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Human capital accumulation, long-run GDP growth and technological frontier

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Accumulation du capital humain, croissance du PIB à long terme et frontière technologique [1]

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Résumé : Alors que la formation initiale est au cœur des modèles de croissance, l'influence de l'accumulation du capital humain sur la croissance à long terme fait moins l'objet de travaux. Notre première étape a été de surmonter l'"énigme du capital humain" par l'introduction de la frontière technologique telle que définie par Vandenbusshe, Aghion et Meghir (2006). L'"énigme du capital humain" signifie que le niveau de capital humain a un effet positif significatif sur la croissance dans les pays où le niveau d'éducation est faible et un effet négatif significatif dans les pays où le niveau d'éducation est élevé. Nous avons spécifié une équation de croissance à long terme agrégée en tenant compte des limites des différentes approches mais sans rejeter l'apport des théories endogènes. En combinant la distance à la frontière technologique et le modèle de régression transnational, notre coefficient sur le niveau et le taux d'accumulation du capital humain est positif, et significatif au niveau de 1 et 10 pour cent pour les prédicteurs du capital humain seuls, et l'interaction entre le taux d'accumulation du capital humain et la distance à la frontière technologique est également significative au niveau de 5 pour cent. La distance à la frontière technologique affecte donc significativement la relation entre l'accumulation de capital humain et la croissance économique, tandis que les différences technologiques entre les pays ne modifient pas la relation entre le niveau initial du stock de capital humain et la croissance économique. De plus, les effets de l'accumulation de capital humain sur la croissance économique ont tendance à augmenter avec les avancées technologiques des pays.

D'après nos résultats économétriques, l'"énigme du capital humain" est donc partiellement résolue en prenant en compte les différences entre les pays en matière d'avancées technologiques, et leur interaction avec les indicateurs de capital humain. Pour traiter l'endogénéité de la variable capital humain, nous nous tournons vers un modèle d'équations simultanées (MES) où l'accumulation de capital humain est également causée par la croissance économique, et où l'accumulation de capital physique peut être endogène. Malgré un ensemble de données moins complet (moins de pays), le niveau et l'accumulation du capital humain ont un effet positif et significatif sur la croissance à long terme du PIB par habitant. Ces premiers résultats étaient nécessaires avant d'étudier la relation entre le capital humain et le développement économique à un niveau plus granulaire et pourraient aider à ne pas sous-estimer l'effet d'entraînement de l'investissement dans l'accumulation du capital humain sur la croissance du PIB à long terme, en particulier dans les pays proches de la frontière technologique.

Mots-clés: capital humain, accumulation de capital humain, croissance du PIB à long terme, frontière technologique, productivité, formation scolaire, équation du capital humain, effets d'entraînement du capital humain

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Human capital accumulation, long-run GDP growth and technological frontier

Abstract: While initial education is at the heart of growth models, less work has been done on the influence of human capital accumulation on long-run growth. Our first step was to overcome the "human capital puzzle" by the introduction of the technological frontier as defined by Vandenbusshe, Aghion and Meghir (2006). The "human capital puzzle" means that the level of human capital has a significant positive effect on growth in countries where educational attainment is low and a significant negative effect in countries where educational attainment is high. We specified an aggregate long-run growth equation while taking account the limitations of the various approaches but without rejecting the contribution of endogenous theories. By combining the distance to technological frontier and the workhorse cross-country regression model, our coefficient on both the level and rate of accumulation of human capital are positive, and significant at the 1 and 10 percent level for the human capital predictors alone, and that the interaction between the rate of accumulation of human capital and distance to the technological frontier is also significant at the 5 percent level. This shows that the distance to the technological frontier significantly affects the relationship between human capital accumulation and economic growth, while cross-country differences in technology do not change the relationship between initial level of human capital stock and economic growth. Moreover, the effects of human capital accumulation on economic growth tend to increase with technological advancements of countries.

According to our econometric results, the "human capital puzzle" is thus partially solved by taking into account cross-country differences in technological advancements, and their interaction with human capital proxies. To address the endogeneity of the human capital variable, we turn toward a simultaneous equations model (SEM) where accumulation of human capital is also caused by economic growth, and where accumulation of physical capital is allowed to be endogenous. Despite a less complete datasets (fewer countries), the both human capital level and accumulation have a positive and significant effect on long-term growth of GDP per capita. These first results were needed before investigating the relationship between human capital and economic development at a more granular level and could help to not underestimate the spillover effect of the investment in human capital accumulation on long-run GDP growth especially in countries close to the technological frontier.

Keywords : human capital, human capital accumulation, long-run GDP growth, technological frontier, productivity, educational training, human capital equation, human capital spillover effects.

"When it comes to measurement, the existing capital market gives us little or no information because it is not organized to finance "investments" that enhance the abilities of people as producers" (Schultz, 1950)

I - Introduction

Despite a large body of theoretical work showing the influence of population "quality" on GDP growth per capita, yet young people not in education, employment or training (NEET) still account for 20% of an age group in many European countries and the UN's basic Sustainable Development Goals 3, "Ensure healthy lives and promote well-being for all at all ages", and 4, "Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all", will not be achieved by 2030; the Lisbon strategy focused on a knowledge-based economy has been a failure.

Is it because governments in developed countries underestimate the impact of human capital on long-term growth and its spillover effects? It is true that the econometric results of growth equations including the level of human capital and its accumulation are ambiguous. A human capital puzzle persists. This may appear obvious given the amount of work that has been done in this area; however, when seeking to demonstrate the aggregate impact of human capital and its accumulation, many theoretical and econometric limitations come into play.

For example, Solow's technological progress model cannot be used to highlight the impact of human capital on growth, since the latter is equal to the long-run exogenous growth rate of technological progress. Work by Mankiw, Romer and Weil (1990) to incorporate the human capital factor into the Cobb–Douglas production function shows that human capital accumulation has a positive and significant influence on per capita income. But the level of human capital has no impact on either growth or long-run per capita income. Endogenous growth theories have highlighted the effects of human capital externalities and innovation. According to such theories, human capital affects economic growth by favoring technological progress and technology adaptation, thus leading to sustainable long-run growth. Econometric testing of the endogenous growth model, by carrying out regression analysis on per capita GDP growth as a function of the stock and accumulation of human capital and a set of control factors, has empirically validated the positive and significant impact of the stock of human capital on GDP growth. For example, Romer (1989) performed regression analysis on per capita GDP growth, educational attainment and accumulation, and a set of structural factors, finding that educational attainment had a significant and positive effect on growth but educational accumulation had no such effect. Barro and Sala-i-Martin (2004), like Benhabib and Spiegel (1994) and Aghion and Cohen (2004), also found that the level of human capital had a significant positive effect on growth but educational accumulation had no significant effect on growth.

Some authors, notably Krueger and Lindahl (2000), **have focused on this lack of effect of human capital accumulation on growth**. Like Topel (1999), **they emphasize that a logarithmic specification of the education variable (both initial level and accumulation) amounts to a mis-specification of the relationship between human capital and growth**. Indeed, such a logarithmic specification implies considering human capital as an additional production factor[2], whereas it in fact has different effects on growth. According to Krueger et Lindahl (2000), the non-significance of human capital accumulation in the majority of growth regressions can be explained by two main factors:

1. Firstly, the inclusion of physical capital would justify the non-significance of human capital accumulation; however, this contradicts growth models. As a consequence of the complementarity between capital and qualifications[3], investment in physical capital can be

[2] Since it is a product of logarithmic differentiation.
[3] See Goldin and Katz for a discussion of complementarity between capital and qualifications.

correlated[4] with education: accumulating human capital within a country can lead to a higher stock of physical capital. The impact of physical capital accumulation on growth could therefore account for a large part of the effect of human capital accumulation. By excluding physical capital accumulation from their variables, Krueger and Lindahl (2000) found that human capital had a significant effect on growth. However, this finding remains inconclusive since it obscures the effects of physical capital. In addition to this high level of correlation, it appears that physical capital accumulation coefficients often exceed the commonly accepted share of physical capital in value added (around one third). Introducing a constraint whereby the coefficient for the effect of physical capital accumulation on growth must be compatible with economic stylized facts would lead to an increase in the significance of human capital accumulation.

2. The second factor put forward to explain the non-significance of human capital as a determinant of growth is measurement error bias. Just about all growth equation regressions use the education data constructed by Barro and Lee (1996) or Kyriacou (1991)[5]. This measurement error can mainly arise during construction of the stock of years' schooling by country, which consists of 40% direct data from UNESCO (census) and 60% data constructed using the perpetual inventory method (PIM). Krueger and Lindahl (2000) proposed to limit this measurement bias by choosing to study growth over longer periods. Indeed, the very nature of human capital is such that its accumulation is a long-term endogenous process that is difficult to observe and capture. Studying its short-term influence thus considerably reduces the possibility of measuring it.

By applying constraints to both physical capital and the period under review, Krueger and Lindahl end up with a growth regression in which both the level and the accumulation of human capital have a significant effect[6]. However, they relax the assumption – required by macroeconomic growth regression – of a relationship between growth and ongoing education between countries[7] and **arrive at a puzzle**. **The effect of education on growth differs from country to country[8]: the level of human capital has a significant positive effect on growth in countries where educational attainment is low and a significant negative effect in countries where educational attainment is high.**

In response to this puzzle, some authors have, first of all, incorporated the composition of human capital into growth regressions.

