Human Capital Composition, Growth and Development in an R&D Endogenous Growth Model*

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Abstract

The effect of human capital composition on growth and development has been somewhat neglected in economic literature. However, evidence has suggested the importance of engineering and technical skills to economic growth and international organizations had suggested their shortage in developed countries. Using a standard increasing variety endogenous growth model, we propose various measures of this composition. We show that human capital composition matters to growth and development, that the decentralized equilibrium leads to less investment in high-techs than the optimum and that the tendency to under-invest in R&D is expanded when human capital composition

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is considered. When compared to data, the model does well in explaining the rate of growth and the level of development (less robustly) as a function of these measures.

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1 Introduction

The effects of general human capital on growth has been widely studied in the economic literature. In Romer (1990), human capital is the key input to the research sector, which generates the new products or ideas that underlie technological progress. This means that countries with a larger stock of human capital tend to grow faster. In multicountry models of technological change the spread of new ideas across countries (or firms or industries) is also important. As Nelson and Phelps (1966) suggested, a larger stock of human capital makes it easier for a country to absorb the new products and ideas that have been discovered elsewhere and the introduction of human capital qualifies the scale-effect of population (Temple and Voth, 1998). Therefore, a follower country with more human capital tends to grow faster than others with less human capital because it catches up more rapidly to the technological leader. When studying a cross-section of countries, Barro (1991) concluded that for a given starting point of *per capita* GDP, a country's subsequent growth rate is positively related to school-enrollment rates, as a proxy of human capital.

Becker, Murphy and Tamura (1990) assume that the rate of return on human capital increases over some range, an effect that could arise because of the spillover benefits from human capital that Lucas (1988) stressed.

Nevertheless, the effects of human capital composition on growth and development is a more recent field in the economic literature. The idea that some types of human capital contribute more to growth than others do is intuitive, mainly if we think about R&D models in the spirit of Romer (1990) or Grossman and Helpman (1991), because there are only certain types of human capital engaged in R&D activities.

The first paper in this class was the one from Murphy, Shleifer and Vishny (1991), which supports the idea that the allocation of talent is important for growth and bases the argument on the choice between being entrepreneur or rent-seeker. They argue that rent-seeking rewards talent more than entrepreneurship. They proxied rent-seeking by the proportion of Law students in colleges and entrepreneurship by the proportion of Engineering students in colleges and show some evidence that the second contribute to growth while the first do not.

With special concern for growth and development (defined as GDP *per capita*), Bertocchi and Spagat (1998) explain the evolution of the ratio between vocational and general education at the secondary level using social stratification and political participation. They show that this ratio is positively correlated with GDP for poor countries and negatively correlated for wealthier countries. Iyigun and Owen (1999) examine the implications for growth and development of the existence of two types of human capital: entrepreneurs and professionals. The first accumulates human capital through work experience and the latter through schooling. The return of entrepreneurship is uncertain. The conclusion is that as technology improves, individuals devote less time to accumulation of human capital through work experience and more time through education, which is also supported by data. Barro (1999) used data on students' scores on comparable international examinations on a growth regression and shows that scores on sciences and mathematics had a positive relationship with economic growth, but scores on the reading test were insignificantly related to growth. Also Crafts (1995), in a well-known survey performing to the British Industrial

Revolution, showed some aspects of the allocation of talent in England in which he shows that Lawyers as a percentage of occupied population have steadily decreased between 1688 and 1871 and the ratios between Engineers and Lawyers and Engineers and Accountants sharply increased between 1841 and 1881. A comparison between the development process of Mexico and USA, in the colonial period, supports the belief that "the British colonies had a better educated population, greater intellectual freedom and social mobility. Education was secular with emphasis on pragmatic skills and yankee ingenuity (...). The 13 British colonies had nine universities in 1776 for 2.5 million people. New Spain, with 5 million, had only two universities in Mexico City and Guadalajara, which concentrated on theology and law." (Maddison, 2001).

A recent range of literature has been considering human capital composition in somewhat different environments. Acemoglu (2001) shows microeconomic evidence on relations between some professions and the stream of wages. As an example, Engineers and computer science jobs explain positively the variations on wages, while Natural Science, Medical and Law occupations (among others) tend to have a negative coefficient from wage regression.

This all seems to suggest that allocation of human capital matters in economic growth.

Until now, no one has addressed the question of allocation of talent in an R&D-model environment.[1] We will base our argument on the role of Human Capital in R&D activities and will account for the relationship between these professionals and growth. In empirical terms we will focus on composition of Human Capital from tertiary education (Colleges and Universities). On the classification of professions, OECD and UNESCO support the belief that

[1]It should be stressed that this kind of model could easily account for technological adoption. It is sufficient to consider a sector for adoption or imitation of technology instead or simultaneously with a sector of creation of new varieties or qualities.

the main labor input on R&D labs are scientists and engineers and its ratio to total human capital is usually used as an R&D indicator for cross-country comparisons.

There is a strong belief that wealthier countries invest more in R&D activities[2] than do poor and middle income countries. However, recent evidence from European Commission (1999) and OECD (2001) showed a relative shortage of engineering and technical skills in the developed countries. In Europe "more than a quarter of the graduates of colleges and universities are from social sciences" (European Commission, 1999). We also address the relationship between a measure of Human Capital composition and the level of development of a country.[3]

In Section 1.1, we carefully define high-tech and low-tech human capital. In Section 2 we present a model that extends Grossman and Helpman (1991) to the inclusion of human capital composition and treat endogenously the choice between different types of human capital. The model also accounts for different allocations of human capital throughout sectors in the economy. First, we describe the supply-side of the labour market equilibrium and derive an equibrium condition for the wage ratio. This is the crucial part of the model. Then, measures of high-tech intensity and the equilibrium relationships between these measures and economic growth and development are obtainned. We compare the decentralized equilibrium with the social planner solution. In Section 3, we present some evidence that supports our model, testing the relationship between measures of high-tech proportion and high-tech stock and economic growth and development.

[2]And then in human capital dedicated to R&D, which are mainly from technical and engineering fields.

[3]Development is measured by GDP *per capita*. This is, of course, a restrictive measure but it is commonly used in the cited literature.

1.1 Defining Human capital composition as high-techs versus low-techs

Generally, High-Tech human capital is defined as the stock of technical and engineering skills in the economy. Thus, High-Tech proportion is the proportion of this stock in total human capital. Low-tech human capital is defined as social and organizational skills. Empirically, due to lack of disaggregated data for total human capital, we use tertiary education data from the UNESCO dataset (see section 3 for details) and we divide high-tech human capital from all the other types (which we define as low-tech).

Definition 1 *Empirically, we define high-tech human capital as the enrollments in "Engineering" and "Mathematics and computer science" fields in the tertiary education level. High-tech proportion is the ratio of high-tech human capital in total enrollment in tertiary education level.*

These data suggests that the allocation of different types of human capital is different across sectors. For instance correlations between the employment share in industry and the proportion of engineering and technical skills are near 40% while correlations between the employment share in services/agriculture and the engineering and technical proportion are near 20% and -30%, respectively. Correlations between the same measure of high-tech proportions and added values shares follow the same tendency. The following table summarizes these results.

Table 1 - Correlations between high-tech proportion and Sectors' shares

	Male Workforce	Female Workforce	Added Values
Agriculture	-29%	-29%	-26%
Industry	40%	41%	26%
Services	20%	14%	9%

Source: Unesco Database and World Development Indicators.

2 The Model

This section describes the model used in the paper which extends Grossman and Helpman (1991, Chapter 3 and Chapter 5.2) to the consideration of two types of human capital.

We assume that the economy is populated with a continuum of agents. Each agent lives for a time interval of finite length T. The age distribution is uniform at every moment, with a density of N/T individuals of every age between 0 and T. At each instant the individuals who die (those who reach age T) are replaced in the population by an equal number of newborns. Therefore, the total population has constant measure N.

At every instant, each agent must allocate his or her time to one of three activities. The individual may choose to take employment as low-tech, to take employment as high-tech or to spend the time accumulating human capital. When one chooses the second option he must spend more time in the educational system and spend more money in training than when he chooses the first. We assume that the time spent in educational programs by high tech workers is fixed, exogenous and equal to S.[4]

Low-tech types work in the homogeneous goods sector (which we call Z) and high-tech types work in the differentiated goods sector (D) and in research labs. This follows the evidence on the allocation of different types of human capital among sectors in the economy (see Table 1). However, the crucial assumption here is that R&D is high-tech intensive.

We also make the assumption that all individuals are alike in their capacity for learning[5].

