_t(b_t)\left[1-\delta_s - G(b_t, b_{t+1})\right] db_t db_{t+1} + + \int_0^1 H\left(K_{e_t}(b_t), S_{e_t}(b_t), U_{e_t}\right) db_t$$

$$\int_0^1 K_{t+1}(b_{t+1})\, db_{t+1} \le \int_0^1 \int_0^1 K_t(b_t)\left[1-\delta_k - G(b_t, b_{t+1})\right] db_t db_{t+1} + I_t$$

Where variables $S(b)$ and $K(b)$ denote the type of the skills and physical capital.

3.2.3. Equilibrium

An equilibrium is defined by a sequence of prices[3],

$\left\{\{w_s(b_t), w_u(b_t), r(b_t)\}_{b=0}^{1}\right\}_{t=0}^{\infty}$[4], allocations

[3]one for each $b \in (0,1)$

[4]Given that the functions $\left\{\{w_s(b_t), w_u(b_t), r(b_t)\}_{b=0}^{1}\right\}_{t=0}^{\infty}$ are only observable at the adopted b, I

$\{C_t, I_t, S_{p_t}, U_{p_t}, K_{p_t}, S_{e_t}, U_{e_t}, K_{e_t}\}_{t=0}^{\infty}$ and technology parameters $\{b_t\}_{t=0}^{\infty}$, such that:

1.- Households maximize utility. That is they solve the problem defined by equation (3.15).

2.- Firms maximize profits. That is, for every technology parameter, equations (3.14) are satisfied.

3.- Initial conditions. That is b_0, S_0, and K_0, are given.

4.- Market clearing condition: $C_t + I_t \leq F\left(S_{p_t}, U_{p_t}, K_{p_t}, b_t\right)$

Since households are identical I focus on the equilibrium where each household supplies to the market only one technology type skilled worker and physical capital and that type is the same across households.

4. Calibration

4.1. Functional forms

The instantaneous utility function is of the form

$$u\left(C_t\right) = \frac{C_t^{(1-\varphi)}}{1-\varphi}$$

The technology adjustment cost function $G()$ is given by

$$G\left(b_t, b_{t+1}\right) = e^{\zeta\left(\frac{b_{t+1}}{b_t}-1\right)^2} - 1 \tag{4.1}$$

can expand the function around that point. Let $b^{\star}$ be the adopted technology, then $w_s(b_t^{\star}) = F_3\left(b_t^{\star}, K_{p_t}, S_{p_t}, U_{p_t}\right)$, $w_u(b_t^{\star}) = F_4\left(b_t^{\star}, K_{p_t}, S_{p_t}, U_{p_t}\right)$ and $r(b_t^{\star}) = F_2\left(b_t^{\star}, K_{p_t}, S_{p_t}, U_{p_t}\right)$.At the equilibrium point, it is possible to determine the derivative of those wages and interest rates with respect to $b_t^{\star}$. In equilibrium, the price functions are linear functions of b such that their slope is given by $\frac{\partial w_s(b_t^{\star})}{\partial b_t^{\star}} = \frac{\partial F_3\left(b_t^{\star}, K_{p_t}, S_{p_t}, U_{p_t}\right)}{b_t^{\star}}$, $\frac{\partial w_u(b_t^{\star})}{b_t^{\star}} = \frac{\partial F_4\left(b_t^{\star}, K_{p_t}, S_{p_t}, U_{p_t}\right)}{b_t^{\star}}$ and $\frac{\partial r(b_t^{\star})}{b_t^{\star}} = \frac{\partial F_2\left(b_t^{\star}, K_{p_t}, S_{p_t}, U_{p_t}\right)}{b_t^{\star}}$.

This function satisfies the requirements stated above, $G(b_t, b_t) = 0$ and $G(b_t, b_{t+1}) > 0$ for $b_t \neq b_{t+1}$.

Note that the function $G(b_t, b_{t+1})$ is convex, which is in line with a whole literature of convex adjustment cost, which induce the planner or the market to take small steps in adjusting the technology instead of taking big jumps. Also note that the function $G(b_t, b_{t+1})$ has the property that its derivatives in steady state are equal to zero, enabling me to write equation (3.13). The function $G(b_t, b_{t+1})$ is affected by only one parameter, ζ. As ζ increases the costs associated with technological change (in terms of skilled workers and physical capital), increase, affecting the dynamic transition outside steady state.

The choice of the production function of final goods, $F()$, is not straightforward. Since one of the features I want the model to capture is the evolution of the skill premium, it should be the case that skilled and unskilled labor are imperfect substitutes. Therefore I restrict attention to the family of nested CES functions, with inputs K_p, S_p and U_p. Let $\Omega(A_t, B_t; a, \varrho)$ be a CES function between inputs A_t and B_t with weights parameter a and elasticity parameter ϱ. The technological choice of interest is constrained to the skill biased parameter, which I will call b for "bias". Therefore I restrict attention to the CES weights between terms containing skilled workers and unskilled workers[5]. Then the possible nested CES forms are:

- $F^1 = \Omega\left(\Omega\left(U_t, S_t; \mathbf{b}, \rho_1\right), K_t; a, \rho_2\right)$
- $F^2 = \Omega\left(\Omega\left(S_t, K_t; a, \rho_1\right), U_t; \mathbf{b}, \rho_2\right)$
- $F^3 = \Omega\left(\Omega\left(U_t, K_t; a, \rho_1\right), S_t; \mathbf{b}, \rho_2\right)$

Of the 3 possibilities, F^3 is the only one that generates an evolution towards skill intensive technologies without imposing a ration of U/S in steady state that is independent of total

[5] Even though it is conceivable that one could make the choice of technologies be that of choosing all the parameters in the production function (ρ_1, ρ_2, a, b), I restrict the attention to only b.

factor productivity. It is also consistent with the data in terms of partial elasticities of substitution as it is shown later[6].