The basis for including differentiation of human capital is found in a theory derived from endogenous growth theory according to which economic growth can be supported by imitation or innovation. This theory, developed in particular by Aghion and Howitt (1998), Vandenbusshe, Aghion and Meghir (2006), Acemoglu, Aghion and Zilibotti (2006) and by Grossman and Helpman (1990), states that countries far from the technological frontier – defined as the maximum level of technology – base their economic growth on imitation since the potential for them to catch up with technological developments is high. Conversely, countries close to the technological frontier – i.e. approaching the maximum level of technology – base their economic growth on innovation since the potential for them to catch up with technological developments is low. By differentiating human capital (by qualification level and type of institution), it is thus possible to distinguish human capital with higher education qualifications favoring innovation, and thus growth in the most developed countries, from human capital with primary- and secondary-level qualifications favoring

[4] See also Benhabib and Jovanovic or Blornstrom and Lipsy for a discussion of the endogeneity of physical capital in a growth regression.
5 Krueger and Lindahl subject these two educational databases to statistical reliability testing and compare them with another source of World Bank data. Their findings lead them to conclude that the most reliable education data are those used by Barro and Lee, which is why we used this data source in our own regression.
[6] They use the total number of years' schooling per person aged over 25, which they consider the optimum measure of education. See article for full discussion.
[7] By including a dummy variable to control for the country's level of development.
[8] This lack of consistency has also been highlighted by Durlauf and Johnson (1995)

imitation, and thus growth in the least developed countries. Thus, according to these models, a marginal increase in the stock of qualified human capital will have a greater impact on growth if the

Vandenbusshe, Aghion and Meghir (2006) find a significant level of interaction between education and the technological frontier. Interaction with distance to the technological frontier is positive for years of tertiary education and negative for years of primary and secondary education. The closer a country is to the technological frontier, the greater the effect of human capital on growth. For a given level of tertiary human capital, the impact of the number of years' primary and secondary education declines as a country approaches the technological frontier. The test thus validates the hypothesis that human capital can be differentiated and that it affects growth differently depending on how far the country is from the technological frontier.

But long-term GDP growth equations including human capital in its general form and not taking into account the technological frontier have sometimes suggested that the general level of human capital had an insignificant effect on growth in the most developed countries. Inclusion of the technological frontier has not been extended to an analysis taking into account the accumulation of human capital, as we are proposing.

In light of the literature and the "human capital puzzle", we tried to estimate the impact of both human capital and its accumulation in an aggregate growth equation. We wanted to specify such an equation while taking into account the limitations of the various approaches but without rejecting the contribution of endogenous theories.

To avoid the "human capital puzzle" and measure the joint influence of the level of human capital and its accumulation, we incorporated the recommendations of Krueger and Lindah (2000). Our chosen measure of long-run growth is the change in log real GDP per capita. We used the logarithmic specification for growth in the labor force and physical capital accumulation. We introduced the initial level of log per capita GDP. However, the stock and accumulation of human capital are expressed as levels, as recommended in the literature and the Mincerian specification. We used Barrow and Lee's measure for the human capital variable and selected a period of 30 years to avoid bias linked to the risk of errors. Furthermore, we sought to eliminate various endogeneity and simultaneity biases by adding a number of control variables, contrary to what we have seen in the literature, such as the consumer price index, government consumption expenditure expressed both as a percentage of GDP and in purchasing power parity, and the openness ratio. After testing our OLS linear regression equation, we decided to introduce the concept of the "technological frontier" into our growth equation using the approach advocated by Vandenbusshe, Aghion and Meghir (2006), both as a variable in its own right and in interaction with human capital measures.

According to our first econometric findings, the coefficients of the variables "initial level of human capital" and "human capital accumulation" are positive and significant. (1) The stock of human capital has a positive and significant impact on long-run growth. (2) Including distance to the technological frontier helped solve one of the riddles of the human capital puzzle, namely the lack of correlation between education and growth in developed countries. The human capital accumulation coefficient is positive and significant. (3) The coefficient of the "human capital accumulation" variable interacting with distance to the technological frontier is significant and positive, which means the closer a country is to the technological frontier, the greater the impact of human capital accumulation on growth.

Although our growth equation gives us greater insight into the correlation between human capital, its accumulation and the increase in GDP per capita, we were keen to take this work further to address two main weaknesses we had identified. First, our equation is still subject to endogeneity issues in spite of our having introduced control variables. Second, given the existence of new databases that allow for a statistical treatment of skills at the aggregate level (Hanushek and Woessmann 2009), we wanted to introduce the idea of quality. Indeed, while these authors have demonstrated the correlation between cognitive skills and growth, adding their calculated cognitive score index to our growth equation has the advantage that it complements our specification of interactions between human capital and growth.

To address these weaknesses, we decided to replace the econometric technique we had used at the outset with simultaneous equations (3SLS). This approach enabled us to better resolve reverse causality and simultaneity biases. Moreover, by simultaneously estimating the growth equation and equations for our endogenous variables (accumulation of physical and human capital), we can take into account correlations between error terms. Lastly, this approach also allows us to open up new areas of research into the channels of influence of human capital, which is our primary concern. Unlike the 2SLS estimate, the simultaneous equation system enables us to directly estimate the determinants of human capital accumulation. **There is very little literature available specifying an aggregate human capital accumulation equation. Our work constitutes a first step in this direction.**

We have therefore built a model of simultaneous growth equations where human capital accumulation is also generated by economic growth and physical capital accumulation is also endogenous. A qualitative criterion has been introduced into the human capital accumulation equation. We have also added the interest rate and lending, given their importance demonstrated by ample literature on economic growth.

- Human capital accumulation is a function of per capita GDP growth, initial level of education, interest rates and net average wages. This equation is based on the afore mentioned macroeconomic work but also on the microeconomic approach to human capital (Becker 1964, Mincer 1974 and Ben-Porath 1967). People invest if they hope to receive a return over and above the cost of investing. The return is estimated using average real wages. The interest rate is a measure of the opportunity cost of investing in human capital; it influences human capital accumulation via the distribution of loans (see Heckman and Hai, 2016). The inclusion of a skills measure is also grounded in the microeconomic literature. Heckman, Humphries and Veramendi (2016) showed that those with the highest skills scores are more likely to invest in education since they hope to receive a higher return from it.
- The physical capital accumulation equation is more standard, being a function of per capita GDP growth, the rate of depreciation of the stock of physical capital, investment, the price level of capital formation and the price level of capital stock. We nevertheless introduced distance to the technological frontier, since we take the view that a country's technological advancement affects physical capital accumulation.

The initial level and accumulation of human capital are always positive and significant and the coefficients are similar to those obtained in our first estimation (linear estimation of growth regression). Our measurement of the impact of human capital on growth is thus robust. In addition, the estimation of simultaneous equations is not affected by measurement bias. The physical capital accumulation coefficient is still similar to the share of physical capital in value added, which shows that our findings are economically sound and remain robust regardless of the econometric methods used.

By deliberately using an aggregate macroeconomic approach while incorporating the most recent work on economic growth, and in particular the work of Vandenbussche, Aghion and Meghir (2006), we were able to show that both the level of human capital and its accumulation are determinative of long-run growth, including for developed countries. Moreover, the coefficient of the "human capital accumulation" variable interacting with distance to the technological frontier is significant and positive, which means the closer a country is to the technological frontier, the greater the impact of human capital accumulation on long-run growth.

II - Conceptual Framework and Empirical Specification

2.1 Theoretical Effects of Human Capital on Economic Growth

A number of articles are considered as representing fundamental steps in determining the theoretical framework for understanding the impact of human capital on growth, in particular those by T.W. Schultz, G. Becker and J. Mincer. While Schultz adopted a macroeconomic approach whereas Becker and Mincer developed a framework for analyzing individual human capital investment choices, they all consider education an investment and not an expense. G. Becker developed a general model explaining the determinants of human capital investment using the internal rate of return. The microeconomic approach may be summarized as a study of the individual private return on education using wage equations. This method is based on the fact that there is a linear relationship between an individual's wages and the number of years' schooling that individual has completed, and consequently the slope of that linear relationship (the regression coefficient) can be used to estimate the return on investment in education. J. Mincer, who popularized this approach[9], estimated that, in the United States, each additional year of education increased wage gains by 10%. Empirical estimates across different countries and periods generally put the return on education at between 5% and 15%[10]. However, the estimated private return on education cannot be used to evaluate its total impact.

T.W. Schultz was the first to use the concept of human investment in 1940 to explain income inequalities among farmers[11]. Indeed, expenditure improves individuals' productive capacity and thus counts as "investments". Furthermore, in his later work "Investing in people: the economics of population quality" (1981), Schultz found that growth in the share of wages in value added was the result of an increase in the value of human time.

Growth theorists then sought to measure the impact of effective labor (as used in the Solow-Swan model) on output growth. However, the turning point came with the introduction of the "human capital" factor into Solow's neoclassical model by Mankiw, Romer and Weil (1990) and subsequently by other authors like Benhabib and Spiegel (1994). A "human capital" factor H is added as a production factor in the same way as physical capital.

The production function is now of the type Y = F (K,AL,H) where Y is output, K is the capital factor, AL is the labor factor and H is human capital. Workers have units of effective labor which fuel output Y. Technological progress, A, increase steadily at exogenous rate g. Growth in A has the effect of increasing the "effective labor" factor. Technological progress thus acts in a similar way to an increase in the population growth rate.