[4]This quantity of time S may be interpreted as the difference between the time spent at school by high-tech workers and by low-tech workers. For simplicity, we neglect the time someone spends at college when he makes the low-tech choice and we also neglect all inputs other than the time devoted by the individual pupil.

[5]As we will analyze data in a cross section of countries, it is not clear that we should introduce *à priori* differences between agents of different countries.

2.1 Labor market - supply side

In the first stage of the model individuals decide whether to be high-tech or low-tech workers. This is the supply side of the labor market equilibrium. In the second stage, supply of H and L are defined and market-clearing conditions may be written to each of the stocks created in the early stage. With this, we make stocks of high-tech and low-tech human capital endogenous.

We first model the discrete decision of becoming a high-tech worker or a low-tech one. It follows that an individual facing this decision must compare the present value of lifetime earnings as a low-tech worker

$$\int_{t}^{t+T} e^{-\rho(\tau-t)} w_L d\tau = \frac{1}{\rho}(1-e^{-\rho T})w_L \tag{1}$$

with the present value of the income that the individual would obtain by spending the first S years in high-tech educational programs and supporting a private entry cost δ. For simplicity, we assume that this cost decreases gross wage in all periods after the first S, although the cost may be supported only in the S first years. This is an assumption of borrowing for education.[6] The present value of these latter streams equals

$$\int_{t+S}^{t+T} e^{-\rho(\tau-t)} \frac{w_H}{\delta} d\tau = \frac{1}{\rho}(e^{-\rho S}-e^{-\rho T})\frac{w_H}{\delta} \tag{2}$$

Since we have assumed that all individuals are identical in their capacity to acquire different skills, in equilibrium, we must have that the two options offer the same discounted lifetime income. Otherwise, there were be no offer of one type, H or L. To ensure that some agents will choose each vocation, it is sufficient for us to suppose that each type of labor is an essential input into production. With this assumption, individuals must be indifferent in

[6] We can calculate the present value of all costs δ an individual has to bear to become a high-tech professional. We also assume that no credit imperfections are present. This cost δ can be thought as a function of the given number of years S. Here S is given, so we do not consider this effect.

equilibrium between becoming a high-tech worker and becoming a low-tech worker. Using (1) and (2), this equilibrium condition can be expressed as:

$$\omega = \frac{w_H}{w_L} = \frac{(1 - e^{-\rho T})\delta}{(e^{-\rho S} - e^{-\rho T})} \tag{3}$$

Note that in equilibrium the net wage of a high-tech worker $\frac{w_H}{\delta}$ must be equal to or greater than the wage of a low-tech worker w_L in order to ensure that the former workers receive compensation for their additional time spent at university[7]. Under our assumptions about entry costs in high-tech tertiary education $\delta \geq 1$. With $T > S > 0$, these implies that $\omega > 1$. From now on, for simplification reasons, we set $\omega = \delta$ and use only δ.

2.2 Consumption of final goods

Lifetime utility of an individual born at time t is given by

$$U_t = \int_t^{t+T} e^{-\rho(\tau - t)} \log(C(\tau)) d\tau \tag{4}$$

where

$$C = Z^{1-\sigma} D^{\sigma} \tag{5}$$

Here we normalize the price of the consumption bundle, $p_c = 1$. This is a closed economy where aggregated product is equal to aggregated consumption, such that $Y_t = C_t$. From the maximization of utility we obtain the rate of growth of consumption $\frac{\dot{C}}{C} = r - \rho$ where r is the real interest rate

[7] In theory, high-tech workers could perform low-tech tasks. This will only happen if high-tech graduates could not find a high-tech job. If this happens, wages will tend to equalize and, in equilibrium, there would be no investment in high-tech. As high-tech workers are valuable (to produce goods that consumers like), this cannot be a steady-state equilibrium.

and ρ is the discount rate. Good D is an aggregate of differentiated goods à la Chamberlain (1933), such that:

$$D = \left[\int_0^n x_i^\alpha di\right]^{1/\alpha} \tag{6}$$

where α is the perceived differentiation of products.

From the instant maximization of consumption, we obtain the demand for aggregated D and homogeneous good Z in terms of the consumption bundle and their respective prices:

$$D = \frac{\sigma C}{p_D} \tag{7}$$

$$Z = \frac{(1-\sigma)C}{p_Z} \tag{8}$$

Given (6), the demand for each variety of D, x_i is given by:

$$x_i = (\frac{p_x}{p_D})^{-\frac{1}{1-\alpha}} D \tag{9}$$

The demand of each variety depends negatively on the relative price of the good i and positively on the quantity D. The expression $\frac{1}{1-\alpha}$ represents the elasticity of substitution between any pair of goods x_i. The higher the elasticity, the more responsive would be the quantity to the relative price. The lower the elasticity, the higher the markup of the monopolist of each variety because the demand is less responsive to changes in prices.

Some expressions which derive from this setup are necessary to the resolution of the model. We present them here. The aggregate structure of differentiated goods (6) with the symmetric hypothesis turns out to be $D = n^{\frac{1}{\alpha}} x$.[8] Solving this in relation to x and summing up the quantities of all varieties ($X = nx$) we can write

[8] In equilibrium, all the varieties will have the same price.

$$X = n^{-\frac{1-\alpha}{\alpha}} D \tag{10}$$

and using (9), (10) and the definition of X:

$$p_D = \frac{p_x}{n^{\frac{1-\alpha}{\alpha}}} \tag{11}$$

Combining (10) and (11), we can write

$$p_x X = p_D D \tag{12}$$

2.3 Production of final goods

Good Z is produced by a great number of price taker producers, which work with constant-returns-to-scale technology that uses low-tech employees. Each variety of good D is produced by a monopolist who owns the respective patent, who also works with constant-returns-to-scale technology using high-tech workers. This allows the producer to have incentives to pay for research and development. The production functions are:

$$x_i = H_{x_i}/a_{Hx} \tag{13}$$

$$Z = L_Z/a_{LZ} \tag{14}$$

Profit maximization given demands (8) and (9), respectively, wage rates w_L and w_H and factorial intensities a_{LZ} and a_{Hx} imply that:

$$p_x = \frac{1}{\alpha} a_{Hx} w_H \tag{15}$$

$$p_Z = a_{LZ} w_L \tag{16}$$

From (15), $\frac{\dot{w_H}}{w_H} = \frac{\dot{p_x}}{p_x}$ and from (11), $\frac{\dot{p_x}}{p_x} = \frac{1-\alpha}{\alpha}\frac{\dot{n}}{n} + \frac{\dot{p_D}}{p_D}$. Then, by (5), $\frac{\dot{Y}}{Y} = \frac{\dot{C}}{C} = \sigma\frac{\dot{D}}{D}$ and by (7), the following holds:

$$\frac{\dot{D}}{D} = \frac{\dot{C}}{C} - \frac{\dot{p_D}}{p_D} \tag{17}$$

Profits in the differentiated good sector depend on the "number" of varieties that exist in the economy at each moment:

$$\pi_{x_j} = \frac{(1-\alpha)\sigma C}{n} \tag{18}$$

2.4 Labour market - demand side

With our assumptions about factor uses in each sector, factor market clearing requires that:

$$a_{Hg}g + a_{Hx}X = H \tag{19}$$

$$a_{LZ}Z = L \tag{20}$$

where a_{ij} is the quantity of human capital type $i = H, L$ *per unit* of production in each sector $j = g, X, Z$. Multiplying (19) by w_H and (20) by w_L and using (7), (8), (15) and (16), we can re-write equations (19) and (20) as:

$$a_{Hg}w_H g + \alpha\sigma C = w_H H \tag{21}$$

$$(1-\sigma)C = w_L L \tag{22}$$

The description that follows is usual in these type of models.

2.5 Research and development sector

High-tech labor is also used in the R&D sector where new varieties are developed. This of course will imply that only high-tech type workers contribute to growth. This is empirically consistent with Murphy, Sheleifer and Vishny (1991) and with historical evidence presented in Introduction by Maddison (1995) and others. This result will also be addressed in Section 3.1.

The technology for R&D is such that to develop a new good a researcher needs a quantity a_{Hg}/n of high-tech workers. As is standard in the literature, we are assuming a linear technology in R&D and the existence of research spillovers. The cost of developing new goods diminishes with the number of existing goods or with the level of knowledge in the economy. So, the technology for research presents constant returns to scale at any moment, but dynamically increasing returns to scale. This feature for R&D technology permits sustainable growth to occur as the cost of research grows at the same rate as the return from this activity.