To summarize the production function used in the quantitative exercise is given by

$$F\left(b_t, K_{p_t}, S_{p_t}, U_{p_t}\right) = z_t \left\{ b_t \left[a U_{p_t}^{\rho_1} + (1-a) K_{p_t}^{\rho_1} \right]^{\frac{\rho_2}{\rho_1}} + (1-b_t) S_{p_t}^{\rho_2} \right\}^{\frac{1}{\rho_2}} \tag{4.2}$$

Under this specification of the production function, the skill premium can be written as:

$$\begin{aligned} \ln\left(\frac{w_s}{w_u}\right)_t &= \ln\left(\frac{1}{a}\right) + \ln\left(\frac{(1-b_t)}{b_t}\right) - (1-\rho_2)\ln\left(\frac{S_{p_t}}{U_{p_t}}\right) \\ &+ \left(1 - \frac{\rho_2}{\rho_1}\right) \ln\left(a + (1-a)\left(\frac{K_{p_t}}{U_{p_t}}\right)^{\rho_1}\right) \end{aligned} \tag{4.3}$$

which shows that there are three terms affecting the skill premium which are derived from three different sources.

[6] F^1 is the production function of choice in both Heckman, Lochner and Taber (1998) and Caselli and Coleman (2006). The problem with this functional form is given by equation (3.13) , since that requires that in steady state $U = \iota S$, where ι denotes some constant, independent of the level of T.F.P. The condition of $U = \iota S$ is a direct consequence of the linearity of the CES function with respect to b. F^2 is the production function used by Krusell et. al. (2000). They argue in favor of F^2 instead of F^3 because data collected by Hamermesh (1993) suggest that the elasticity of substitution between S and U is higher than that between S and K, and function F^3 restrict them to be equal. This feature in the data comes from estimates of the partial elasticity of substitution, which depends on the levels of S, U and K, and not only on the substitution parameter. As I show later, the partial elasticity of substitution in specification F^3 between S and U is higher than that between S and K. The problem with specification F^2 is that under the parameters suggested by Krusell et. al. (2000), the endogenous technological change goes towards higher intensities in the use of unskilled labor. One alternative would be to use F^2 under a different set of parameters, but that would violate the moments estimated by Krusell et. al. (2000), in particular the elasticities of substitution between capital, skilled workers and unskilled workers. That is why I choose form F^3 as the production function in the paper. F^3 is also the production function of choice in Funk and Vogel (2004). Under the set of parameters chosen in table 1, the form F^3 does match the elasticities of substitution estimated by Hamermesh (1993), which were close to the ones estimated by Krusell et. al. (2000)

$$L_t = \ln\left(\frac{(1-b_t)}{b_t}\right)$$

$$M_t = -\left(1-\rho_2\right)\ln\left(\frac{S_{p_t}}{U_{p_t}}\right)$$

$$N_t = \left(1-\frac{\rho_2}{\rho_1}\right)\ln\left(a+(1-a)\left(\frac{K_{p_t}}{U_{p_t}}\right)^{\rho_1}\right)$$

The term L_t is the "technological" factor, M_t the "relative supply of skills" factor and N_t the "capital deepening" factor. As b_t decreases (which we interpret as skilled bias technological change) the term L_t increases which results in a higher skill premium. As the stock of skilled workers grows (and the stock of unskilled workers shrinks) the relative supply factor, M_t, decreases, decreasing the skill premium, given that ρ_2 is negative. Finally as the amount of capital per unskilled worker grows, the capital deepening factor increases, together with the skill premium. Therefore the final evolution of the skill premium will be a result of a horse race between these three different factors. Murphy, Riddell and Romer (1998) have a similar decomposition for the skill premium (with only the technological factor and the relative supply of skills) where they exogenously input a log linear technological term, and find that for Canada the technological factor grows at around 3.5% per year. In this paper I derive the technological factor endogenously and find a slower rate of growth, which is expected given that in this case we also have the capital deepening factor growing. The average sum of the rate of growth of L_t and N_t for 1940 to 2000 in the model is 4.25%.

Finally the function $H()$ is assumed to be Cobb-Douglas:

$$H\left(U_{e_t}, S_{e_t}, K_{e_t}\right) = \psi U_{e_t}^{\mu} S_{e_t}^{\xi} K_{e_t}^{1-\mu-\xi} \tag{4.4}$$

The specification of the law of motion for the stock of skilled workers in equation (3.6) does not restrict S_t to be less than 1, in the case of high enough K_e. Even though this is possible, the planner never chooses an $S_t > 1$ because the productivity of the unskilled workers approaches infinity as U_t approaches zero.

4.2. Choice of Parameters

In order to obtain the parameters of the model, I calibrate the system to the US circa 1990. I can only calibrate out of steady state, otherwise ζ would not be identified[7]. So, the model is calibrated to a transition point in 1990. In order to do that, the path of GDP per worker that will be perfectly matched by the model is constructed as follows: first, from 1940 to 2000 it is determined by the data, and then there is a convergence phase to a new steady state in the future. The 1940-2000 part is a smoothed series of the GDP per worker. The convergence phase is constructed to make the growth rate of GDP decline from its average value for 1996-2000 to zero in 50 years and remain constant thereafter. This phase of convergence to a new steady state is needed since the model does not have a balanced growth path. In other words, the exogenous path of TFP (z_t) is such that the endogenous GDP per worker follows its observed path (1940 - 2000) and also converges to a new steady state as explained above.

4.2.1. Parameter values

Some parameters are set according to the existing literature. For instance $\delta_k = .08$ is the average of the depreciation rates for structures and equipments used by Krusell et. al. (2000), $\varphi = 2$ is in the middle of the range of parameters between the logarithmic specification and the value used by Hubbard et. al. (1994), following Manuelli and Seshadri (2005) $\delta_s = .02$, finally $\beta = .96$. The rest of the parameters are calibrated to match the moments presented in Table 2.

[7] Since in steady state there is no technological adoption friction

The parameters of the model are presented in table 1

Table 1: Parameter values in the model

Parameter	z_{1940}	ρ_1	ρ_2	a	μ	ξ	ψ	ζ
Value	.5	.75	-0.2	.5	.75	.1759	.2	23

Table 2 presents the identifying moments used to calibrate the model.

Table 2: Identifying moments.