Differentiating the aggregate production function with respect to time gives the following:

$$\frac{\dot{Y}}{Y} = \left(\frac{F_k K}{Y}\right)\frac{\dot{K}}{K} + \left(\frac{F_{AL} L}{Y}\right)\frac{A\dot{L}}{AL} + \left(\frac{F_H H}{Y}\right)\frac{\dot{H}}{H} \quad (1)$$

[9] D. Gorseline (1932), J.R. Walsh (1935), H. Miller (1955), Wolfe and Smith (1956).
[10] Ashenfelter and Kruger (NBER 1992), Lindahl and Krueger (2000), Angrist and Krueger (1992). For a review of microeconomic estimates of the return on education, see G. Psacharopoulos (1991)
[11] T. W. Schultz, "Reflections on poverty within agriculture", 1940, Journal of Political Economy.

Growth is affected by the increase in the number of units of effective labor but also by the rate of human capital accumulation. Stating the production function as a Cobb-Douglas production function gives the following:

$$Y = (A(t)L(t))^{1-\alpha-\beta}K(t)^{\alpha}\, H(t)^{\beta} \quad (2)$$

where human capital H(t) depreciates at rate δ_h and physical capital K(t) depreciates at rate δ_k.

We can restate the output per unit of effective labor as follows:

$$\hat{y}(t) = k^{\alpha}(t)h^{\beta}(t) \; (3)$$

The long-run equilibrium values are as follows:

$$k^* = \left[\left(\frac{sk}{n+g+\delta_k}\right)^{1-\beta}\left(\frac{sh}{n+g+\delta_h}\right)^{\beta}\right]^{\frac{1}{1-\alpha-\beta}} \quad (4)$$

$$h^* = \left[\left(\frac{sk}{n+g+\delta_k}\right)^{\alpha}\left(\frac{sh}{n+g+\delta_h}\right)^{1-\alpha}\right]^{\frac{1}{1-\alpha-\beta}} \quad (5)$$

A high rate of investment in physical capital increases not only the long-run equilibrium level of physical capital but also the level of human capital. Similarly, a high rate of investment in human capital increases not only the level of human capital but also the steady-state level of physical capital in the economy.

The long-run equilibrium output per capita of a country i is given by the following:

$$\left(\frac{Y(t)}{L(t)}\right)^* = yi^* = Ai\left(\frac{sk,i}{ni+gi+\delta_k}\right)^{\frac{\alpha}{1-\alpha-\beta}}\left(\frac{sh,i}{ni+gi+\delta_h}\right)^{\frac{\beta}{1-\alpha-\beta}} \quad = Ai\hat{y}^* \quad (6)$$

Taking the logarithm gives:

$$\ln\left(\frac{Y(t)}{L(t)}\right) = \ln A(0) + gt + \frac{\alpha}{1-\alpha-\ \beta}\ln\left(\frac{sk,i}{ni+gi+\delta_k}\right) + \frac{\beta}{1-\alpha-\ \beta}\ln\left(\frac{sh,i}{ni+gi+\delta_h}\right) + \varepsilon_i \quad (7)$$

Or :

$$\ln yi^* = \ln A(0) + gt + \frac{\alpha}{1-\alpha-\ \beta}\ln(sk,i) - \frac{\alpha}{1-\alpha-\ \beta}\ln(ni+g+\delta_k) + \frac{\beta}{1-\alpha-\ \beta}\ln(\boldsymbol{sh,i}) - \frac{\beta}{1-\alpha-\ \beta}\ln(ni+gi+\delta_h) + \varepsilon_i \quad (8)$$

By definition, when long-run equilibrium is reached, $\hat{k}$, $\hat{y}$ and $\hat{c}$ are constant. According to (19), we can thus see that in the long run, per capita GDP growth is equal to growth in A, i.e. at exogenous rate g, even when human capital is included. Including human capital as a production factor does not change the long-run equilibrium growth rate, which is always equal to the exogenous growth rate of technological progress.

Using the growth accounting and growth regression approaches, we can directly calculate the Solow residual, which is used as total factor productivity (TFP), and estimate a growth equation by explaining the increase in per capita GDP (as a proxy for TFP growth) as the result of structural and fundamental economic variables. However, under the growth accounting approach, the problem is that the relative weighting of the various forms of labor is approximated using wage rates, which can lead to bias, mainly due to labor coefficients12 negatively skewing growth. Another limitation is that this approach only establishes the accumulation of production factors as determinative of growth; it does not take into account the effects of the level of human capital or of human capital externalities. In the case of growth regression, it is not growth but rather equilibrium output per capita that is estimated. Growth is given by the exogenous growth rate of technological progress.

Furthermore, regressions (26) and (27) exclude any effect of the quality of human capital. We are dealing here with a so-called neoclassical model that uses units of effective labor: since labor is considered homogeneous, workers cannot be differentiated by their qualifications. The only way to capture the effect of the composition of the labor force is to study the relative growth of each category of workers (see page 8 for detailed reasoning).

$$\ln\left(\frac{Y(t)}{L(t)}\right) = a + \frac{\alpha}{1-\alpha}\ln(s) - \frac{\alpha}{1-\alpha}\ln(g+n+\delta) + \epsilon \ (9)$$

Or, in the case of an aggregate production function with human capital such as (13):

$$\ln yi^{*} = \ln A(0) + gt + \frac{\alpha}{1-\alpha-\beta}\ln(sk,i) - \frac{\alpha}{1-\alpha-\beta}\ln(ni+g+\delta_k) + \frac{\beta}{1-\alpha-\beta}\ln(sh,i) - \frac{\beta}{1-\alpha-\beta}\ln(ni+gi+\delta_h) + \varepsilon_i \ (10)$$

Lastly, as with the growth accounting approach, we only estimate the effect of human capital accumulation$sh,$ j, whereas the economic literature has shown that the level of human capital has a very significant effect on growth and total factor productivity13. One final limitation is that g, sh and sk are highly correlated, which can lead to estimation bias.

We can estimate growth and total factor productivity by econometrically estimating the growth accounting equation shown above. A regression could, for example, take the following form, with differentiation for the composition of the labor factor:

$$\frac{\dot{Y}}{Y} = \alpha + \beta_0\frac{\dot{K}}{K} + \beta_1\frac{\dot{Lq}}{Lq} + \beta_2\frac{\dot{Lnq}}{Lnq} + \varepsilon_j \ (11)$$

where per capita GDP growth is now the dependent variable, each estimated coefficient could be seen as the factors' relative shares of value added, and the regression constant term represents the Solow residual. However, this approach does not capture the effects of human and physical capital depreciation.

The models and equations set out above are all derived from the neoclassical model: they all assume **exogenous technological progress** and explain growth in total factor productivity as the result of the **accumulation** of production factors (physical and human capital and units of effective labor). Moreover, labor is considered homogenous, which excludes any efficiency effects. Qualified

[12] Acemoglu and Pischke (1998)
[13] Barro and Sala-i-Martin (2004), Griliches (1970), Benhabib and Spiegel (2005), Krueger and Lindahl (2000)

and less qualified workers differ only in the number of units of effective labor they represent: put trivially, this means one worker representing three units of effective labor is exactly equivalent to three workers each representing one unit of effective labor. In this sense, qualified and unqualified workers are sometimes defined as perfect substitutes in Solow's model with "labor-augmenting" technological progress[14]. Furthermore, these models and equations cannot be used to estimate the effect of the level of human capital, which the literature has shown to have a significant effect on growth and total factor productivity, not to mention estimation bias.

If we want to arrive at a growth equation that also takes into account the effects of the level of human capital[15], we must follow another more general formulation[16] proposed in the recent economic literature, which explains per capita GDP growth (as a proxy for total factor productivity) as the result of the initial level of GDP and a set of structural and fundamental economic variables specific to each country.

The standard equation is as follows:

$$\Delta yit = X_i' \beta_0 + \beta_1 \mathrm{yi,t-1} + \varepsilon i,t \; (12)$$

Or logarithmically:

$$\log yi,t - \log yi,t-1 = X_i' \beta_0 + \beta_1 \log(yi,t-1) + \varepsilon i,t \; (13)$$

where Δyit is growth in per capita output between t-1 and t

2.2 – Model specification

Given the limitations of growth accounting models, even when a differentiated measure of the accumulation of qualified and unqualified labor is introduced, and of Solow's long-run model introducing the human capital factor, we chose to use a growth equation that takes into account the contributions of endogenous growth theories.

a) Growth equation

The more general approach consists of regressing the growth rate on the initial level of GDP and a number of other country-specific structural and fundamental factors that can explain growth. As highlighted by Nelson and Phelps (1966) and Benhabib and Spiegel (2005), expressing human capital as an additional production factor within an aggregate production factor, as in the growth accounting approach or Solow's augmented human capital model, amounts to mis-specifying the role of human capital in growth. Indeed, these approaches consider only the rate of accumulation of the effective labor factor or of human capital, without taking into account either quality or externality and diffusion effects, even though these have been highlighted in economic theory[17]. Consequently, a number of authors[18] have adopted a "growth regression" approach whereby per capita GDP growth approximates total factor productivity growth[19] as a function of the initial level of GDP and a set of country-specific variables. The general approach may be written as follows:

[14] Aghion and Cohen (2004).
[15] Romer (1989) and Lucas (1988) have written abundantly on the effect of the stock of human capital on economic growth and total factor productivity
[16] Barro and Sala-i-Martin (2004), Griliches (1970), Benhabib and Spiegel (2005), Krueger and Lindahl (2000)
[17] Romer (1989) and Lucas (1988)
[18] Barro and Sala-i-Martin (2004), Benhabib and Spiegel (2005), Krueger and Lindahl (2000), Vandenbusshe, Aghion and Meghir (2006) and Grossman and Helpman (1990, 1991)
[19] Vandenbusshe, Aghion and Meghir (2006), Aghion and Howitt (1998), Barro (1991), Lucas (1988), Acemoglu, Aghion and Zilibotti (2006)

$$\Delta yit = \alpha + \beta_0 \log(skt, i) + \beta_1 \quad (sht, i) + \beta_3 ht - 1, i + \beta X + \beta_4 \log(yi, t-1) + \varepsilon_{it} \ (14)$$

where Δyit represents the per capita GDP growth rate between t-1 and t, hi,t-1 represents the initial stock of human capital of country i, and X represents a set of country-specific factors.