A researcher who develops a new good owns the patent for producing that good. Free-entry in the R&D sector implies that the cost of research for a new good must be equal to the expected return of that research. Thus,

$$\begin{cases} v_t = a_{Hg}\frac{w_{H_t}}{n_t},\ for\ \frac{\dot{n}_t}{n_t} > 0 \\ v_t < a_{Hg}\frac{w_{H_t}}{n_t},\ for\ \frac{\dot{n}_t}{n_t} = 0 \end{cases} \tag{23}$$

where v_t is the value of a patent, which is equal to the present value of the profits earned with the production of the good. We consider that the producer never loses the monopoly, thus the value of a patent is given by

$$v_t = \int_t^{\infty} e^{-[R(\tau)-R(t)]}\pi(\tau)d\tau, \text{ where } R(\tau) = \int_0^t r(s)ds \tag{24}$$

The rate of growth of n is the rate of innovation in the economy, which we call g. Each researcher equates his private returns to his costs and does not take into account the consumer surplus which he does not appropriate, nor the loss of profits for the installed producers.

2.6 Decentralized Equilibrium

We first derive the resource constraint and the arbitrage condition in this economy. Then, we achieve a steady-state high-low-tech ratio (H/L) and the growth rate of varieties (g). Finally, we determine the relationship between g and high-tech proportion (h) and between GDP and h.

A resource constraint is obtained summing up (21) and (22):

$$a_{Hg}w_H g + \alpha\sigma C + (1-\sigma)C = w_H H + w_L L \tag{25}$$

By the usual arguments, a non-arbitrage condition equates the sum of the profit rate for the representative producer of a state-of-the-art product with the expected increase in the value of that product to the return of a riskiness loan: $\pi + \dot{v} = rv$. Dividing this expression by v and using the expression for profits (18) we reach

$$\frac{\dot{v}}{v} = r - \frac{(1-\alpha)\sigma C}{nv} \tag{26}$$

To ensure that $\frac{\dot{v}}{v}$ is constant in the steady-state we must have $\frac{\dot{C}}{C} = g + \frac{\dot{v}}{v}$. Then, using (26) and $\frac{\dot{C}}{C} = r - \rho$, we finally get to:

$$\frac{(1-\alpha)\sigma C}{nv} = \rho + g \tag{27}$$

Using free entry condition (23), we obtain:

$$\frac{(1-\alpha)\sigma C}{a_{Hg}w_H} = \rho + g \tag{28}$$

In order to obtain a constant growth rate of the number of varieties (g) in steady-state, it must be true that $\frac{\dot{C}}{C} = \frac{\dot{w_H}}{w_H}$. Using (17) and the expression for $\frac{\dot{w_H}}{w_H}$, it is straightforward to show that $\frac{\dot{Y}}{Y} = \frac{\dot{C}}{C} = \sigma\frac{1-\alpha}{\alpha}\frac{\dot{n}}{n}$. This means that growth rate of GDP *per capita* in the model is proportional to the growth rate of varieties, as is usual in this kind of model.

Proposition 1 *In the decentralized equilibrium steady-state, the economy is defined by a constant high-low-tech human capital ratio, which determines a constant growth rate of varieties, given by:*

$$\frac{h}{1-\delta h} = \frac{\frac{1}{\delta}\frac{\sigma}{1-\sigma} - \frac{\rho a_{Hg}}{P}}{1+\delta\frac{\rho a_{Hg}}{P}} \tag{29}$$

and

$$g = (1-\alpha)h\frac{P}{a_{Hg}} - \alpha\rho = (1-\alpha)\frac{H}{a_{Hg}} - \alpha\rho, \text{ where } P = \delta H + L \tag{30}$$

This means that the high-low-tech and high-tech ratios depend positively on the share of differentiated goods sector (σ) and on R&D sector productivity ($1/a_{Hg}$) and negatively on the wage ratio or in the entry cost ($\omega = \delta$). The growth rate of varieties is standard in this type of model, depending on differentiation (α), preference for the future (ρ) (negatively), productivity of R&D sector ($1/a_{Hg}$) and total labor force (P) - the so-called scale effect (positively). However, now it also depends positively on the high-tech human capital ratio (h).

Proof. In the appendix. ■

The expression for the growth rate of varieties (30) can be re-written using the expression for h in the proof of this proposition as follows:

$$g = (1-\alpha)\sigma\frac{P}{\delta a_{Hg}} - (1-\sigma(1-\alpha))\rho \tag{31}$$

From this expression, we can see that the new exogenous parameter that influence growth is δ. The lower is the entry cost in high-tech schools, the higher is the stock of high-tech human capital in the economy and then the higher is the economic growth rate. This seems to have potentially important policy implications, as this parameter can be controlled by education policy.

The growth rate of the economy would be then:

$$g_Y = \sigma \frac{(1-\alpha)^2}{\alpha} h \frac{P}{a_{Hg}} - \sigma(1-\alpha)\rho \tag{32}$$

or, using (31):

$$g_Y = \frac{(1-\alpha)^2}{\alpha} \sigma^2 \frac{P}{\delta a_{Hg}} - \frac{\sigma(1-\alpha)}{\alpha}(1-\sigma(1-\alpha))\rho \tag{33}$$

Finally, we address the relationship between h and Y. Proposition 2 states the main result.

Proposition 2 *The relationship between high-tech ratio and GDP per capita is given by*

$$Y_t = n_0^{\sigma\frac{1-\alpha}{\alpha}} e^{g\sigma\frac{1-\alpha}{\alpha}t} (\frac{a_{LZ}}{a_{Hx}})^{\sigma} (\alpha h P + a_{Hg}\alpha\rho)^{\sigma} ((1-\delta h)P)^{1-\sigma} \frac{1}{a_{LZ}} \tag{34}$$

and may be decomposed into three parts: the first one, $e^{g\sigma\frac{1-\alpha}{\alpha}t}$*, is the influence of* h *in the past growth rates which influence the actual level of GDP; the second one,* $(\alpha h P + a_{Hg}\alpha\rho)^{\sigma}$ *is the influence of* h *in the actual production of the differentiated goods sector, and the last one,* $((1-\delta h)P)^{1-\sigma}$*, is the influence of* h *in the homogeneous goods sector. The first two effects are positive and the last is negative, reflecting the opportunity cost of investing heavily in* h*. Thus, the total effect of* h *on* Y *depends on the relative strength of these three effects.*

Proof. In the appendix. ■

In section 3 of the paper we will test condition (32) and (34).

2.7 Efficiency

In this section we will describe the social planner solution for this economy. Social planner maximizes the representative agent intertemporal utility. It maximizes $U_t = \int_t^{\infty} e^{-\rho(\tau - t)} \log(C(\tau)) d\tau$ subject to $\frac{\dot{n}}{n} = \frac{H - H_x}{a_{gH}}$, using H and Hx as control variables and $\tilde{n}(= log(n))$ as state variable[9]. In appendix, we present the first order conditions. The computed high-low-tech human capital ratio and the optimal *per capita* GDP growth rate are the following:

$$(h/(1-\delta h))^* = \frac{1}{\delta}\left[\frac{1}{\delta}\frac{1-\alpha}{\alpha}\frac{\sigma}{1-\sigma}\frac{P}{a_{H_g}\rho} - 1\right] \tag{35}$$

and

$$g^* = \frac{P}{\delta a_{Hg}} - \frac{\alpha}{1-\alpha}\frac{1}{\sigma}\rho \tag{36}$$

These expressions can be compared with (29) and (31), respectively.

Theorem 1 *Both the high-low tech human capital ratio and the growth rate of per capita GDP are smaller in the decentralized equilibrium (DE) than in the social planner (SP) solution for all interior solutions of those optimization problems.*

Proof. In the appendix. ■

This is obtained assuming that the private entry cost is equal to the social entry cost. If the private entry cost were higher than the social one, this increases the tendency to have the result in the Theorem. Otherwise, it would decrease the tendency to have higher growth in the social planner solution. For huge differences it could revert the result.

We base our calibration for α and P/a_{Hg} on Caballero and Jaffe (1993) and assumed ρ in a range that is common in the literature (e.g. Caballero

[9]The social planner is concerned with all the individuals present in society.

and Jaffe (1993),Jones (1995) and Funke and Strulik (1995)). We took what we thought to be *reasonable* σ. The parameters α and ρ proved to be the most important ones in these calibration exercises. Table 2 show the benchmark values for calibration exercises in this paper.

Table 2 - Calibration

α	ρ	σ	P/a_{Hg}
0.5	0.02	0.5	0.12

The following Table shows that for our benchmark calibration high to low-tech ratio and varieties growth rate are in fact sub-optimal.

Table 3 - Comparison between the DE and the SP

δ	$(H/L)^*$	H/L	g^*	g
1	5	0.71	0.08	0.015
1.1	4.05	0.63	0.07	0.012
1.5	2	0.4	0.04	0.005
2	1	0.25	0.02	0
2.5	0.56	0.16	0.008	0*

* indicates a corner solution.