Comparison between the model and the data in 1990

Moment	Model	Data US, 1990
Skill Premium	1.88	1.87[8]
Skilled workers	.87	.94[9]
Consumption Output Ratio	.83	.79[10]
Primary students over Labor Force	.177	.164[11]
Expenditure per pupil over GDP per worker	.1258	.1132[12]
Capital Share of GDP	.2915	.3
Wage expenditure in education	.7036	.7036[13]
$\frac{\sigma_{S,U}}{\sigma_{S,K}}$	2.62	2.49[14]

[8] Return to 8 years of schooling calculated as $\exp(\omega_t 8)$, where ω_t equals the return to one year of high school for "All men" reported by Goldin and Katz (1999).

[9] From DeLong, Goldin and Katz (2003) average between 1980 and 2000 for workers with less than 8 years of schooling.

[10] This is the ratio of Personal Consumption Expenditures to Personal income reported by the Bureau of Economic Analysis, in its table 2.1 for the year 1990

[11] Calculated as the ratio of students enrolled in primary school times the participation rate over the total labor force. Source: Statistical Abstract of The US for 1994 (data taken for 1990).

[12] Obtained from the Statistical Abstract of the US 1990

[13] Obtained from the Statistical Abstract of the US for 1990

[14] $\sigma_{S,U}$ equals the partial elasticity of substitution between S and U. Therefore, $\frac{\sigma_{S,U}}{\sigma_{S,K}}$ is the ratio of partial elasticities of substitution between S and U and S and K. According to Krusell et al (2000) it is 2.49, which is based in turn in calculations reported by Hamermesh (1993). It is computed following Uzawa (1962)

4.2.2. US Data

In order to construct the series for GDP per worker for the US, I take data from 1950 to 2000 from Heston, Summers and Aten (2002) and add to that data from 1940 to 1950 from the NIPA tables. I extend the data backwards to capture the 1940s phenomenon that the skill premium displayed a decreasing trend, contrasting the behavior after 1950. Additionally, 1940 is the first point in time where the data for skill premium is collected from census sources. From an economic point of view there seems to be evidence that starting in WWII the availability of technologies may have increased. That is, we can think of the set of technologies being expanded during the war and from that point on economic agents can endogenously choose technologies that were not available before[15].

The results are not sensitive to the choice of future paths of GDP per worker as long as abrupt changes close to the data window are not introduced[16].

Since this paper focuses on the long run behavior of the economy, the series of GDP per worker is smoothed using a Hodrick Prescott filter.

Following DeLong, Goldin and Katz (2003), the number of skilled workers in the US, is taken from decennial census data from 1940 to 2000. A skilled worker is defined as an individual with educational achievement higher than primary school. The reason for using a relatively low cutoff is that in poor countries a large fraction of the workforce has less than 6 years of schooling.

The skill premium data for the US, is constructed using the return to High School reported by Goldin and Katz (1999) from 1940 onwards. The evolution of different measures of skill premium, such as the return to high school and college indicate an U shape pattern with a minimum around 1950.

Other data used to calibrate the model come from standard sources.

[15] In their study Baier et al (2004) find that TFP was constant up to 1940 and in that year it stated increasing in an almost linear way.

[16] Both the convergence horizon and the speed of convergence do not affect the results as long as enough time and no abrupt change in the growth rate of GDP per worker is introduced

Consumption-output ratio, is taken from the NIPA tables and educational expenditures per pupil over GDP per worker and expenditures in educational wages over total educational expenditures are obtained from the Statistical Abstract of the US.

5. US Dynamics

The goal of this section is to analyze the endogenously generated dynamics of the skill premium and skill bias once the economy is confronted with a path of total factor productivity that perfectly matches the evolution of the GDP per worker in the US after 1940.

For this experiment the US economy is assumed to be in steady state before 1940[17]. At that point it is assumed that the set of available technologies expanded. This does not imply that the new technologies would be adopted immediately. The growth in TFP induces the adoption of those technologies as the stocks of physical and human capital become available. The idea in the experiment is that these technologies were available from the beginning of time but were slowly implemented as total factor productivity grew.

The model determines the stock of capital, unskilled workers, skilled workers, their distribution across the educational and production sectors, their prices and the bias in the technology. The results in terms of dynamics for the US are shown in the next set of figures[18]. The endogenous dynamics in terms of skill premium implied by the model are shown in Figure 5.1. The model provides a unified explanation for the evolution of the skill premium both before and after 1950. The U shape in the skill premium is generated with an endogenous skill biased technological change. During the whole period endogenous skill biased technological change is generated, not only after 1950 as previously explored by the literature. This effect is generated by the simultaneous effects of technological change and

[17] Even though the starting point matters for the dynamics of the model, the main results remain valid if the model is started at different points in time, both before and after 1940.

[18] A detailed explanation of the computational algorithm and data construction is given in appendices 3 and 4.

investments in skills and physical capital as depicted in Figure 5.2.

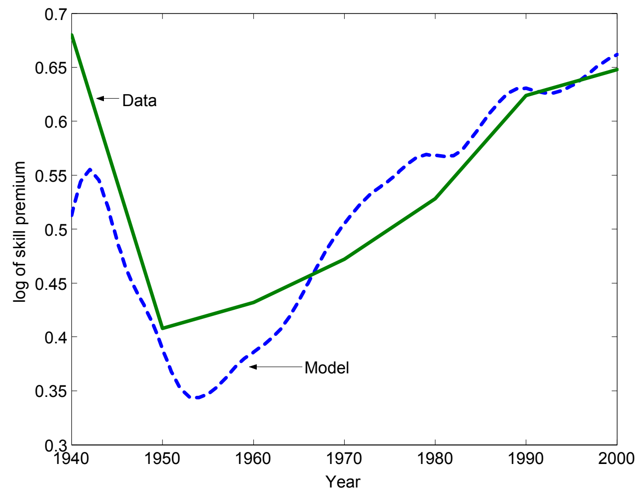

Figure 5.1: Skill premium in the US from 1940 to 2000 in the data and predicted by the model

The decomposition of the skill premium into the technological factor, the relative supply of skills factor and the capital deepening factor is shown in Figure 5.2.

From Figure 5.2 it is clear that the decreasing phase of the skill premium up to around 1950 is primarily determined by the behavior of the ratio unskilled to skilled workers devoted to production. Later, it is the effects of the technological change and investment in physical capital that determine the increase in skill premium.