In order to go beyond the findings of Krueger and Lindahl (2000), described by Vandenbussche , Aghion and Meghir (2006) as a "human capital puzzle", we introduced distance to the technological frontier into our economic growth equation (14).

The basis for including differentiation of human capital is found in a theory derived from endogenous growth theory according to which economic growth can be supported by imitation or innovation. This theory, developed in particular by Aghion and Howitt (1998), Vandenbussche, Aghion and Meghir (2006), Acemoglu Aghion and Zilibotti (2006), and Grossman and Helpman (1991), states that countries far from the technological frontier – defined as the maximum level of technology – base their economic growth on imitation since the potential for them to catch up with technological developments is high. Conversely, countries close to the technological frontier – i.e. approaching the maximum level of technology – base their economic growth on innovation since the potential for them to catch up with technological developments is low. By differentiating human capital (by qualification level and type of institution), it is thus possible to distinguish human capital with higher education qualifications favoring innovation, and thus growth in the most developed countries, from human capital with primary- and secondary-level qualifications favoring imitation, and thus growth in the least developed countries. Such differentiation thus helps solve Krueger and Lindahl's puzzle: the fact that human capital has no effect on economic growth in developed countries is rooted in the non-differentiation of human capital by qualification level and the non-inclusion of the country's distance to the technological frontier, which can be used to identify the differentiated impact of education based on the technological advancement of the country under review. Thus, according to this model, a marginal increase in the stock of qualified human capital will have a greater impact on growth if the country in question is at the technological frontier. Different authors calculate distance to the technological frontier differently: while it always denotes the technological advancement of the country under review relative to the most advanced level of technology in the global economy, a number of different variables can serve as proxies for it. Aghion and Meghir measure total factor productivity (TFP) as output per adult less capital per adult multiplied by the share of capital in output. Distance to the technological frontier is then calculated as the ratio of total factor productivity in the country in question to the highest total factor productivity of all countries under review.

The equation then becomes the following:

$$\begin{aligned}\Delta yit = \alpha + \beta_0 H_{i,t-1} + \beta_1 logn_{pop_{i,t}} + \beta_2 proximit\acute{e}_{i,t-1} + \beta_3 \Delta Ht, i + \\ \beta_4 H_{i,t-1} \times proximit\acute{e}_{i,t-1} + \beta_5 \Delta Ht, i \times proximit\acute{e}_{i,t-1} + \beta_6 \log\left(y_{i,t-1}\right) + \\ \beta_7 Inflation_{i,t-1} + \beta_8 \Delta \log K_{i,t} + \beta_9 Govt_{cons_{i,t-1}} + \beta_{11} openess_{i,t} + \\ \varepsilon_{it} \quad (15)\end{aligned}$$

However, the estimation contains endogeneity and simultaneity biases, which we will reduce by introducing a number of control variables. Moreover, this model is less microfounded than those based on an aggregate production function. **However, in light of the existing literature, equation (15) appears to us to be the best specification for estimating the various effects of human capital on growth in per capita output.**

It is thus this equation that we have opted to use to estimate the impact of human capital and its accumulation on per capita GDP growth. However, the econometric estimation of growth equation (15) poses model specification problems. There are several sources of endogeneity bias:

- **Omitted variable/measurement error bias**: non-inclusion of certain factors in the regression that skew the results or mis-specification of human capital leading to biased coefficients.
- **Simultaneity bias**: we want to show that human capital influences growth in per capita output (as a proxy for TFP), but TFP itself can also influence human capital accumulation, leading to double determination and endogeneity.
- **Correlation bias between errors**: the error terms of the different observations are not independent and the estimators are no longer minimum variance (BLUE).
- **Seemingly unrelated regression (SUR):** we want to estimate a system of equations that are seemingly independent but whose error terms are, in fact, correlated, leading to estimation bias in the main equation.
- **Simultaneity equation:** we want to estimate an equation system where certain variables are determined simultaneously (the explanatory variable in one equation becomes the endogenous variable in the other), leading to endogeneity bias and correlation between the system's residuals.

These biases can be resolved using various econometric techniques:

- **IV/2SLS**: this method consists of using instrumental variables to eliminate endogeneity from an econometric equation. The instrumental variables must be correlated with the endogenous variable ($Cov(z,xi)\neq 0$) and uncorrelated with the error term ($Cov(z,ui)=0$). The technique consists of regressing each endogenous variable on the variables of the first equation and the instrumental variable: this gives the estimated theoretical value of the endogenous variables. These estimated values are then included in the first specification and give an effective estimate of the independent variable while eliminating endogeneity bias.
- **IV/3SLS:** this technique is similar to the 2SLS technique but applied to a system of structural equations: it thus combines the IV (2SLS) method with the **SUR** method, which itself can be used to estimate simultaneous equation systems. Typically, the independent explanatory variables of equation (40) are sometimes dependent variables of other equations in the system, leading to correlation with error terms within the structural equation system. The first two steps in the procedure are the same as those set out for the 2SLS method. The first step is to instrumentalize the endogenous variables (using chosen instrumental variables or by regressing each endogenous variable on all exogenous variables in the system). The second step is to estimate a variance–covariance matrix of the equation system's error terms based on estimation of residuals from step 1. This ensures that errors are not correlated within the equation system and eliminates the source of endogeneity bias. Lastly, a final estimation is made using the variance–covariance matrix and the instrumentalized variables in place of the endogenous variables.

We used a three-step process to estimate equation (15) while eliminating endogeneity bias. The first step consisted of performing endogeneity tests on the supposed endogenous variables, using in particular the Hausman test for endogeneity. During the second step, we carried out a standard OLS regression of equation (15) with a homoscedasticity constraint on the residuals (robustness) and then instrumentalized[20] those variables found to be endogenous in step 1 using 2SLS (two-stage least squares) regression and observed variance differences from the simple OLS regression. The final step was to estimate the structural equation system using the 3SLS method.

b) Simultaneous equation model specification

This equation system consists of equation (15), a human capital accumulation equation and a physical capital accumulation equation.

To specify human capital accumulation, we first studied the law of human capital accumulation in the absence of depreciation. The equations are of the same type as physical capital accumulation laws in a discrete-time Solow model.

Let Ht be the stock of human capital at date t and Ht-1 the stock of human capital at date t-1. The investment in human capital between t-1 and t is the flow of additional human capital acquired during the period, i.e.:

$$It = H_t - H_{t-1}$$

Let us initially suppose that human capital cannot depreciate, i.e.:

$$H_t = H_{t-1} + It$$

We can then calculate gross human capital accumulation such that:

$$\Delta H_t = \frac{H_t - H_{t-1}}{H_{t-1}}$$

In the case of null depreciation, gross human capital accumulation is positive if and only if investment between the two periods is positive, i.e. if:

$$H_t > H_{t-1}$$

Which is to say $It > 0$

Let us now suppose that human capital depreciates at rate δ ≥ 0 between t-1 and t.

We now have the stock of human capital at date t net of depreciation:

$$\widetilde{H_t} = (1 - \delta)H_{t-1} + It$$

where It is still gross investment, i.e. the difference in value of the stock between t-1 and t.

Human capital accumulation net of depreciation is then given by:

$$\widetilde{\Delta H}_t = \frac{\widetilde{H_t} - H_{t-1}}{H_{t-1}}$$

$$\widetilde{\Delta H}_t = \frac{(1 - \delta)H_{t-1} + It - H_{t-1}}{H_{t-1}} = \frac{It - \delta H_{t-1}}{H_{t-1}}$$

Replacing It with its value gives:

[20] By carrying out a Breusch–Pagan test to test the instruments' validity.

$$\widetilde{\Delta H_t} = \frac{Ht - H_{t-1} - \delta H_{t-1}}{H_{t-1}} = \frac{Ht - H_{t-1}}{H_{t-1}} - \frac{\delta H_{t-1}}{H_{t-1}}$$

$$\boxed{\widetilde{\Delta H_t} = \frac{Ht - H_{t-1}}{H_{t-1}} - \delta = \Delta H_t - \delta}$$

In order for net human capital accumulation to be positive, i.e. for the net change in depreciation of the stock of human capital between t-1 and t to be positive, we therefore need:

$$\widetilde{\Delta H_t} > 0$$

$$\frac{Ht - H_{t-1}}{H_{t-1}} > \delta$$

$$\boxed{\Delta H_t > \delta}$$

We therefore have $\widetilde{\Delta H_t} > 0$, which implies $\Delta H_t > \delta$.

For net human capital accumulation to indeed be positive taking into account human capital depreciation between t-1 and t, gross human capital depreciation must be greater than the human capital depreciation rate. This approach can be generalized with n periods, where Ht-1 must also be net of depreciation. The result is the same, and net accumulation is equal to gross accumulation less depreciation.