Results in the table highlight the fact that the introduction of human capital composition analysis may increase the distortion between growth rates because the levels of high-tech, low-tech and consequently high to low-tech ratio are also distorted. The observed values of H/L (the average value for H/L in the data is 0.17) implies an entry cost of near 2. However, the predicted decentralized growth rate of the economy is far from the observed[10]. Some modifications to the benchmark calibration help to solve this problem. Modifications in the calibration of P/a_{Hg} or the industrial share are shown in appendix (Tables 1.B and 2.B). We continue to face a predicted high value for the entry cost in high-tech human capital.

[10] According to Maddison (1995), *per capita* GDP had increased 1.2% between 1820 and 1992 in the whole world. For a $\sigma = 0.5$ and $\alpha = 0.5$, $g_Y = 0.5 * g$.

3 Some Evidence

In this section we show some empirical results which we compare with the theoretical results. First, we concentrate on the relationship between the measures of composition of human capital and growth (g) and then, on the relationship between the same measures and development (Y). As the benchmark measure of human capital composition we take from the last section the ratio of high-tech human capital to total human capital ($\frac{H}{P}$). There are other possible measures, such as the ratio of high-tech to low-tech human capital ($\frac{H}{L}$) and also the ratio between high-tech human capital and total population, ($\frac{H}{N}$). As a measure of "scale-effects", the model suggests total High-tech human capital.[11] In the text we present results for the first measure and we compare them with the results from other composition and level measures, which we show in appendix.

We define high-tech human capital as the enrollments in engineering, mathematics and computer science fields and low-tech human capital as the enrollment in all other fields of science.[12] So, we will concentrate on the distribution of human capital at the tertiary education level (colleges and universities). According to our model, $h = \frac{H}{P}$ (given P), $\widetilde{h} = \frac{H}{L}$ (given L), $\frac{H}{N}$ (given N) or even total H have a positive relationship with the growth rate of GDP.[13]

[11] Remember that $\frac{h}{1-\delta h} = \frac{H}{L}$. Among the composition variables ($\frac{H}{P}$, $\frac{H}{L}$, $\frac{H}{N}$), the last one has a serious problem of interpretation: as we are measuring high-tech human capital in tertiary education, dividing high-tech human capital in tertiary education by total workforce may under-estimate the actual proportion, as there are, of course, some proportion of non-tertiary human capital that would be classified into high-tech if we had data to do so.

[12] See Definition 1 and data description in appendix. Data were supplied by UNESCO, replying to our request and corresponds to various issues of the Unesco Statistical Yearbook from 1970 to 1997. However, enrollments and graduates by major fields of education could be downloaded from the UNESCO site at http://www.uis.unesco.org/pagesen/DBEnrolTerField.asp.

[13] Note that h and $\frac{h}{1-\delta h}$ are clearly directly related. Although h and H are more directly related to g and Y in the model, $\frac{h}{1-\delta h}$ express better the opportunity cost of investing in H. Although total H do not directly express composition, we will present it as comparison.

We have data for these variables from 1970 until 1997, in a total of 380 observations. In order to decrease the business-cycles and measurement errors effects, we have divided the sample into three decades (1970 to 1979, 1980 to 1989 and 1990 to 1997 - 124, 139 and 117 observations, respectively). From the whole sample, we have excluded the ex-communist Eastern-Europe countries. We believe these countries have had strong institutional interferences in the decentralized choices of becoming high and low-tech and also in economic growth.

Table 4 shows an average of some statistics on these variables across the three decades.

Table 4 - Statistics

	Mean	St-Dev.	Maximum	Minimum	$C(x,\widetilde{h})$	$C(x,h)$	$C(x,\frac{H}{N})$
h	0.14	0.09	0.54	0.002	1	0.99	0.53
$\widetilde{h}$	0.17	0.14	1.16	0.002	0.99	1	0.47
$\frac{H}{N}$	0.003	0.003	0.022	0.000	0.53	0.47	1

3.1 Relationship between *human capital composition ratio* and growth

Our model suggests a new variable that is related to economic growth, which is a measure of composition of human capital, h. In particular we will test the following relationship:

$$g_Y * 100 = C + \beta_1 X \tag{37}$$

where X could be the following possible variables: H/P ($= h$), H/L ($= \widetilde{h}$), H/N and H. This equation is the empirical counterpart of equation (32). For each of these variables, there correspond a constant C and a parameter β_1 in terms of the parameters in the model: $C = -\sigma(1-\alpha)\rho * 100$ and $\beta_1 = \sigma\frac{(1-\alpha)^2}{\alpha}\frac{100*P}{a_{Hg}}$. Using the benchmark values for the parameters defined above, the intercept C should be near -0.5. As it is very difficult to get values for "scale-effects" terms in this expression, as is recognized by Caballero and Jaffe (1993), we assume a value of 0.12 and say that the expected value for β_1 will be near 3[14], according to the same benchmark values defined in the last section ($\alpha = 0.5$, $\rho = 0.02$, $P/a_{Hg} = 0.12$, $\sigma = 0.5$).

We will test these equations econometrically and we expect to find values in this range in order to verify the theory. We will use a system equation approach with three equations, one for each decade, in which we always allow for time specific intercepts[15]. With the two last sub-periods of the sample, we perform IV estimations which account for endogenous problems, as h is given endogenously in the model. We will, preferably, refer to them. For comparison, we also add results which assume that entry cost is equal to 2, as suggested by Table 3. Experimental results that consider entry costs between 2 and 3 introduce little changes in the t-statistics and do not change statistical significance.

Table 5 - Human Capital Composition and Economic Growth

Dependent variable: growth rate of GDP per capita				
	Without Entry Costs		With $\delta = 2$	
Equation 1 (H/P)	SUR	IV	SUR	IV
H/P	5.69***	8.00***	7.18***	10.23***
	(3.35)	(3.04)	(3.16)	(2.96)
R^2	0.01, 0.08 0.03	0.06, 0.06	0.00, 0.07 0.03	0.05, 0.06
Serial Correlation	0.22, 0.15	0.19	0.22, 0.15	0.19
Number Obs.	107, 116 94	102, 88	107, 116 94	102, 88

Notes: t-statistics are presented in parentheses. They are based on white-consistent variance matrix in IV estimation. Constants are omitted in the table.

[14]This (0.12) is the value for δ/β of 0.119 in Caballero and Jaffe (1993). A value of 0.18 will give a $\beta_1 = 4.5$ and a value of 0.07 will give a value of $\beta_1 = 1.75$.

[15]This does not change the significance of the coefficients, but allows for better fit of the models, particularly in instrumental variables estimation. This is a common procedure in the literature (see Barro and Sala-i-Martin (1995), for instance).

Table 5 shows us a direct, significant and positive effect of H/P (h) on the economic growth rate. This does not change much when entry cost in high-tech schools is increased to 2. When compared to other measures (see Table 1.C.), it can be said that the intercepts (which are not shown) vary between -0.6 and 2.13 for the SUR equations and between -1.69 and 0.67 for the IV equations, where the most positive values are obtained in equation 3 and the most negative ones in equation 4. There are three main conclusions: (1) the effect of the four variables are clearly significantly positive; (2) quantitatively, the value of the estimated coefficient is above the calibration values (at least for the composition variables, $H/P, H/L$ and H/N), although for the first two equations the values are in the same range (less than 10) and (3) the intercepts are near the calibrated value -0.5, at least for equations 1 and 2 in the instrumental estimation. Nevertheless, estimators of coefficients of H and $\frac{H}{N}$ are always far from that on calibration. These quantitative departures from the calibration procedure may indicate either a measurement error in the variables[16] or an under-calibration of $1/a_{Hg}$. It may suggest that the productivity of the research sector is much greater than we are supposing in calibration. To reach a value of $\beta_1 = 7$, we would need a value of 0.28 instead of 0.12 for the "scale-effect" term.

3.1.1 A complete specification

As a robustness test, we will introduce some control variables that may be linked with the definitions of the constants ρ and L, P and N[17]. For ρ, we introduce as proxies the saving rate and life expectation. These are natural

[16] Which could be caused only by the way we measure high-tech human capital, because it is the possible proxy, but may differ for the actual stock of high-tech human capital in the economy.

[17] We could not find an appropriate proxy for α. As is well recognized, finding a proxy for elasticities of substitution or markups is very difficult. We kept α as part of the estimation procedure, even for robustness tests. L and P were defined previously.

proxies for the discount rate as the first is linked with the preferences trade-off between present and future consumption and the second goes along with higher health and better work habits and education, as Barro and Sala-i-Martin (1995) recognized, and may also be naturally linked with higher preference for the future, as the expected returns of savings may be higher where life expectancy is high. For N we introduce the log of working-age population, as labor force is known to have more measurement errors[18]. For P, we introduce the sum of L and H, which corresponds to set $\delta = 1$ and $P = H + L$. Results with $\delta = 2$ are presented. Of course we had eliminated variable P in the estimation of the equation with H. Results are shown in Table 6.