The intuition behind the initial reaction is that once the economy is faced with the new paths for total factor productivity, it starts producing skilled workers at a high rate since it has to get to a higher level of skilled workers in the new equilibrium and also because it is experiencing a faster rate of obsolescence of its existing stocks. But after the initial effects heavily driven by skills creation, investment in physical capital and technological change become more important and determine an increase in the skill premium. Changes in technology directly affect the marginal productivities of skilled workers vs. unskilled ones, but the term based on capital per unskilled worker is affected by both decreasing stocks of unskilled workers and higher levels of physical capital. Both elements contribute to increases

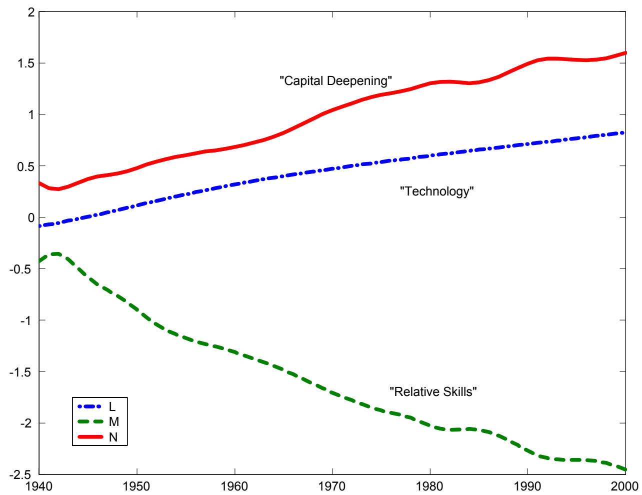

Figure 5.2: Decomposition of skill premium from 1940 to 2000 ; $L = \ln\left(\frac{(1-b)}{b}\right)$; $M = (\rho_2 - 1)\ln\left(\frac{S_p}{U_p}\right)$; and $N = \left(1 - \frac{\rho_2}{\rho_1}\right)\ln\left(a + (1-a)\left(\frac{K_p}{U_p}\right)^{\rho_1}\right)$

in the skill premium. Even though capital and skills depreciate in the same way as a result of technological change, since $\delta_s < \delta_k$, the stock of skilled workers is relatively (to its steady state evolution) more affected by the accelerated obsolescence induced by the evolution of b_t. Therefore the initial response to TFP favors the creation of skills.

The key element in the model is the skilled biased technological change. In the model it is endogenous and expressed by the variable $(1 - b_t)$. The dynamic evolution of that variable is shown in Figure 5.3. Where we see both the results implied by the model and the estimates from the data, and in both cases a transition towards a technology intensive in terms of skill premium is observed. In order to estimate the skill bias parameter shown in Figure 5.3 I calculate b_t as:

$$b_t = \left\{ \frac{skp_t \left[a + (1-a)\left(\frac{K_{p_t}}{U_{p_t}}\right)^{\rho_1}\right]^{\frac{\rho_2}{\rho_1} - 1} a}{\left(\frac{S_{p_t}}{U_{p_t}}\right)^{\rho_2 - 1}} + 1 \right\}^{-1}$$

where skp_t represents the skill premium at time t.[19]

The model delivers endogenous skill bias technological change, which is a direct result of increases in the exogenous path for TFP. As TFP grows, the economy can devote more resources to the production of skilled workers and once more skilled workers are available it is optimal to undertake production under ever more skill intensive technologies.

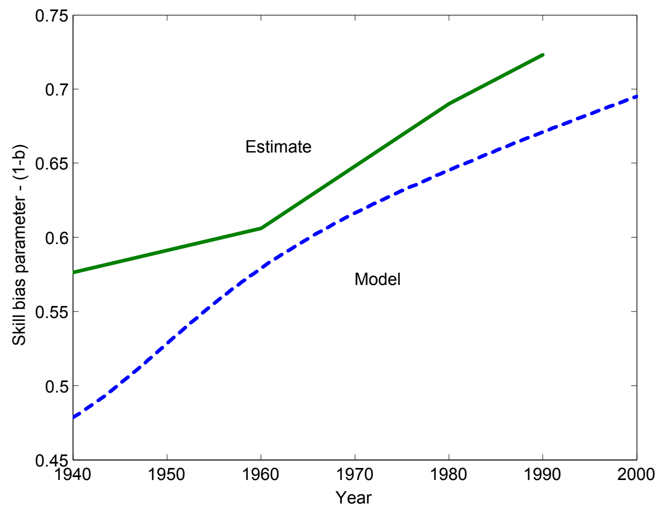

Figure 5.3: Evolution of the skill bias parameter $(1-b)$ in the US from 1940 to 2000, predicted by the model and estimated from the data

In other words, once the economy is confronted with a new path for TFP this changes the demand for skilled workers and physical capital, since the equilibrium technology shifts towards a new one more intensive in skilled workers. The initial decreasing phase in the evolution of the skill premium is driven by rapid changes in the ratio of unskilled to skilled workers devoted to the production sector. Both skilled and unskilled workers are reallocated as a result of the new path of total factor productivity to the educational sector in greater numbers than in the previous steady state. This reallocation is driven by two forces. First, when total factor productivity is higher, so is the steady state level of $(1-b)$ and, therefore,

[19] Using the data for S_{p_t} and U_{p_t}, K_t and the skill premium and the parameters chosen in the calibration shown in table 1 I am able to compute every term needed for b_t.

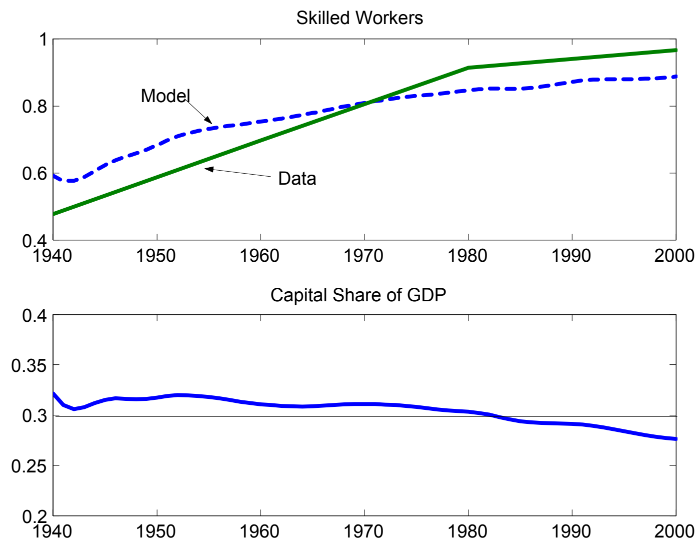

Figure 5.4: Evolution of the stock of skilled workers over labor force and the capital share of GDP

the optimal level of skilled workers is also higher, given that their marginal product grew. Second, during the transition the rate at which the stocks of skilled workers become obsolete is higher than in the steady state equilibrium. Therefore, in equilibrium the economy chooses a higher level of skilled workers and higher rate of obsolescence, which implies that more and more resources are devoted to the educational sector at the expense of the production one.