We thus have the required condition for net human capital accumulation to be positive. We are seeking to express the determinants of human capital accumulation and human capital depreciation, i.e. the determinants of $\Delta H_t - \delta$.

A number of determinants of human capital accumulation and depreciation have been highlighted in microeconomic studies of the human capital investment decision, notably those initiated by G. Becker (1964) and Ben-Porath (1967). The number one determinant of human capital accumulation is real wages. Agents decide whether or not to continue their education by trading off the future wage premium they will obtain once they enter the labor market against the immediate loss of income they will suffer (wages they could have received plus cost of education) by continuing their education. Investment in human capital, like traditional investments, consists of a cost-benefit-risk calculation, i.e. a *trade-off* between immediate losses and future income (Mincer 1974). Human capital investment decreases with age, since any increase in wages increases the opportunity cost of investing in human capital, and because the return on investment in human capital decreases with age since the number of years required for the investment to “pay off” also decreases. Thus, while the private return on education or training decreases with age, the same is not necessarily true of the total return: it may thus be beneficial for a business to train older employees even where those employees have not themselves invested in training (Ben-Porath,. 1967). A compressed wage structure (i.e. where wages rise more slowly than individual marginal productivity) will disincentivize investment in human capital at the microeconomic level (Acemoglu and Pischke, 1998).

Risk, irreversibility, credit market illiquidity, psychological costs and other frictions associated with human capital investment would entail the need for individuals to secure a return on human capital in excess of the risk-free interest rate and would hamper human capital investment. Comparing the internal rate of return (the discount rate at which costs and benefits are equal) of the investment with the borrowing interest rate can help inform the choice between the immediate gain through labor and the deferred gain through training. Human capital accumulation (human capital investment whether or not financed by borrowing) continues throughout life as long as the marginal return on the investment in human capital exceeds the interest rate. Indeed, if the interest rate falls, the relative return on a human capital investment as against a financial investment increases. When interest rates are very low, as they are at present, investing in human capital becomes highly profitable. Moreover, low interest rates lower the cost of investing in human capital for individuals who need to borrow to finance such an investment. We therefore introduce the interest rate as a control variable within our aggregate human capital accumulation equation. Finally, because some microeconomic studies have shown the importance of cognitive skills in human capital accumulation, we also add variables related to cognitive skills to our specification.

Our structural economic model may be summarized by the following system of equations:

$$\Delta logy_t = \alpha_0 + \beta_0 Proximity + \beta_1 H_{t-1} + \beta_2 H_{t-1} * Proximity + \beta_3 * \Delta H_t + \beta_4 * \Delta H_t * Proximity$$

$$+ \beta_5 \Delta logL_t + \beta_6 logy_{t-1} + \beta_7 P_t + \beta_8 \Delta logK_t + \beta_9 Gvtcons + \beta_{10} Openess + \beta_{11} Real_t +$$

$$\beta_{12} Lending_t + \varepsilon_{it}$$

$$\Delta H_t = \delta_0 + \delta_1 H_{t-1} + \delta_2 logL_t + \delta_3 Lending_t + \delta_4 Top + \delta_5 Cognitive + \delta_6 WageShare$$

$$+ \delta_7 \Delta logy_t + \delta_8 NetAverageWage + \epsilon_{it}$$

$$\Delta logK_t = \sigma_0 + \sigma_1 \delta_{capital} + \sigma_2 \frac{FBCF}{GDP} + \sigma_3 P_{FBCF,t} + \sigma_4 Real_t + \sigma_5 Proximity + \sigma_6 \Delta logy_t + u_{it}$$

(2)

III - Data

In order to investigate the relationship between the stock and the growth of human capital on economic growth per capita, we now turn to the empirical analysis of the effects of human capital on economic growth. For this purpose, we build a dataset that combines rich information on macroeconomic variables, human capital variables, and additional control variables that can be used for our regression analysis.

We use GDP, factor inputs and trade data from the Penn World Tables 9.0 compiled by Heston and al. (2006). We build output per capita by dividing total real GDP by the size of the population. We build an indicator for international openness by taking the sum of imports and exports as a share of total GDP. We use data on capital stock and depreciation to compute the rate of physical capital accumulation net of the average depreciation rate of the capital stock. We complete this rich set of macroeconomic variables with measure of human capital at the country level.

Human capital measurement

The first empirical challenge faced when studying the effect of human capital on growth is to correctly measure the stock of knowledge in the economy. We build on a large body of literature that has addressed the question of how to include human capital measure in growth regression.

Early research on human capital and growth has mainly used literacy rates or school enrolment ratio to measure human capital stock and accumulation (see for example Romer (1990), Barro (1991) or Mulligan and Sala-i-Martin (1995)). However, school enrolment ratios and adult literacy rates do not measure accurately the stock of human capital that is available for current production, as emphasized by Barro and Lee (1993). It is mainly because current enrolment ratios measure the flow of schooling: the cumulation of these flows creates future stock of human capital. As the educational process takes many years, there is a long lag between flows and stocks (Psacharopoulos and Ariagada 1986). Hence, the construction of human capital stocks requires an estimate of initial stocks, and to consider the appropriate lag, which is not always obvious. Migration, mortality, repetition of grades and drop-outs also introduce a large number of errors in the human capital stock estimation process using enrolments ratio (see Barro and Lee (1993) for an exhaustive discussion on the subject). Adult literacy rates also induce an important number of issues regarding international comparability, since the evaluations are not based on any objective tests, thus introducing mechanical measurement biases in cross-country regressions. In addition of this measurement errors, literacy is only the first stage in the path of human capital formation and accumulation. Our analysis goes beyond this stage, as we aim to investigate and discuss the effects of the level and accumulation of education on countries' output.

Because of the measurement and conceptual issues related to other measures, educational attainment, that is to say average years of schooling per capita, has been considered as the best available education measure at the aggregated level. As emphasized by Krueger and Lindahl (2000), the widely used Barro and Lee measure of average years of schooling per adult shows the best reliability ratio compared to other educational attainment measures such as Kyriacou (1991) or the World Value Survey measure. In particular, the Barro and Lee measure is the most reliable when it comes to measure the *changes* in human capital stock measured as changes in years of education, which is the first focus of our paper. We therefore use the average years of schooling per adult measure built by Barro and Lee as a proxy of the initial level of human capital and use this measure to compute the rates of human capital accumulation over time by country. We define the rate of accumulation of human capital as the percentage variation in the average year of schoolings over a given period of time within a given country. If average years of schoolings provide a measure of knowledge that is comparable across countries and over time, the seminal paper of Krueger and Lindahl (2000) also shows that measurement errors in educational attainment data could severely attenuate estimates of the effect of the change in schooling in GDP growth. Because of this attenuation bias, measurement errors could bias our estimates towards zero. Our coefficients estimates can thus be interpreted as lower bound effects of change in education on growth per capita.

While Barro and Lee measure of schooling allows us to measure human capital quantity, it shows few interest in investigating the human capital quality, such as individuals' ability at the country level. Hence, we complete our educational attainment measure using the dataset of Hanushek and Woessman (2000) which gives (i) the average score of students at international tests for the period 1964-2003 and (ii) the share of students surperforming these tests. We use these variables as proxies for cognitive ability of individuals across countries, that allow us to control for differences in quality of knowledge that would not be captured by the simple level and accumulation of years of schooling. We finally add to our dataset a rich set of controls collected from various national sources, such as average wages and labour taxes collected from the OECD Taxing Wages Database.

Empirical Specification

Our main focus is to shed light on the correlation between the level and the rate of accumulation of human capital and economic growth. While this question has been at the core of a large body of theoretical work, dating back the neoclassical Solow model and the recent work on endogenous growth theory and innovation, few empirical studies have managed to uncover the causal relationship between human capital and economic growth. The main empirical challenge faced by the literature in studying the effects of human capital on economic growth lies in the fact that unobserved determinants of human capital level and growth may also be correlated to changes in GDP per capita, and could thus bias the estimates of the linear regression of human capital on growth. Another concern is that anticipated increases in future economic growth may lead to more investment in human capital, thus leading to a reverse causality problem (Bils and Klenow, 1998).

We take several steps in order to tackle this challenge. First our regression analysis focuses on long-term changes in human capital and economic growth. As emphasized by the study of Krueger and Lindahl (2000), over short time periods, the transitory component of measurement error in schooling would be large relative to variability in the true change. Because human capital stock is slow to adjust, year-on-year regressions are not the best suited to the empirical analysis. Measurement error bias in growth regression are also more likely to appear over 5- and 10-years horizons. We therefore choose a larger time span (30 years) for our estimation, in order to avoid downward bias due to measurement errors and estimate a first difference model. Second, our specification includes both the level of initial human capital and its rate of accumulation. The empirical macro literature omits the rate of accumulation of schooling and only focuses on the initial level of human capital variable. However, controlling simultaneously for both the initial level and the change in the stock of human capital may allow to capture the general equilibrium effects of schooling at the country level, a point that has been originally made by the Krueger and Lindahl (2000) paper. Third, we build on the endogenous growth theory and include the concept of distance to the technological frontier in our empirical analysis. We introduce in the standard regression of education on growth an interaction between the stock and change of human capital an interaction and countries' level of technological advancement. Most of the studies relying on cross-country growth regressions without controls for cross-country differences in the level of technology have estimated null effects of human capital on education especially for more advanced economies. However, cross-country differences in technological advancement may explain part of the effects of human capital on growth. As emphasized by a large body of theoretical work, from the seminal contribution of Aghion and Howitt (1998), endogenous growth can be driven by imitation or innovation. If a country is far from the technological frontier, its economic growth will be mostly explained by imitation process and will thus be more importantly affected by the stock of physical capital than human capital. By contrast, a country with a high initial technological advancement will need large investments in human capital to grow through innovation. Therefore, at a given level of initial level of human capital, we can expect a differentiated effect of human capital accumulation on economic growth depending on the counties' differences in technological advancements. Our approach builds on Vandenbusshe.J, Aghion and Meghir (2006) and corrects for the omission of cross-country differences in technological level by controlling for the distance to the frontier, and by interacting the human capital variables to countries' initial technological advancement. This allows our analysis to capture potential differential effects of human capital stock and accumulation on growth depending on countries' initial state of technology.