Table 6 - Robustness

Dependent variable: growth rate of GDP per capita				
	Without Entry Costs		With $\delta = 2$	
Equation 1 (H/P)	SUR	IV	SUR	IV
H/P	3.44**	4.28*	4.09*	5.07
	(2.14)	(1.73)	(1.91)	(1.54)
Sav./GDP	0.06***	0.05***	0.06***	0.05***
	(4.39)	(3.05)	(4.43)	(3.02)
Life exp.	0.02	0.02	0.02	0.02
	(1.13)	(1.16)	(1.13)	(1.18)
log(P)	0.09	0.09	0.09	0.09
	(1.55)	(1.31)	(1.56)	(1.27)
R^2	0.11, 0.13	0.13, 0.26	0.10, 0.12	0.12, 0.26
	0.29		0.29	
Serial Correlation	0.23, 0.09	0.08	0.23, 0.08	0.08
N	86, 105	97, 87	86, 105	97, 87
	92		92	

Notes: Standard-errors are presented in parentheses. They are based on white-consistent variance matrix in IV estimation. Constants are omitted in the table.

[18]See Barro and Sala-i-Martin (1995).

Now, it is of course more difficult to identify parallels between estimation and calibrations in which (37) is concerned. However, the main result remains unchangeable. High-tech proportion seems to be positively related to economic growth conditional on proxies for the discount rate and total stocks of human capital (at tertiary education level). Here, the consideration of entry costs ($\delta = 2$) decrease the significance of high-tech proportion, making coefficients marginally significant.

Qualitatively, the relationship between H/P, H/L and H (see Tables 6 and 2.C) and economic growth stays significantly positive, despite a full rejection of the relationship between H/N and economic growth. This may occur because this is not a good measure of composition, as we have already explained. Quantitatively, the departures from calibration about β_1 coefficient seem to be smaller.

We also present growth regressions using the benchmark specification in Barro (1991)[19], and including h and $h/(1-h)$ (Table 1.D). Although far from what this model suggests as sources of growth, this is closer to the existing empirical literature and also shows a positive relationship between these variables and economic growth, following and supporting the evidence in Murphy, Shleifer and Visnhy (1991). Results in these regressions are in the spirit of Barro's (1991) results, showing positive and significant effects of human capital (secondary enrolment), physical capital (investment) and a significant convergence effect[20] and a negative effect of bad institutions (Black Market Premium) and Government Spending, and a negative although weakly significant effect of Assassinations[21]. Although not reported

[19]This replicates the Barro (1991) regression, in a system equation applied to the three decades under observation and with the use of Black Market Premium in substitution of PPP deviations of the investment deflator so as to measure market distortions and institutional differences. This is in line with more recent studies.

[20]A USD$1000 increase in GDP *per capita* would lower the economic growth rate by 0.1 to 0.2% per year.

[21]In the IV specification we have eliminated Assassinations because the lagged value is a bad instrument, as is shown in the variables description. Note that, contrary to the

in Table 1.D, our data can also show a positive and significant relationship between the log of total high-tech human capital either in SUR or IV estimations in this Barro-regression type.

Here we can see that the positive effects of the high-tech and the high-low-tech ratios are consistent with the usual conditional convergence and with the positive effect of human and physical capital. The introduction of this variable does weaken the relationship between economic growth and general human capital and the negative relationship between growth and government spending, but strengthens the relationship between bad institutions or market distortions (measured by Black Market Premium) and growth. These results seems to indicate that a 1% increase in growth rate of GDP *per capita* could occur either by a 0.35 increase in h (with a coefficient of near 3) or by a 35% increase in the secondary school enrollment (with a coefficient of 0.03)[22], *ceteris paribus.*

3.2 Relationship between *human capital composition* and development

Proof 2 and condition (34) imply that there is a non-linear relationship between Y and h. Recurring to calibration we try to determine what we should see in data. We now obtain conditions to define the sign of the total effect. We write (34) in logs and derive the expression in reference to h. This gives us the sufficient condition for a positive effect of h on GDP *per capita*:

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author, we have always used GDP and enrolments in the first year of the period. All the remaining differences may arise due to different periods and consequently possible different samples.

[22]Further research about the relationship of this measure of human capital composition and all the growing examples of possible proxies for human capital (see Barro and Lee (1993) and Barro and Sala-i-Martin (1995)) would be interesting, but is beyond the scope of this paper.

$$\frac{\partial \log(Y_t)}{\partial h} = \sigma \frac{(1-\alpha)^2}{\alpha} \frac{P}{a_{Hg}} t + \frac{\alpha P(\sigma - \delta h) - (1-\sigma) a_{Hg} \alpha \rho}{(\alpha h P + a_{Hg} \alpha \rho)(1 - \delta h)}. \quad (38)$$

The Y_t that maximizes the log of (34) divides a region of total positive effects of h on GDP from a region of total negative effects of h. Intuitively, it is possible that after some value of h, the opportunity cost of dedicating resources to produce good X or to R&D becomes so strong that the product decreases. The value of h that maximizes Y_t increases with the differentiation of industrial products ($1/\alpha$), with the share of the industrial sector (σ) and decreases with the inverse of productivity in R&D activities (a_{Hg}), but essentially increases as time (t) passes and previous economic growth becomes more and more relevant.

Next corollary argues that we should expect an almost positive relationship between both variables, but a small opportunity cost of high investments in high-tech could arise.

Corollary 1 *We reach values for high-tech human capital ratio which maximize GDP per capita that suggest a positive relationship between the high-low-tech ratio and GDP per capita. The following table shows departures from the benchmark parameters in Table 2. In fact, for the more developed countries (in which, past growth rates represent much of the level of GDP per capita), countries with higher h must have higher GDP per capita.*

Table 7 - Maximum GDP		
	t=1	*t=50*
Changes in Parameters	h^*	h^*
Benchmark values	*0.43*	*0.76*
$\alpha = 0.6$	*0.41*	*0.63*
$\rho = 0.05$	*0.31*	*0.74*
$P/a_{Hg} = 0.7$	*0.36*	*0.81*
$P/a_{Hg} = 1.8$	*0.46*	*0.89*
$\sigma = 0.4$	*0.31*	*0.64*
$\sigma = 0.6$	*0.53*	*0.83*

We argue that values in Table 7 are hardly achieved in data (see Table 4), and so we may have an almost positive relationship between high-tech ratio and GDP *per capita*. There are 42 observations above $h = 0.31$ (the minimum value in Table 7) in data in a total of 380 (11.0%).

In conclusion, beginning with a small GDP, h increases with GDP until quite a high value of h (which increases with development) and then decreases. It can also be said that very rich countries should always have a higher h than very poor countries and almost always higher than middle-income ones.

We will test econometrically equation (34), which we can re-state as:

$$\log(Y) = C + \beta_1 h + \beta_2 \log(h + 0.1) + \beta_3 \log(1 - h). \tag{39}$$

This equation is more difficult to test than the previous one. We have decided to proxy (34) by (39), where 0.1 accounts for the term $a_{Hg}\alpha\rho$ in (34). We have also tested (39) without this term and conclude that the results change very little. According to corollary one we would expect two clear positive effects (β_1, $\beta_2 > 0$) and the third effect close to zero, as we would expect the above-mentioned opportunity cost to be quite small ($\beta_3 \approx 0$). To avoid the expected multicollinearity problems (as these three regressors are closely related), we will only be concerned with the total positive and negative effects of h in $log(Y_t)$. First we will test the equation without the β_2 term and then without the β_1 term. We cannot provide IV estimations, as serial-correlations between equations are high.

Table 8 - Human Capital Composition
and Economic Development

Dependent variable: Log of GDP per capita			
	SUR	SUR	SUR
	(1)	(2)	(3)
h	2.00**	18.00**	-
	(2.75)	(2.17)	-
log(1-h)	-	12.98*	2.32
	-	(1.93)	(1.23)
log(h+0.1)	-	-	1.20**
	-	-	(2.14)
R2	0.04, 0.06	0.06, 0.08	0.06, 0.08
	0.05	0.08	0.08
Serial Correl	0.73, 0.65	0.73, 0.64	0.73, 0.64
N	105, 116	105, 116	105, 116
	100	100	100

Notes: Standard-errors are presented in parentheses. They are based on white-consistent variance matrix in IV estimation. Constants are omitted in the table.