The increasing phase in skill premium post 1950 is generated almost exclusively by the changes in technology and the increases in physical capital into the production sector that enter in full effect after the stocks of skilled workers had been created and can enter the production sector.

As independent evaluation of the model, the evolution of the capital share of GDP and the evolution of the stock of skilled workers are reported in Figure 5.4. Capital share, over the period 1940 - 2000, remains close to 30%, which is what many studies suggest should be the number for the US[20]. In terms of the ratio of skilled workers to total labor force, the model predicts a range smaller than what the data suggests, but still it captures most of its

[20] This is not straight forward since the production function is of the CES form

evolution.

6. Cross Country Evidence

This section serves a dual purpose. First it serves as an independent evaluation of the model, because the same parameter values that were obtained from the calibration for the US are used in the cross country context. Second, it endogenously generates the evolution of the skill premium and technology adoption for different countries, with completely different paths for GDP per worker, matching its cross section around 1990.

In order to conduct cross-country comparisons, an international database is set up. Instead of following individual countries I follow deciles of the GDP per worker distribution in 1990[21]. GDP per worker is computed as an unweighted average per decile for the countries with long enough series (those with complete series from 1960 to 1996), from Heston, Summers and Aten (2002), expanded back to 1940 taking the average growth rate in the period (1960-1965). The stock of skilled workers is computed using data from Barro and Lee (1993), using the same definition as for the US case. The skill premium is computed using data from returns to schooling from Bils and Klenow (2000), and the duration of primary school as Caselli and Coleman (2006).

6.1. Experiment

The experiment across countries is the following: Begin in 1940 in steady state for every decile of the distribution of the GDP per worker and choose a sequence of TFP that matches the evolution of GDP per worker for each decile from 1940 to 2000, and impose convergence to a decile specific level by taking the last 5 years of data and letting the growth rate of GDP per worker decrease linearly from the average growth rate from the last 5 years to 0 in

[21] The countries included in the database are those with long series of GDP per worker (1960 to 1996) and that have an estimate of skill premium in the database by Bils and Klenow (2000).

50 years, and after that stay constant for ever.

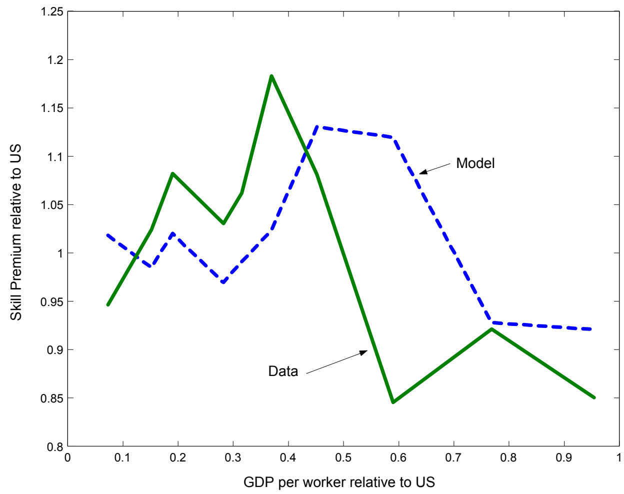

Figure 6.1: Skill premium as a fraction of the US in the data and model across deciles of the world distribution of GDP per worker

With this strategy it is possible to compute a dynamic path for every 1990-decile. When comparing the data to the model, I take the 1990 cross section and, therefore, I take the transitional point that corresponds to 1990 in the model. I compute the skill premium as $\exp((\omega n)_i)$ where ωn is the median by decile of the skill premium and ω represents the coefficients for schooling in the Mincer regressions reported by Bils and Klenow (2000)[22] and n the length of the primary school in years from Caselli and Coleman (2006)[23]. The comparison between the model and the data is reported by Figure 6.1

The model is shifted to the right with respect to the data, but it is in the right scale and predicts a hump shape in skill premium, much as the one obtained from the data. As in the US case, the skill premium can be decomposed into three terms which depend on

[22] An additional complication arises with the comparison between model and data in terms of skill premium across deciles, because we do not have data gathered in the same year across countries, so instead of checking what the model implies for 1990 in terms of skill premium, I take the average by decile of the year in which the observation reported by Bils and Klenow (2000) was made and bring that number from the model for each decile.

[23] I use the median by decile of the returns to schooling instead of the averages so as to avoid the effects induced by outlyers. In particular Jamaica, Honduras and Indonesia.

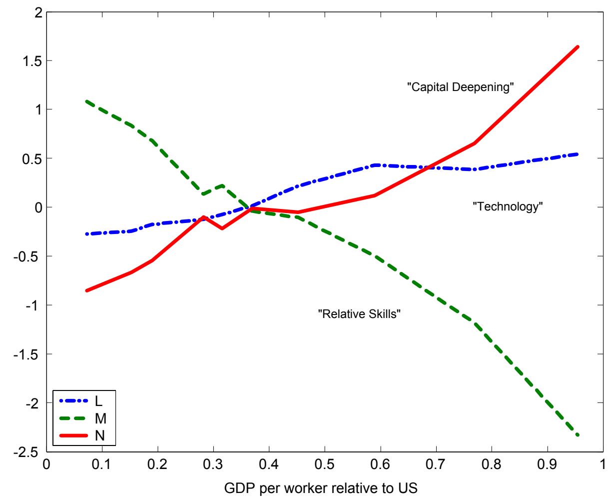

Figure 6.2: Cross section of: $L = \ln\left(\frac{(1-b)}{b}\right)$; $M = (\rho_2 - 1)\ln\left(\frac{S_p}{U_p}\right)$; and $N = \left(1 - \frac{\rho_2}{\rho_1}\right)\ln\left(a + (1-a)\left(\frac{K_p}{U_p}\right)^{\rho_1}\right)$

$\left(\frac{1-b}{b}\right)$, $\left(\frac{S_p}{U_p}\right)$ and $\left(\frac{K_p}{U_p}\right)$. Figure 6.2 depicts the influence of each term in the skill premium pattern across countries around 1990.