We complement the Vandenbusshe.J, Aghion and Meghir (2006) specification, which is the closest to ours, by investigating the effects of overall human capital rather than tertiary schooling alone, by focusing on long-term differences to avoid measurement biases driven by short-term measurement biases in the education variable, and by including simultaneously initial stock and changes in the stock of human capital. Our baseline linear regression can be summarized by:

$$\begin{aligned}\Delta \log\left(y_{i,t}\right) = \alpha + \beta_0\, Proximity_{i,t-1} + \beta_1\, H_{i,t-1} + \beta_2\left(H_{i,t-1} \times Proximity_{i,t-1}\right) + \beta_3 \Delta H_{i,t} \\ + \beta_4\left(\Delta H_{i,t} \times Proximity_{i,t-1}\right) + \beta_5 \Delta \log\left(L_{i,t}\right) + \beta_6 \log\left(y_{i,t-1}\right) + \beta_7 P_{i,t-1} \\ + \beta_8 \Delta \log\left(K_{i,t}\right) + \beta_9 GC_{i,t-1} + \beta_{10} OP_{i,t-1} + \varepsilon_{it}\end{aligned}$$

Equation (1) is specified in first-difference between 1980 and 2010, therefore country-specific . The dependent variable $\Delta \log\left(y_{i,t}\right)$ is the change in log real GDP per capita between 1980 and 2010 of country i, measured in log differences. $Proximity_{i,t-1}$ is the proximity to the technological frontier in 1980 defined following the methodology described by Vandenbusshe.J, Aghion and Meghir (2006).[21]

$H_{i,t-1}$ measures the initial level of human capital measured as the initial level of years of schooling by adult at the beginning of the period, e.g. 1980. $\Delta H_{i,t}$ captures the accumulation of human capital over the period and is proxied by the change in average years of schooling by adult (expressed in %) between 1980 and 2010. We follow the micro-foundation of the Mincerian approach and specify the human capital variables in levels, rather than in logs. This can be rationalized by the fact that following the workhorse model of Mincer (1974) at the individual level, the aggregate Mincer equation shows that the relationship between aggregate output and human capital is log-linear.[22] By contrast, the log-log specification used by Ben Habib and Spiegel (1994)

[21] The distance to the technological frontier of a given country is defined as the difference between a country's log TFP (total factor productivity level) and that of the US in a similar spirit as Aghion and Meghir (2006). We compute log TFP as log output per adult minus log capital per adult times the capital share.
[22] The Mincer equation can be written as $\log(W_i) = \alpha + \gamma_1 S_i + \gamma_2 X_i + \gamma_3 X_i^2 + \varepsilon_{it}$ where $\log(W_i)$ is the log wage of the individual, S_i denotes individual's schooling and X_i is work experience. Rewriting the Mincer equation at the aggregate level

who found no effect of changes in education on growth relies on the hypothesis that schooling enters an aggregate Cobb-Douglas production function linearly. As emphasized by Heckman and Klenow (1998), Topel (1999) and Krueger and Lindahl (2000), the estimation of the Mincer model validates that human capital is more likely to be an exponential function of schooling in a Cobb Douglas production function. Therefore, the log-linear specification is our preferred specification.

We interact the measures of human capital stock and accumulation with the distance to technological frontier. The coefficients β_2 and β_4 will thus capture the differential effect of human capital stock and accumulation on growth depending on the level of distance to technological frontier.

Finally, $\Delta \log(L_{i,t})$ is the log change of employed population between 1980 and 2010 while $\Delta \log(K_{i,t})$ captures the log change of net physical capital stock per capita for the same period. In a Cobb Douglas economy, the estimated coefficient on physical capital accumulation in a GDP growth regression should be approximated by capital's share of national income. Therefore, β8 should be close to 0.35. Controlling for the rate of accumulation of physical capital is crucial, as some studies have demonstrated that in some specifications, the positive and significant coefficient on human capital is not robust to the inclusion of a control for physical capital (see Pritchett (1996); Cohen and Sotto (2007)). Finally, for each country, $P_{i,t-1}$ is the price level of household consumption, $GC_{i,t-1}$ is the government consumption as a share of real GDP in current PPPs and $OP_{i,t-1}$ is the openess ratio. The rich set of control variables used in our specification compared to past studies aims at controlling for potential unobserved determinants of economic growth and human capital that could bias our estimates.

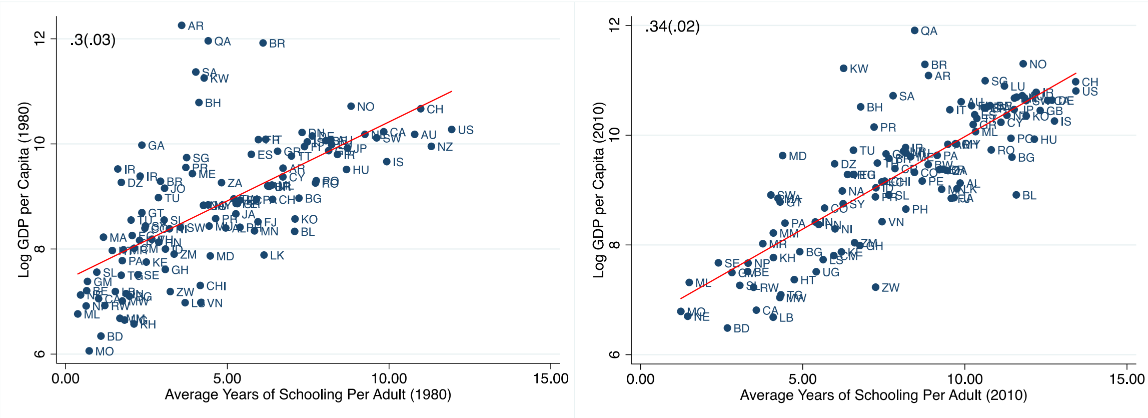
following Heckman and Klenow (1977) or Topel (1999) gives a log-linear relationship between aggregate output and average years of schooling per capita.

IV - Stylized Facts and Baseline Empirical Results

Before turning to the direct estimation of our linear baseline specification summarized by Equation (1), we leverage our dataset to describe some important and motivating stylized facts on human capital and economic growth. We start by showing the empirical relationship between our proxy of human capital and the level of GDP per capita in Figure 1 for the sample of 113 countries in our dataset. The Figure shows a strong and positive correlation between the years of schooling and the level of GDP per capita, that has been stable over time. The Figure shows an overall positive shift in the average level of schooling across countries between 1980 and 2010 that demonstrates a general improvement in educational outcomes over the past 40 years. Of course, this positive relationship is not causal, and partially loads the effects of unobserved variables that are both correlated to the level of schooling and the level of GDP. To go beyond the simple cross-country correlations showed in Figure 1, we estimate the empirical relationship described by Equation (1) and implement econometric specifications that alleviate the worries related to endogeneity of human capital.

Figure 1: Empirical Relationship Between GDP and Human Capital Stock, 1980-2010

Panel A. 1980 Panel B: 2010



Note: This Figure shows the correlation between the log GDP per capita and the human capital stock proxied by the average years of schooling in 1980 (left panel) versus 2010 (right panel). The coefficients of correlation are displayed in the Figure with robust standard errors in parentheses. The dataset is detailed in the section Data.

4.1 Linear Growth Equation

We then turn to the empirical estimation of Equation (1) and display the estimates in Table 1. We find that when combining the distance to technological frontier with the workhorse cross-country regression model, the coefficient on both the level and rate of accumulation of human capital are positive, and significant at the 1 and 10 percent level for the human capital predictors alone, and that the interaction between the rate of accumulation of human capital and distance to the technological frontier is also significant at the 5 percent level. This shows that the distance to the technological frontier significantly affects the relationship between human capital accumulation and economic growth, while cross-country differences in technology do not change the relationship between initial level of human capital stock and economic growth, as β_2 is not significantly different from zero. The fact that the interaction term β_4 is positive suggests that the effects of human capital accumulation on economic growth tend to increase with technological advancements of countries. Formally, taking the partial derivative of Equation (1), we can see that the total effect of the human capital accumulation on economic growth can only be uncovered conditionally on the value taken by $Proximity_{i,t-1}$ for each observation. For the simple case where the distance to technological frontier is zero (it is mechanically the case for the U.S), the total effect of human capital accumulation on economic growth is positive and given by β_4 alone. For countries that had a higher TFP level than the US in 1980 (and for which $Proximity_{i,t-1}$ is positive by definition), the total effect of human capital accumulation on economic growth can be recovered by taking $\beta_4 + \beta_5\, Proximity_{i,t-1}$, and is thus positive and rather large especially for countries with high levels of technological advancements. The total effect of human capital on economic growth then decreases when the proximity to the technological frontier decreases and can even be negative for some countries with very low initial level of technology.