Results in Table 8 show that there is an overall positive relationship between GDP *per capita* and the high-tech ratio, and that the opportunity cost also occurs with lower statistical significance, as predicted (β_1, $\beta_2 > 0$ although $\beta_3 > 0$ also). With $\delta = 2$ (results are not shown), the relationship in column (1) becomes stronger but the significance of coefficients on equations in columns (2) and (3) becomes weaker. However, the positive effect continue to be statistically significant in all the specifications.

Table 9 - Robustness

Dependent variable: Log of GDP per capita	
	SUR
	(1)
h	3.76
	(0.66)
log(1-h)	3.38
	(0.72)
Sav./GDP	0.02***
	(5.53)
Life exp.	0.06***
	(15.13)
Log(P)	0.03*
	(1.67)
R2	0.80, 0.75
	0.63
Serial Corr	0.49, 0.44
N	85, 105
	97

Notes: Standard-errors are presented in parentheses. They are based on white-consistent variance matrix in IV estimation. Constants are omitted in the table.

Table 9 shows that all the expected results statistically fail at the usual levels under a more complete specification, although keeping the positive sign. We present only one specification (which corresponds to column (2) in Table 8), but other specifications, namely linked with that in column (3) of Table 8, would not change the results at all. We have also tested linear relationships between development and h with and without controls and polynomial relationships between GDP *per capita* and h. If the simple linear relationships seem to be significantly positive, the multiple regression with controls shows coefficients of h statistically not different from zero, as is the case in Table 9.

4 Conclusion

The effect of human capital composition had not been considered yet in R&D endogenous growth models. However, both historical and econometric evidence has shown some positive relationship between some types of human capital and economic growth. Furthermore, we have pointed out that the allocation of human capital (from tertiary education) differ across sectors in the economy.

We introduced these features in a simple and standard increasing-variety R&D model of endogenous growth. Thus the model accounts for human capital composition, in the sense that only high-tech human capital participate in R&D activities and predicts a positive relationship between growth and different possible measures of human capital composition (high-tech human capital ratio, for instance). It also predicts an almost always positive relationship between the ratio and the level of GDP. Moreover, it introduces an endogenous choice between different types of human capital. A crucial variable is the entry cost in high-tech schools. When this cost increases it lowers the stock of the human capital employed in R&D labs and then decreases economic growth. These highlights potentially interesting policy implications of this entry cost, as it has direct influence on human capital composition and indirect influence on economic growth. This variable may be influenced through education policy.

This model also shows that the social planner GDP growth rate is above that of decentralized equilibrium, and that spillovers and monopolies also introduce a distortion in the optimal decision of investing in high-tech and low-tech human capital. Specifically, our model suggests that there is a lower high to low-tech human capital ratio in the decentralized equilibrium than in the social planner solution. Additionally, this consideration of human capital composition also quantitatively increases the traditional distortion in the growth rate of GDP *per capita*.

The use of an ideas-based growth model (Grossman and Helpman (1991) type) with constant returns to scale in the production of ideas deserves some discussion, as this is a crucial assumption to have a theoretical relationship between growth rates and the level and the proportion of high-techs, which is indeed verified in data. This kind of model implies the so-called "scale-effect", which supports that: (1) the economy growth rate is directly related with its dimension and (2) as a consequence, the growth rate of the economy becomes explosive when its dimension (e.g. population) increases. The data evidence of increasing population with no explosive economic growth is the most striking evidence for rejection of these models, although cross-section studies do not show clear evidence of rejection of a positive relationship between growth rates and population (see Barro and Sala-i-Martin (1995) and our own results). The existence of the scale-effect has been rejected with time-series tests, however (Jones (1995b)). This has led Jones (1995a) to propose a new model where the economy's growth rate is directly related with population growth. However, as the author recognizes, "the model still contains a very strong prediction for scale effects" (Jones, 1995a), as an economy with more researchers will grow faster in the transition to the steady-state, which goes along with the evidence of Kremer (1993) on a cross-sectional or long-run "scale-effect".

We believe this is a plausible model to explain the evidence on human capital composition because it predicts a steady-state ratio of high to low tech human capital (which in a model like that of Jones (1995a) would not be possible) which enables a clearer perception of the determinants of the composition of human capital (high and low-tech) and its influence on growth and development, which are the main objectives of this research.

Finally, we test the theoretical implications of the model using data from human capital composition in tertiary education level, as data on entry-costs are unavailable. We also deal with possible endogeneity of human capital composition variables, as suggested by the model. Proposed measures of human capital composition are positively related to growth and, less robustly, to the level of development, measured as GDP *per capita*. In fact, estimations also show a small direct opportunity cost of investing in high-tech human capital.

Some motivation to future research is linked with the exploration of the relationship of human capital composition variables with other traditional variables of human capital and with the explanation of different levels of the proposed measures of human capital composition across countries. Without a clear positive relationship between high-tech proportion and GDP *per capita* (as Jones (1995b) predicted for human capital employed in R&D[23]), exploring the data relationship between these variables and the level of development becomes an interesting path to follow. It could also be interesting to extend this model to a setting of increasing quality, as this setup allows for over-investment in R&D where our model increases the tendency to under-invest in R&D.

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A Proofs of Propositions

Proof. (PROPOSITION 1) Part (1). Solving simultaneously (25) and (28) gives us the varieties growth rate, which is given in function of the stocks of high-tech and low-tech workers:

$$g = (1-\beta)\frac{H + \frac{1}{\omega}L}{a_{Hg}} - \beta\rho, \text{ where } \beta = (1 - \sigma(1-\alpha)) \tag{40}$$

Dividing (21) by (22), we reach a steady-state H/L ratio, which depends on the relative wage.

$$\frac{H}{L} = \frac{1}{\omega}\frac{\frac{g}{\rho+g}(1-\alpha)\sigma + \sigma\alpha}{1-\sigma} \tag{41}$$

Solving (40) and (41) simultaneously gives us the steady-state high-tech to low-tech human capital ratio. First we have constructed the term $\frac{g}{\rho+g}(1-\alpha)\sigma$ beginning with (40). Then we solved a quadratic equation on $\frac{H}{L}$ and eliminated the negative root[24]. The positive root of the equation is then:

$$\frac{H}{L} = \frac{1}{\omega}\frac{\sigma}{1-\sigma} - \frac{\rho a_{Hg}}{L} \tag{42}$$

In order to get a $\frac{H}{L}$ ratio independent of L, we set $\omega = \delta$ to get an entry cost of high-tech which is not time-dependent and re-defined the variables, setting $L + \delta H = P$ so as to have $h = \frac{H}{P}$ and $1 - \delta h = \frac{L}{P}$, where P is the total labor force in the model (the sum of high-tech and low-tech human capital). Making the necessary substitutions, we get our result of high-low tech ratio in (29).

Part (2). Using the re-definition of variables made in part (1) and (29), we can simplify the growth rate of varieties (40) to:

[24]The quadratic equation was $\omega\frac{L}{a}(\frac{H}{L})^2 + (\frac{1-2\sigma}{1-\sigma}\frac{L}{a} + \rho\omega)\frac{H}{L} + (\rho - \frac{\sigma}{\omega(1-\sigma)}\frac{L}{a}) = 0$.

$$g = (1-\beta)(\frac{h}{1-\delta h} + \frac{1}{\delta})\frac{P}{a_{Hg}}(1-\delta h) - \beta\rho \text{ where } \beta = 1-(1-\alpha)\sigma \quad (43)$$

Using $\frac{1}{\delta}$ given by (29) we get to our second result (30). Also with h that is given by $h = \frac{1}{\delta}\left[\sigma - \delta(1-\sigma)\frac{\rho a_{Hg}}{P}\right]$, which is directly calculated from (29), we easily reach equation (31). ■

Proof. (PROPOSITION 2) First we use (10) to substitute D for X in GDP function (5). Then we replace X and Z from (19) and (20), respectively, in (5). We obtain:

$$Y_t = n^{\sigma\frac{1-\alpha}{\alpha}}(\frac{a_{LZ}}{a_{Hx}})^{\sigma}(\frac{h}{1-\delta h} - \frac{a_{Hg}g}{1-\delta h}\frac{1}{P})^{\sigma}(1-\delta h)\frac{P}{a_{LZ}} \quad (44)$$

Next we set $n_t = n_0 e^{gt}$, where n_0 is an initial value of the number of varieties, and finally we substitute (30) in (44) to get the expression in the proposition. ■

Proof. (THEOREM 1) The current value Hamiltonian is the following:

$$£ = \log\left(n^{\sigma\frac{1-\alpha}{\alpha}}\left(\frac{H_x}{a_{Hx}}\right)^{\sigma}\left(\frac{P-\delta H}{a_{Lz}}\right)^{1-\sigma}\right) + \lambda(\frac{H-H_x}{a_{gH}}) \quad (45)$$