Even though the model predicts that countries will adopt ever more skill biased technologies as they develop, the dominating mechanisms in terms of the cross-country comparison of the skill premium are those generated by differences in the capital to unskilled worker ratio and the skilled to unskilled workers ratio in the production sector

Even more interesting is the dynamic behavior for skill premium for all the deciles over time. The fact that they follow different trajectories of TFP so as to match GDP per worker makes the skill premium differ greatly in terms of its dynamic path across deciles. Figure 6.3 depicts the whole path for each decile from 1940 to 2000, where the U shape pattern displayed by the US and the first decile (induced by the US) is not generic to any departure from steady state. Both the initial conditions and future path of TFP matter in terms of reaction for the economy in terms of skill premium.

What is clear from Figure 6.3 is that the reaction of the skill premium differs from decile to decile, describing three main patterns. First, in the first decile we see a U shape pattern.

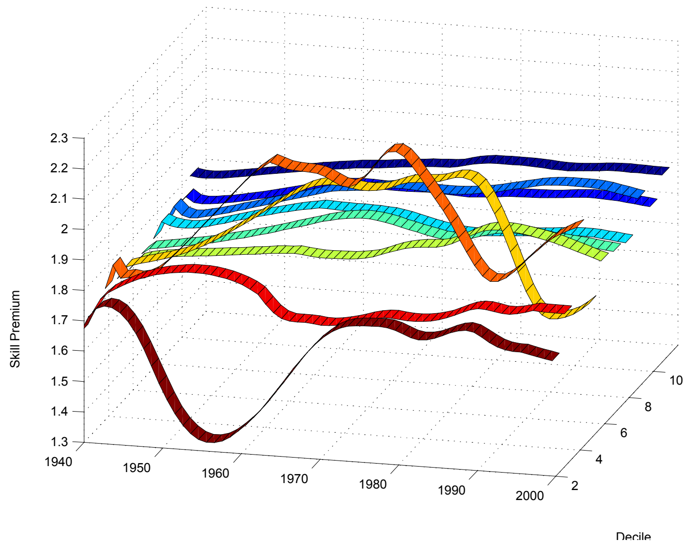

Figure 6.3: Skill premium predicted by the model across deciles from 1940 to 2000

Deciles 3 and 4 start in 1940 with increases in skill premium but then decline by 1980. In the remaining deciles there seems to be a small change in skill premium. The differences across deciles arise from differences in the initial conditions and the paths of total factor productivity necessary to match the evolution of GDP per worker.

In terms of technology adoption, the parameter $(1 - b)$ chosen across deciles is depicted in Figure 6.4. There it is clear that the production technology in use in the higher deciles is relatively more intensive in the use of skills. Also, those countries with GDP per worker above half the level of the US are very close in terms of skill bias technology, whereas the poorer half of the distribution chooses a fairly different technology

Figure 6.5 presents the dynamic behavior across deciles of the parameter $(1-b)$ from 1940 to 2000. There, it is the top 4 deciles which have incurred major technological change, and the rest of the distribution remained with a technology that did not change much over this period, suggesting the existence of "technology adoption clubs", where the richer countries adopt more skill intensive technologies faster than the poor ones generating a pattern of divergence in the use of technology. It can be seen that over the period 1940 - 2000 the

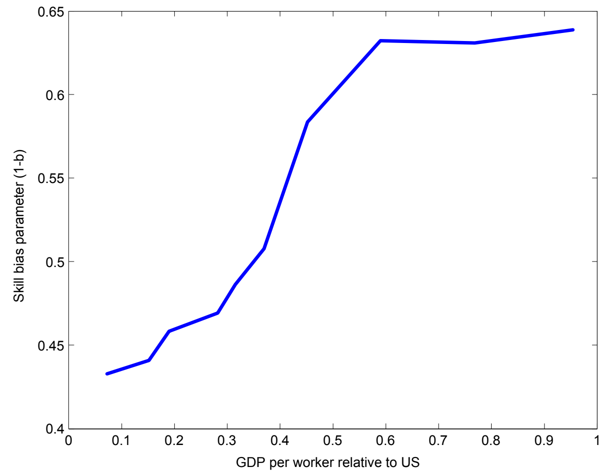

Figure 6.4: Skill bias parameter $(1-b)$ across deciles in 1990

parameter $(1-b)$ has diverged across deciles, from a range from .4 to .48 in 1940 to between .43 to .65 in 2000.

I find that richer countries endogenously choose technologies that are intensive in the use of the skilled labor factor, but the adoption of these technologies is far from linear in the level of development. The results show the existence of technology adoption clubs at the top half of the distribution of GDP per worker.

As an independent evaluation of the model, Figure 6.6, shows the evolution of the stock of skilled workers across deciles in 1990. The model's overprediction the stock of skilled workers is a direct consequence of the fact that it is calibrated to US, data which can be considered an outlier even in the top decile. Therefore , apart from the scale bias discussed above, the model predicts the correct relationship between the stock of skilled workers and level of GDP.