Interacting the human capital variable with a variable capturing countries' technological advancement allows to shed light on the differential effects of human capital accumulation depending on the initial state of technology in the economy. In line with the theory laid-out by Vandenbusshe, Aghion and Meghir (2006), we find that countries with a high initial level of technology that are more likely to grow through innovation, are the countries that see the higher effects in terms of economic growth of human capital accumulation over 1980 and 2010. By contrast, our results estimate a smaller effect of human capital accumulation on growth for countries that are far from the technological frontier in 1980.

The "human capital puzzle" is thus partially solved by taking into account cross-country differences in technological advancement, and their interaction with human capital proxies. We find a significant positive effect of the initial level of human capital stock on economic growth, that is not significantly affected by the initial level of technological advancement of countries, and that is reassuringly of similar magnitude than the one estimated by previous studies.[23] We find a significantly differentiated effect of the rate of accumulation of human capital on economic growth, that suggests that changes in human capital stocks between 1980 and 2010 had higher effects on growth per capita over the same period in countries that had the higher initial level of technology in 1980. By contrast to other studies, our results are robust to controlling for changes in physical capital. In addition, we find a coefficient on physical capital accumulation that is economically consistent, and close to capital share estimates, which confirms the accuracy of our analysis.

[23] To compare our results to the past literature, it is necessary to note that we do not present our results in in terms of annualized changes, but in terms of overall changes between 1980 and 2010, expressed in percentage terms.

TABLE 1 – Linear estimation of growth regression, 1980-2010

VARIABLES	(1) Growth of real GDP per capita
Proximity	-0.956***
	(0.226)
H_{t-1}	0.0640***
	(0.0237)
H_{t-1} x Proximity	-0.0258
	(0.0248)
ΔH_t	0.00154*
	(0.000823)
ΔH_t x Proximity	0.00122**
	(0.000524)
$\Delta log L_t$	0.331***
	(0.114)
log(GDP/capita)	0.444***
	(0.123)
Price level of consumption	-0.151
	(0.253)
$\Delta log K_t$	0.334***
	(0.0388)
Gvtcons	-0.371
	(0.339)
Openess	0.0354
	(0.0667)
Constant	-6.290***
	(1.292)
Observations	108
R-squared	0.684

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Note : This Table shows OLS estimates of equation (1). The dataset used for the estimation is built from the Summer and Heston Penn World Tables, and Barro and Lee (2010) dataset for educational attainment. Data appendix gives more detailed information for each variable included in the estimation. The dependent variable in the change in log real GDP per capita for the period 1980-2010. Ht−1 is the initial level of schooling, proxied by the average years of schooling per adult, and ∆Ht is the percentage change in schooling between t-1 and t. Proximity refers to the proximity to the technological frontier, and the computation of this variable is detailed in Data appendix. ∆logLt is the log change of the employed population during 1980-2010, and ∆logKt is the log change of net physical capital stock for the same period. Finally, log(GDP/capita) refers to the initial level of real GDP per capita expressed in logarithm, Gvtcons is the government consumption in PPP's as a share of GDP during the period, price level of consumption is the price level of household consumption for the period, and openness is the openness ratio of the country (see computation in appendix). Robust standard errors are showed in parentheses.

4.2 Structural Equation

The results of the estimation performed in Equation (1) shows that taking into account potential differentiated effects of human capital accumulation on per capita growth yields positive and significant effects of human capital changes on growth for countries with high level of initial technological advancement. If our regression approach includes a large number of control variables that allow to partially alleviate the endogeneity concerns related to unobserved variables that could be correlated with both economic growth and human capital proxies, such factors could still bias our estimates. Another important concern relates to reverse causality: if human capital accumulation could cause economic growth, economic growth could also cause human capital accumulation for instance through more investment in education, and would in turn bias our estimates.

To address the endogeneity of the human capital variable, we now turn to a more structural approach. One way to deal with this endogeneity could be to use instrumental variables through 2SLS estimation. However, implementing efficiently such estimation rely on our ability to find a good instrument, meaning a country-level variable that would be correlated to the changes in human capital accumulation (relevance) and would be uncorrelated to economic growth (exogeneity). Finding such instrument seems challenging, especially because the exogeneity assumption is ultimately untestable.[24] We believe that using a more structural approach, such as the simultaneous equations model ("SEM" henceforth), presents two main advantages. The first advantage is that SEM allows to better take into account reverse causality and simultaneous bias than the IV, because the simultaneity is explicitly expressed in the system of equation. In particular, we believe that our linear equation (1) should be thought of as part of a system of simultaneous macroeconomic equation that jointly determine both economic growth and our endogenous variables (accumulation of human capital and physical capital). Estimates are therefore more efficient if all equations are estimated together because joint estimation takes into account the correlation between the error terms. The second advantage of SEM is that the issue of understanding the effects of human capital accumulation on economic growth is directly linked to the study of human capital accumulation determinants at the aggregated level. SEM allows directly writing and estimating the human capital accumulation equation in the data. We propose an attempt to write and estimate an aggregate equation of human capital accumulation.

We model a system of equations for economic growth where accumulation of human capital is also caused by economic growth, and where accumulation of physical capital is allowed to be endogeneous. We use exogeneous variations to identify our system of equations, e.g variables that only appear in one equation of the system. To implement this analysis, we collect various additional variables that are not included in our initial dataset. We use a measure of average wages from the OECD Taxing Wages Database, measures of real and lending interest rates from the World Bank Database and measures from the quality of institutions from a new database built by Kucik (2014). We further complement the measure of human capital accumulation with data on the quality of human capital that is proxied by the international tests and collected from Hanushek and Wossman. The diversity of the control variables that we are able to leverage in order to model and estimate a system of simultaneous equations that tackle the endogeneity of human capital accumulation comes at the cost of a much lower number of observations, and leads us to focus on a sample of advanced economies for which these variables are available and comparable.

[24] See Young (2020) for a discussion on biases generated by IV regressions compared to standard OLS specification.

Growth of GDP per Capita Equation

We express economic growth as the log change in real GDP per capita as a function of the initial log GDP per capita following the growth equation model presented in section 2 and a set of macroeconomic variables. We now allow the accumulation of both human and physical capital to be endogenous. We add to the list of explanatory variables lending and real interest rates over the period, as these variables may explain part of real GDP per capita changes. We also control for the quality of institutions that may be significant predictors of economic growth as showed by the contributions of Acemoglu and Robinson (2005).

Human Capital Accumulation Equation

The human capital accumulation is now explicitly expressed as endogenous in our model. To address simultaneity, we model human capital accumulation as a function of GDP per capita growth, and initial level of schooling that is also included in the determinants of economic growth. This is because the change in schooling is likely to be jointly determined by economic growth that can for instance affect expected returns of human capital for individuals. Because the change in years of schooling is also likely to be affected by the abundance of labour factor, that is to say by the increase in the working age population, we also include population growth as an explicative variable of our human capital accumulation model.

Our equation of aggregated human capital accumulation is both micro and macro founded. We rely on the microeconomic literature in several ways. First, following Becker (1964), Mincer (1974) and Ben-Porath (1967), we expect that human capital accumulation will depend on interest rates and net average wages. This is because individuals decide to invest in education if the expected returns of their investment in human capital are higher than its cost. We proxy the expected return of human capital at the country-level by the net average wage and the wage share during the period. We control for interest rates to proxy for the opportunity cost of human capital investment e.g forgone earnings that an individual could have learned if he had invested in money or assets rather than its education. Interest rates also affect human capital accumulation through lending and credit constraint channels, as emphasized by Heckman and Hai (2016). We finally control for the quality of human capital through a control for cognitive scores, that also follows the microeconomic literature. Cunha, Heckman et al (2005) have for instance emphasized the importance of cognitive ability in the individual accumulation of human capital, finding that roughly one third of individual education attainment can be explained by their measure of cognitive and non cognitive skills. As cognitive ability seems to matter at the individual level, we therefore expect that at the aggregate level, cognitive scores at the country-level will significantly impact national accumulation of human capital.