From this we get the first order conditions:

$$(H)\ -\frac{(1-\sigma)\delta}{P-\delta H} + \frac{\lambda}{a} = 0 \quad (46)$$

$$(H_x)\ \frac{\sigma}{H_x} - \frac{\lambda}{a} = 0 \quad (47)$$

$$(N)\ \sigma\frac{1-\alpha}{\alpha} = \rho\lambda - \dot{\lambda} \quad (48)$$

Dividing the first FOC by the second and using $P - \delta H = L$, we get $\frac{L}{H_x} = \frac{\delta\sigma}{1-\sigma}$. In addition, from the third FOC, we achieve the following growth rate for the multiplier: $\frac{\dot{\lambda}}{\lambda} = \rho\text{-}\sigma\frac{1-\alpha}{\alpha}\frac{1}{\lambda}$. In steady-state $\frac{\dot{\lambda}}{\lambda} = 0$, because human capital and population are constant in the model:

$$\lambda = \sigma \frac{1-\alpha}{\alpha} \frac{1}{\rho} \Rightarrow \ \frac{H_x}{a} = \rho \frac{\alpha}{1-\alpha} \tag{49}$$

Using $\frac{L}{H_x} = \frac{\delta\sigma}{1-\sigma}$ and this last result, we get:

$$L = \rho \frac{\alpha}{1-\alpha} \frac{1-\sigma}{\sigma} a \tag{50}$$

As $H{=}\frac{P-L}{\delta}$, H can be written as:

$$H = \frac{P - \frac{1}{\delta}\frac{\alpha}{1-\alpha}\frac{1-\sigma}{\sigma}\rho a}{\delta} \tag{51}$$

Dividing H by L we get:

$$\begin{aligned} \left(\frac{H}{L}\right)^* &= \frac{P - \rho\frac{\alpha}{1-\alpha}\frac{1-\sigma}{\sigma}a}{\delta\left(\rho\frac{\alpha}{1-\alpha}\frac{1-\sigma}{\sigma}a\right)} = \frac{1}{\delta}\left[\frac{P}{\rho a}\frac{\sigma}{1-\sigma}\frac{1-\alpha}{\alpha}\frac{1}{\delta} - 1\right] = \\ &= \frac{\frac{\sigma}{1-\sigma}\frac{1-\alpha}{\alpha}\frac{1}{\delta} - \frac{\rho a}{P}}{\delta\frac{\rho a}{P}} \end{aligned} \tag{52}$$

Then we reach (35) in the theorem. The condition under which $(H/L)^*$ in (35) is higher than (H/L) in (29) is the following:

$$\frac{P}{\delta\rho a_{Hg}} > \frac{\alpha}{1-\alpha}\frac{1}{\sigma} - 1. \tag{53}$$

This condition is verified for all interior solutions of the decentralized equilibrium and the social planner solution. To see this, we must note that, to have a positive growth rate of GDP per capita in the decentralized solution, for instance, we must verify a condition which implies an higher $\frac{P}{\delta\rho a_{Hg}}$ than that required by the latter one:

$$\frac{P}{\delta\rho a_{Hg}} > \frac{\alpha}{1-\alpha}\frac{1}{\sigma} + \frac{\sigma}{1-\sigma}\frac{1}{\rho}. \tag{54}$$

The same applies to a positive growth rate of the optimal solution: $\frac{P}{\delta \rho a_{Hg}} > \frac{\alpha}{1-\alpha}\frac{1}{\sigma}$. ■

B Comparing DE and SP

Table 1.B - DE and SP with $P/a_{Hg} = 1.8$

δ	$(H/L)^*$	H/L	g^*	g
1	8	0.80	0.14	0.03
1.1	6.53	0.71	0.12	0.026
1.5	3.33	0.47	0.08	0.015
2	1.75	0.32	0.05	0.008
2.5	1.04	0.22	0.03	0.003

Table 2.B - DE and SP with $\sigma = 0.6$

δ	$(H/L)^*$	H/L	g^*	g
1	8	1.14	0.09	0.02
1.1	6.53	1.01	0.08	0.018
1.5	3.33	0.67	0.05	0.01
2	1.75	0.44	0.03	0.004
2.5	1.04	0.31	0.001	0.0004

C Alternative Measures (High-Low tech ratio, High-tech total workforce ratio and high-tech stock)

Table 1.C - Human Capital Composition
and Economic Growth

Dependent variable: growth rate of GDP per capita		
Equation 2 (H/L)	SUR	IV
H/L	4.17***	5.56***
	(3.66)	(3.21)
R^2	0.01, 0.09	0.07, 0.06
	0.03	
Serial Correlation	0.21, 0.15	0.19
Number Obs.	107, 116	102, 88
	94	
Equation 3 (H/N)	SUR	IV
H/N	94.94**	115.86**
	(2.13)	(2.21)
R^2	0.02, 0.01	0.01, 0.04
	0.03	
Serial Correlation	0.22, 0.16	0.18
Number Obs.	106, 112	102, 87
	94	
Equation 4 (H)	SUR	IV
log(H)	0.11**	0.22***
	(2.08)	(3.37)
R^2	0.01, 0.02	0.05, 0.12
	0.03	
Serial Correlation	0.22, 0.14	0.17
Number Obs.	107, 116	102, 88
	94	

Table 2.C - Robustness

Dependent variable: growth rate of GDP per capita		
Equation 2 (H/L)	SUR	IV
H/L	2.68**	3.95**
	(2.50)	(2.51)
Sav./GDP	0.05***	0.06***
	(4.30)	(3.48)
Life exp.	0.02	0.01
	(1.17)	(0.97)
log(L)	0.09	0.11
	(1.55)	(1.59)
R^2	0.12, 0.13	0.15, 0.27
	0.29	
Serial Correlation	0.22, 0.08	0.09
N	87, 105	98, 88
	92	

Table 2.C - Robustness (continued)

Equation 3 (H/N)	SUR	IV
H/N	-12.11	-88.52
	(-0.27)	(-1.21)
Sav./GDP	0.05***	0.05***
	(4.28)	(2.70)
Life exp.	0.04**	0.06***
	(2.43)	(3.16)
log(N)	0.18**	0.25***
	(2.63)	(2.91)
R^2	0.08, 0.15	0.18, 0.26
	0.26	
Serial Correlation	0.22, 0.07	0.09
N	86, 105	97, 86
	92	

Equation 4 (H)	SUR	IV
log(H)	0.11**	0.13*
	(1.98)	(1.77)
Sav./GDP	0.06***	0.05***
	(4.38)	(2.92)
Life exp.	0.02	0.02
	(1.46)	(1.29)
R^2	0.08, 0.12	0.12, 0.25
	0.28	
Serial Correlation	0.23, 0.08	0.08
N	86, 105	97, 87
	92	

Notes: Standard-errors are presented in parentheses. They are based on white-consistent variance matrix in IV estimation. Constants are omitted in the table.

D Barro Regressions

Table 1.D. - Robustness in a Barro Growth Regression

Dependent variable: growth rate of GDP per capita						
	SUR	SUR	SUR	IV	IV	IV
	(1)	(2)	(3)	(4)	(5)	(6)
GDP	-0.0001**	-0.0001*	-0.0001*	-0.0002***	-0.0001***	-0.0001***
	(-2.48)	(-1.87)	(-1.90)	(-3.32)	(-2.28)	(-3.23)
Prim. Enrolment	-0.0124	-0.0126*	-0.0122*	-0.0094	-0.0161**	-0.0163**
	(-1.50)	(-1.98)	(-1.97)	(-1.25)	(-2.13)	(-2.19)
Sec. Enrolment	0.0188**	0.0135*	0.0136*	0.0330***	0.0259**	0.0259**
	(2.42)	(1.76)	(1.76)	(3.30)	(2.28)	(2.31)
Revolutions	-0.0076	0.0536	0.0407	0.4597	0.8228	0.8007
	(-0.02)	(0.15)	(0.11)	(0.68)	(1.21)	(1.17)
Assassinations	-2.0694**	-1.4861	-1.4825	–	–	–
	(-2.15)	(-1.06)	(-1.06)	–	–	–
$G_Cons.$	-0.0427***	-0.0357***	-0.0354***	-0.0454***	-0.0360**	-0.0355**
	(-3.33)	(-2.82)	(-2.80)	(-2.65)	(-2.10)	(-2.08)
Inv/GDP	0.1027***	0.1046***	0.1053***	0.0805***	0.0827***	0.0830***
	(5.85)	(6.02)	(6.06)	(2.85)	(3.45)	(3.44)
log(1+BMP)	-3.1287***	-3.4901***	-3.5004***	-3.2757***	-5.1016***	-5.1065***
	(-3.67)	(-4.17)	(-4.17)	(-2.01)	(-3.28)	(-3.26)
h/(1-h)	-	3.6898**	-	-	2.7289*	-
	-	(2.29)	-	-	(1.64)	-
h	-	-	3.6638**	-	-	3.5323
	-	-	(2.19)	-	-	(1.45)
R2	0.22, 0.38	0.21, 0.38	0.21, 0.38	0.38, 0.17	0.40, 0.17	0.40, 0.14
	0.25	0.25	0.25			
Serial Correlation	0.05, 0.11	0.02, 0.08	0.02, 0.09	0.17	0.15	0.15
N	75, 86	74, 85	74, 85	80, 84	74, 72	74, 72
	94	83	83			

Notes: Standard-errors are presented in parentheses. They are based on white-consistent variance matrix in IV estimation. Constants are omitted in the table.