7. Conclusion

The literature on skill biased technological change argues that it explains the observed patterns of skill premium both in the US and across countries. In this model I endogenize the

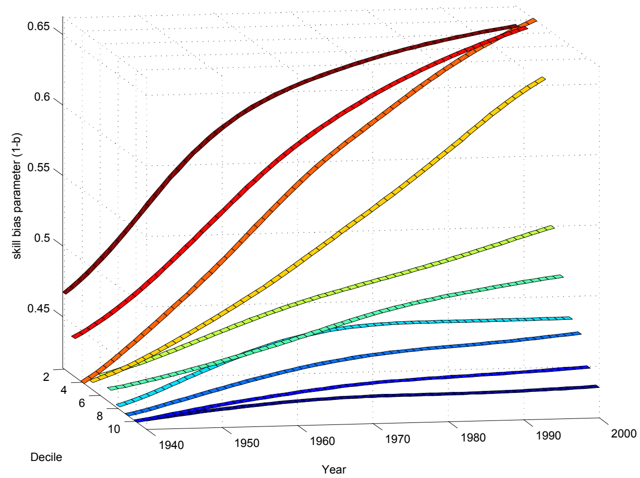

Figure 6.5: Skill bias parameter $(1 - b)$ across deciles from 1940 to 2000

technology adoption decision, and generate endogenous skill biased technological change that is consistent with the data for the US time series and the cross country evidence in terms of skills formation and skill premium.

The model has potential in explaining why it is that poor countries do not adopt newer technologies when they are readily available and implemented in more advanced countries. The fact that there is a cost associated with changing the technology in terms of inputs makes that transition costly and may take long periods of time. It is an alternative argument to the barriers of adoption argued by Parente and Prescott (2000). Here, instead of monopoly groups protecting their rents, it is optimal in a competitive setting to delay the adoption of more advanced technologies in the face of technology adoption costs.

Total factor productivity still plays a major role in the paper suggesting that there may still be a channel similar to that of Parente and Prescott (2000), in the sense that T.F.P. differences are still needed to account for income differences across countries and time.

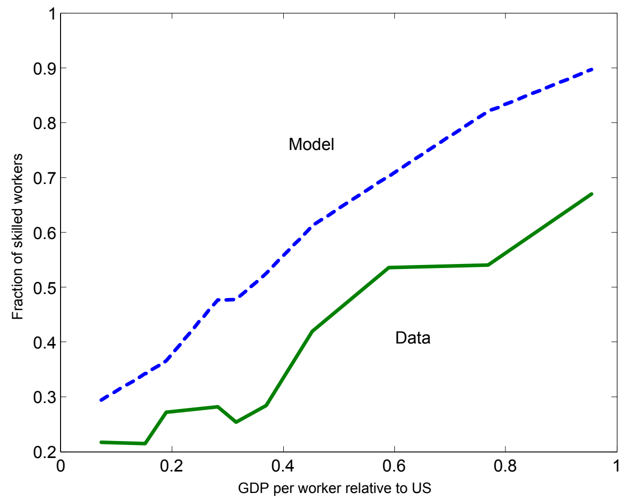

Figure 6.6: Skilled workers across deciles in 1990

References

[1] Acemoglu, Daron. 2002. Directed Technical Change. *The Review of Economic Studies*, 69: 781-809.

[2] Baier, Scott, Sean Mulholland, Robert Tamura and Chad Turner. 2004. How Important are Human Capital, Physical Capital and Total Factor Productivity for Determining Economic Growth in the United States, 1840 - 2000, Clemson University mimeo.

[3] Barro, Robert J. and Jong-Wha Lee. 1993. International Comparisons of Educational Attainment. *Journal of Monetary Economics*, 32(3): 363-394.

[4] Bils, Mark, and Peter Klenow. 2000. Does Schooling Cause Growth?. *American Economic Review*, 90(5):1160:1183.

[5] Caselli, Francesco and Wilbur John Coleman II. 2006. The world Technology frontier. *American Economic Review*, 96(3): 499-522.

[6] Chari, V.V. and Hugo Hopenhayn. 1991. Vintage human capital, growth and the diffusion of new technology. *The Journal of Political Economy*, 99(6): 1142-1165.

[7] DeLong, J Bradford, Claudia Goldin and Lawrence Katz. 2003. "Sustaining US Economic Growth". In *Agenda for the Nation,* H. Aaron, et al., eds., 17-60, Washington, D.C.: The Brookings Institution.

[8] Funk, Peter and Thorsten Vogel. 2004. Endogenous skill bias. *Journal of Economic Dynamics & Control*, 28: 2155-2193.

[9] Goldin, Claudia and Lawrence Katz. 1999. "Decreasing (and then increasing) Inequality in America: A Tale of Two Half-Centuries". In *The Causes and Consequences of Increasing Income Inequality*, F. Welch, ed., 37-82, Chicago: University of Chicago Press.

[10] Greenwood, Jeremy and Mehmet Yorokoglu. 1997. 1974. *Carnegie-Rochester series on public policy*, 46(6): 49-95.

[11] Hamermesh, Daniel. 1993. *Labor Demand*. Princeton: Princeton University Press.

[12] Heckman, James, Lance Lochner and Christopher Taber. 1998. Explaining rising wage inequality: Explorations with a dynamic general equilibrium model of labor earnings with heterogeneous agents. *Review of Economic Dynamics*, 1: 1-58.

[13] Heston, Alan, Robert Summers and Bettina Aten. 2002. Penn World Table Version 6.1, Center for International Comparisons at the University of Pennsylvania (CICUP).

[14] Hubbard, Glenn, Jonathan Skinner and Stephen Zeldes. 1994. The importance of precautionary motives in explaining individual and aggregate saving. *Carnegie-Rochester Conference Series on Public Policy*, 40: 59-125.

[15] Jovanovic, Boyan. 1998. Vintage capital and inequality. *Review of Economic Dynamics* 1: 497-530.

[16] Jovanovic, Boyan and Yaw Nyarko. 1996. Learning by doing and the choice of technology. *Econometrica*, 64(6): 1299-1310.

[17] Krusell, Per, Lee Ohanian, Jose Rios-Rull and Giovanni Violante. 2000. Capital-Skill Complementarity and Inequality: a macroeconomic analysis. *Econometrica*, 68(5): 1029-1053.

[18] Manuelli, Rodolfo and Ananth Seshadri. 2004. Human Capital and the Wealth of Nations. University of Wisconsin - Madison, Mimeo.

[19] Murphy, Kevin, Craig Riddell and Paul Romer. 1998. Wages, Skills and Technology in the United States and Canada. NBER Working Paper 6638.

[20] Parente, Stephen and Edward Prescott. 2000. *Barriers to Riches.* Cambridge: MIT Press.

[21] Uzawa, Hirofumi. 1962. Production Functions with constant elasticities of substitution. *The Review of Economic Studies*, 29(40: 291-299.

8. Appendix 4: Data

8.1. US data

The data for the dynamic analysis concerning the US was constructed as follows:

GDP per worker: The figures for GDP per worker comes from Heston, Summers and Aten (2002) for the period 1950 - 2000. For the periods 1940-1950 and 2001-2004 the series is complemented with data from the BEA constructed as GDP/Labor force. The series is smoothed with a Hodrick Prescott filter with parameter equal to 100, since these are yearly data. Finally I make the series converge to a future steady state by taking the average growth rate for the period 1999 - 2004 and make it decline linearly for 50 years to zero. After that GDP per worker stays constant into the infinite future.

Skilled workers: The definition of skilled workers is "those with more than primary schooling". Obtained from DeLong, Goldin and Katz 2003, Figure 2.4.

Skill Premium: The skill premium data is constructed from Goldin and Katz (1999). They report returns to High School and College for young men and all men. I take the return to High school for all men as the return to education for each year. The return to 8 years of schooling calculated as $\exp(\omega_t 8)$, where ω_t equals the return to high school "All men" reported by Goldin and Katz (1999).

Skill bias parameter b: In order to construct the skill bias parameter shown in Figure 5.3 I calculated the skill premium as $skp_t = \frac{w_{s_t}}{w_{u_t}} = \frac{(1-b_t)}{b_t} \frac{S_{pt}^{\rho_2 - 1}}{\left[aU_{pt}^{\rho_1} + (1-a)K_{pt}^{\rho_1}\right]^{\frac{\rho_2}{\rho_1} - 1} aU_{pt}^{\rho_1 - 1}}$

Therefore we can recover the parameter b_t as $b_t = \frac{A_t}{skp_t + A_t}$

where $A_t = \frac{S_{pt}^{\rho_2 - 1}}{\left[aU_{pt}^{\rho_1} + (1-a)K_{pt}^{\rho_1}\right]^{\frac{\rho_2}{\rho_1} - 1} aU_{pt}^{\rho_1 - 1}}$

Using the data described above and the parameters chosen in the calibration shown in table 1, I was able to construct a series for A_t. The only missing data was the evolution of K_t. And, not only that, but also the fact that there is a scale issue with the capital stock. The data for the capital stock is obtained in per worker terms from the BEA in the

Fixed reproducible Tangible Wealth series as do Baier et al (2004). In order to solve the scale issue I use the model to guide my decision. In the model $K_{1940} = 0.7043$, therefore I rescaled the whole series of capital stocks such that it matches the model in 1940.

Consumption Output ratio in 1990: Obtained as the ratio of personal consumption expenditure to personal income reported by the BEA in table 2.1.

Primary students over labor force in 1990: Obtained from the Statistical Abstract for the US for 1994 (checking the 1990 data). Is the ratio of enrolled primary students * participation rate over labor force.

Expenditure per pupil over GDP per worker in 1990: Taken as the ratio of expenditures in primary schooling over enrolled students and that ratio divided by GDP per worker. Source Statistical Abstract of the US 1994, for year 1990.

Wage expenditure in education in 1990: Taken from the Statistical Abstract for the US 1994 for year 1990. Is the ratio of wage expenditures to total expenditures in education.

Ratio of elasticities of substitution: Taken from Hamermesh (1993), and Krusell et al (2000).

8.2. Cross Country data

Countries: The countries included in the database are those which fulfill the following criteria: Have skill premium data, have long enough GDP per worker data, have data on skilled workers as specified in the next set of items.
The list of included countries is the following:

Table 3: Countries included in the cross country database[24]

Argentina	El Salvador	Kenya	Sri Lanka
Australia	France	Korea, Rep. of	Sweden
Bolivia	Ghana	Malaysia	Switzerland
Botswana	Greece	Mexico	Taiwan
Brazil	Guatemala	Netherlands	Thailand
Canada	Honduras	Nicaragua	Tunisia
Chile	Hong Kong	Pakistan	United Kingdom
China	India	Panama	United States
Colombia	Indonesia	Paraguay	Uruguay
Costa Rica	Israel	Peru	Venezuela
Cyprus	Italy	Philippines	
Dominican Rep.	Jamaica	Portugal	
Ecuador	Japan	Singapore	

With that list of countries, I ordered them by GDP per worker in 1990 and constructed deciles. Then I followed the 10 fictional countries constructed as averages of GDP per worker per decile over the period 1940 - 2240.

GDP per worker: The list of countries above includes the countries with long enough data for GDP per worker in Heston, Summers and Aten (2002) for the period 1960 -1996. If a country does not have a complete series of GDP per worker for the mentioned period it was deleted from the database. The GDP per worker for the years 1940 to 1960 was constructed as a constant growth rate equal to that in the first 5 years of data, and the convergence to a final steady state was created following the same procedure as for the US. Then I averaged GDP per worker over deciles and made the series of GDP per worker converge to a decile specific steady state following the procedure used for the US data. The data was also smoothed with a Hodrick Prescott filter with parameter equal to 100.

Skill premium: Using the returns from Bils and Klenow (2000) and the duration of primary school used by Caselli and Coleman (2006) I construct the skill premium $\exp((\omega n)_i)$ where ωn is the median by decile of the skill premium and ω represents the coefficients for schooling in the Mincer regressions reported by Bils and Klenow (2000) and n the length of

[24]This is basically the same list of countries used by Caselli and Coleman (2005) with the exception of Germany, Poland and Hungary because of the lack of complete 1960 - 1996 GDP per worker series.

the primary school in years from Caselli and Coleman (2006). An additional complication arises with the comparison between model and data in terms of skill premium across deciles, because we do not have data gathered in the same year across countries, so instead of checking what the model implies for 1990 in terms of skill premium, I take the average by decile of the year in which the observation reported by Bils and Klenow (2000) was made and bring that number from the model for each decile. The result is reported by Figure 6.1. The countries that are in the Bils and Klenow (2000) database and are dropped here are: Germany, Hungary and Poland. These countries were dropped because the GDP per worker series was not long enough (from 1960 to 1996).

Skilled workers: The stocks of skilled workers, defined as "those with more than primary school" are constructed from Barro and Lee (1993), for the year 1990.