E Country List (in Table 5)

Countries in Table 5

1970-79	1980-89	1990-97
Algeria	Algeria	Algeria
Angola	Angola	Angola
Argentina	Argentina	Argentina
Australia	Australia	Australia
Austria	Austria	Austria
Bangladesh	Bahrain	Bahrain
Belgium	Bangladesh	Belgium
Benin	Barbados	Benin
Bermuda	Belgium	Bolivia
Bolivia	Benin	Botswana
Botswana	Bhutan	Brazil
Brazil	Bolivia	Burkina Faso
Burkina Faso	Botswana	Burundi
Burundi	Brazil	Cameroon
Cameroon	Burkina Faso	Canada
Canada	Burundi	Central African Republic
Central African Republic	Cameroon	Chad
Chad	Canada	Chile
Chile	Central African Republic	China
China	Chile	Colombia
Colombia	China	Congo, Rep.
drc	Colombia	Costa Rica
Congo	Democratic Rep. of the Congo	Cote d'Ivoire
Costa Rica	Congo	Denmark
Cyprus	Costa Rica	Dominica
Denmark	Ivory Coast	Dominican Republic
Dominican Republic	Cyprus	Ecuador
Ecuador	Denmark	Egypt, Arab Rep.
Egypt	Dominican Republic	El Salvador
El Salvador	Ecuador	Equatorial Guinea
Ethiopia	Egypt	Ethiopia
Finland	El Salvador	Finland
France	Ethiopia	France
Gabon	Fiji	Ghana
Ghana	Finland	Greece
Greece	France	Guinea
Guinea	Gabon	Honduras
	Ghana	Hong Kong, China

Countries in Table 5 (cont.)

1970-79	1980-89	1990-97
Guyana	Greece	Iceland
Haiti	Grenada	India
Honduras	Guinea	Indonesia
China, Hong Kong SAR	Guyana	Ireland
Iceland	Haiti	Israel
Indonesia	Honduras	Italy
Iran, Islamic Republic of	China, Hong Kong SAR	Jamaica
Iraq	Iceland	Japan
Ireland	India	Jordan
Israel	Indonesia	Kenya
Italy	Iran, Islamic Republic of	Korea, Rep.
Jamaica	Ireland	Lesotho
Japan	Israel	Madagascar
Jordan	Italy	Malawi
Kenya	Jamaica	Malaysia
Korea, Republic of	Japan	Malta
Kuwait	Jordan	Mauritania
Lesotho	Kenya	Mauritius
Liberia		Mexico
Luxembourg	Kuwait	Mongolia
Madagascar	Lesotho	Morocco
Malawi	Luxembourg	Mozambique
Malaysia	Madagascar	Nepal
Mali	Malawi	Netherlands
Malta	Malaysia	Nicaragua
Mauritius	Mali	Nigeria
Mexico	Malta	Norway
Morocco	mauritania	Pakistan
Mozambique	Mauritius	Panama
Myanmar	Mexico	Papua New Guinea
Nepal	Morocco	Paraguay
Netherlands	Mozambique	Peru
New Zealand	Nepal	Philippines
Nicaragua	Netherlands	Portugal
Niger	New Zealand	Saudi Arabia
Nigeria	Nicaragua	Senegal
Norway	Niger	South Africa
Pakistan	Nigeria	Spain
Panama	Norway	Sri Lanka

Countries in Table 5 (cont.)

1970-79	1980-89	1980-89 (cont.)	1990-97
Papua New Guinea	Pakistan	Turkey	St. Kitts and Nevis
Paraguay	Panama	Uganda	Swaziland
Peru	Papua New Guinea	United Arab Emirates	Sweden
Philippines	Paraguay	United Kingdom	Switzerland
Portugal	Peru	Uruguay	Syrian Arab Republic
Rwanda	Philippines	Venezuela	Tanzania
Saudi Arabia	Portugal	Yemen, Rep.	Thailand
Senegal	Qatar	Zambia	Togo
Sierra Leone	Rwanda	Zimbabwe	Trinidad and Tobago
Singapore	Samoa		Tunisia
Somalia	Saudi Arabia		Turkey
Spain	Senegal		Uganda
Sri Lanka	Sierra Leone		United Arab Emirates
Sudan	Singapore		United Kingdom
Swaziland	Somalia		United States
Sweden	Spain		Uruguay
Switzerland	Sri Lanka		Zimbabwe
Syrian Arab Republic	St. Kitts and Nevis		
United Republic of Tanzania	St. Lucia		
Thailand	St. Vincent and the Grenadines		
Togo	Sudan		
Trinidad and Tobago	Suriname		
Tunisia	Swaziland		
Turkey	Sweden		
Uganda	Switzerland		
United Kingdom	Syrian Arab Republic		
United States	United Republic of Tanzania		
Uruguay	Thailand		
Venezuela	Togo		
Yemen, Rep.	Trinidad and Tobago		
Zambia	Tunisia		

F Data Description

Variable	Date	Instrument	C(V,I)
Dependent variable: growth rate of GDP per capita in 3 decades (1970-97) or GDP per capita (an average across each period).			
h, h/(1-h), H/N, H	an average of the period.	each lagged in the previous decade	0.83, 0.83
Life expectancy	in the first year in the period.	predetermined	–
Log(N)	an average of the period.	predetermined	–
Sav./GDP	an average of the period.	predetermined	–
GDP	in the first year in the period.	GDP five years before	0.99, 0.99
Primary Enrolment	in the first year in the period.	predetermined	–
Sec. Enrolment	in the first year in the period.	predetermined	–
$G_{C}ons.$	an average of the period.	Consumption Sp. Lagged the previous five-year period	0.95, 0.99
Investment/GDP	an average of the period.	Inv/GDP Lagged the previous five-year period	0.81, 0.65
log(1+BMP)	an average of the period.	log(1+BMP) Lagged the previous five-year period	0.59, 0.61
Revolutions	an average of the period.	Revolution lagged the previous five-year period	0.61, 0.65
Assassinations	an average of the period.	Assassinations lagged the previous five-year period	0.59, 0.27

Variable	Definition	Source
H	Enrolment in Engireering+Mathematics +Computer Science in tertiary education	UNESCO database.
L	Enrolment in all other fields in tertiary education.	UNESCO database.
elife	Life Expectancy at birth.	World Development Indicators.
Log(P)	Log(H+L)	UNESCO database.
Sav./GDP	Total Savings/GDP.	World Development Indicators.
GDP	real GDP per capita, international prices.	PWT 5.6, citted in World Development Network Database, World Bank.
Prim	Enrolment in Primary education: percentage of students in . primary school in the population with primary-school age.	World Development Indicators Finance, citted in World Development Network Database, World Bank.
Sec	Enrolment in Secondary education.	World Development Indicators Finance, citted in World Development Network Database, World Bank.
$G_{C}ons.$	Ratio of the government consumption to GDP less ratio of the spending on defence to GDP less ratio of the spending on education to GDP.	Penn World Tables 6.0 + Government Finantial Statistics, citted in World Development Network Database, World Bank.
Inv/GDP	Gross Domestic Investment/GDP	World Development Indicators Finance, citted in World Development Network Database, World Bank.
log(1+BMP)	log(1+black market premium)	Levine and Renelt , World's Currency Yearbook; Wood (1985) and World Development Indicators citted in World Development Network Database, World Bank.
Revolutions	Number of revolutions and coups per year	Arthur S. Banks, citted in world development network database, World Bank.
Assassinations	Number of Assassinations per million population per year	Arthur S. Banks, citted in World Development Network Database, World Bank.
Log(N)	Working-age population (population with an age between 15 and 64 years old).	World Development Indicators.