Physical Capital Accumulation Equation

We finally model the physical capital accumulation which is a function of GDP per capita growth as described by the standard growth model. Because expected returns of capital is determined by interest rates, we control for real interest rates over the period. In addition, we add as control variables the depreciation rate of the physical capital stock and investment measures including the share of gross capital formation, the price level of capital formation and the price level of capital stock, as all of these factors will affect past and future returns of capital. Finally, we also model the capital accumulation as a function of the technological frontier, as the theory hinges on the fact that the overall level of technology in one country will impact potential investment and therefore physical capital accumulation.

$$\Delta logy_t = \alpha_0 + \beta_0 Proximity + \beta_1 H_{t-1} + \beta_2 H_{t-1} * Proximity + \beta_3 * \Delta H_t + \beta_4 * \Delta H_t * Proximity$$
$$+ \beta_5 \Delta logL_t + \beta_6 logy_{t-1} + \beta_7 P_t + \beta_8 \Delta logK_t + \beta_9 Gvtcons + \beta_{10} Openess + \beta_{11} Real_t +$$
$$\beta_{12} Lending_t + \varepsilon_{it}$$

$$\Delta H_t = \delta_0 + \delta_1 H_{t-1} + \delta_2 logL_t + \delta_3 Lending_t + \delta_4 Top + \delta_5 Cognitive + \delta_6 WageShare$$
$$+ \delta_7 \Delta logy_t + \delta_8 NetAverageWage + \epsilon_{it}$$

$$\Delta logK_t = \sigma_0 + \sigma_1 \delta_{capital} + \sigma_2 \frac{FBCF}{GDP} + \sigma_3 P_{FBCF,t} + \sigma_4 Real_t + \sigma_5 Proximity + \sigma_6 \Delta logy_t + u_{it}$$
(2)

We present the estimates of the structural model in Table (2). Because of the significant data work that requires to merge several datasets from various sources, the sample of estimation is significantly trimmed compared to our baseline linear regression and is restricted to 22 OECD countries. However, for the set of countries for which we can model the simultaneous system equation, we find that both human capital level and accumulation have a positive and significant effect on long-term growth of GDP per capita. The magnitude of the coefficients is roughly similar to the standard linear regression thus indicating the robustness of the estimates. The interaction between human capital accumulation and technological frontier is still positive but is not statistically significant anymore, suggesting that the interaction effect of the first specification has been captured by the selected estimation sample of Table 2. The estimates indicate that for a country at the frontier, increasing by one unit (in percentage point) the rate of human capital accumulation between 1980 and 2010 is associated with a change in GDP growth by 0.6 percent. The estimated coefficient of human capital accumulation is higher than the one estimated with the linear specification, reflecting that the empirical relationship between human capital accumulation and economic growth is larger for the set of countries that are included in our sample of estimation for the simultaneous equation model, and after accounting for endogenous determinants of growth. Table 2 shows that even after controlling for potential endogeneity in the human capital accumulation process, we still find a positive and significant effect of changes in years of schooling per adult on economic long-term growth. Regarding other variables, we find that the coefficient estimated for physical capital accumulation is still very close to the capital share, indicating that our results are economically consistent and robust across specifications, even after controlling for potential endogenous capital accumulation. For robustness check, we include in our final specification a control for the quality of institutions (see the seminal contribution of Acemoglu and Robinson on this topic). We use the new dataset on institutions quality built by Kuncic (2014) that assembles more than thirty institutional indicators. We use the aggregation of these indicators to proxy for the overall quality of political, economic and legal institutions in our specification. Results showed in Table 4 indicate no changes in our estimates from this additional control. Therefore, even after controlling for the quality of institutions, a variable that may be correlated with education choices and economic growth, we still find a positive and significant relationship between human capital accumulation and long-term economic growth per capita.

Overall, the estimation of the simultaneous equation model allows to control for potential endogeneity in the variables of interest used in our linear regression model. We find that after accounting for potential endogeneity bias through this model, the effect of human capital accumulation on economic growth is still positive and significant.

TABLE 2 – Simultaneous Equation Model for Economic Growth, 1980-2010

VARIABLES	(1) Growth of real GDP per capita	(2) ΔH_t	(3) $\Delta logK_t$
Proximity	0.0323		-0.243
	(1.042)		(0.468)
H_{t-1}	0.0849***	-9.824***	
	(0.0256)	(1.323)	
H_{t-1} x Proximity	-0.0671		
	(0.124)		
ΔH_t	0.00635***		
	(0.00228)		
ΔH_t x Proximity	0.00341		
	(0.00743)		
$\Delta logL_t$	0.351***	-30.76*	
	(0.120)	(15.96)	
log(GDP/capita)	0.0522		
	(0.336)		
Price level of consumption	0.727***		
	(0.282)		
$\Delta logK_t$	0.395***		
	(0.0957)		
Gvtcons	-1.080		
	(0.840)		
Openess	0.0800		
	(0.0667)		
Real interest rate	-0.00262		-0.0217
	(0.00635)		(0.0253)
Lending interest rate	0.0193**	-0.506	
	(0.00835)	(0.595)	
Top		127.7	
		(27.02)	
Cognitive		-63.12**	
		(27.07)	
Wage share		99.72*	
		(51.73)	
Growth of real GDP per capita		-25.91	0.800
		(17.80)	(0.627)
Average net wage		13.12	
		(10.36)	
Depreciation rate of physical capital			12.75
			(12.05)
Share of gross capital formation			-1.575
			(1.111)
Price level of capital formation			4.930**
			(2.244)
Price level of capital stock			-4.663***
			(1.703)
Constant	-3.445	248.4*	4.722***
	(3.746)	(134.5)	(0.781)
Observations	22	22	22
R-squared	0.668	0.814	0.412

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 3 – Simultaneous Equation Model for Economic Growth, 1980-2010

		(1)	(2)	(3)
VARIABLES		Growth of real GDP per capita	ΔH_t	$\Delta logK_t$
Proximity		0.00377		
		(1.023)		
H_{t-1}		0.0922***	-9.698***	
		(0.0254)	(1.329)	
H_{t-1} x Proximity		-0.0416		
		(0.124)		
ΔH_t		0.00623***		
		(0.00213)		
ΔH_t x Proximity		-0.000151		
		(0.00755)		
$\Delta logL_t$		0.371***	-29.18*	
		(0.116)	(16.01)	
Institutions		-0.00419		
		(0.00372)		
log(GDP/capita)		-0.0609		
		(0.358)		
Price level of consumption		0.791***		
		(0.278)		
$\Delta logK_t$		0.425***		
		(0.0924)		
Gvtcons		-1.055		
		(0.816)		
Openess		0.0489		
		(0.0698)		
Real interest rate		-0.00126		-0.00674
		(0.00639)		(0.0211)
Lending interest rate		0.0224***	-0.517	
		(0.00829)	(0.598)	
Top			134.2	
			(132.7)	
Cognitive			-64.69**	
			(27.16)	
Wage share			105.0**	
			(51.96)	
Growth of real GDP per capita			-25.01	
			(17.65)	
Average net wage			11.84	
			(10.34)	
Depreciation rate of physical capital				15.64
				(12.44)
Share of gross capital formation				-1.611
				(1.163)
Price level of capital formation				6.762***
				(2.137)
Price level of capital stock				-6.174***
				(1.704)
Constant		-2.507	263.6*	4.905***
		(3.915)	(135.7)	(0.806)
Observations	15	22	22	22
R-squared		0.668	0.814	0.363

V - Conclusion

We aim to investigate and discuss the effects of the level and accumulation of education on countries' output. We know that the impact of quality of human capital is more and more investigate but our first step was to overcome the "human capital puzzle" by the introduction of the technological frontier as defined by Vandenbusshe, Aghion and Meghir (2006).

We find that when combining the distance to technological frontier and the workhorse cross-country regression model, the coefficient on both the level and rate of accumulation of human capital are positive, and significant at the 1 and 10 percent level for the human capital predictors alone, and that the interaction between the rate of accumulation of human capital and distance to the technological frontier is also significant at the 5 percent level. This shows that the distance to the technological frontier significantly affects the relationship between human capital accumulation and economic growth, while cross-country differences in technology do not change the relationship between initial level of human capital stock and economic growth. Moreover, the effects of human capital accumulation on economic growth tend to increase with technological advancements of countries. The "human capital puzzle" is thus partially solved by taking into account cross-country differences in technological advancements, and their interaction with human capital proxies.

On our econometric results, the significant positive effect of the initial level of human capital stock on economic growth is not significantly affected by the initial level of technological advancement of countries, and that is reassuringly of similar magnitude than the one estimated by previous studies. We find a significantly differentiated effect of the rate of accumulation of human capital on economic growth, that suggests that changes in human capital stocks between 1980 and 2010 had higher effects on growth per capita over the same period in countries that had the higher initial level of technology in 1980. By contrast to other studies, our results are robust to controlling for changes in physical capital. In addition, we find a coefficient on physical capital accumulation that is economically consistent, and close to capital share estimates, which confirms the accuracy of our analysis.

To address the endogeneity of the human capital variable, we turn toward a simultaneous equations model (SEM) where accumulation of human capital is also caused by economic growth, and where accumulation of physical capital is allowed to be endogenous. Despite a less complete datasets (fewer countries), the both human capital level and accumulation have a positive and significant effect on long-term growth of GDP per capita. The estimated coefficient of human capital accumulation is higher than the one estimated with the linear specification, reflecting that the empirical relationship between human capital accumulation and economic growth is larger for the set of countries that are included in our sample of estimation for the simultaneous equation model, and after accounting for endogenous determinants of growth.

We built an equation to explain the capital human equation based on the microeconomic and macroeconomic review of literature. Even if our new database has begun to make easier to introduce a variable of human capital quality equation, the results lead us to continue our statistical and econometric investigations towards a microdata methodology. Our research agenda aims at investigating the relationship between human capital and economic development at a more granular level. In particular, in a future paper, we will measure investment in human capital at the firm level with a novel database on companies to measure empirically how it relates to firms' performance.

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Appendix: Data description and definition

Physical capital stock

The measure of physical capital stock in the PWT that we use in our analysis is built through the perpetual inventory methodology. The methodology uses an initial physical capital stock and adds investment flows net of capital depreciation. The PWT dataset from Summer and Heston take into account differences in investment composition across countries. The PWT database considers 6 different types of assets in investments. For each country, investment flows are decomposed between these 6 asset classes from national account data and EU-KLEMS and ECLAM databases. For countries with missing information, the commodity flow method is applied, which makes the assumption that investment in one asset class varies at the same rate of the supply of this asset in the national economy. After this first step, investment flows are deflated with data based on EU-KLEMS, OECD National Accounts and ECLAC. The PWT estimate the initial capital stock with a formula that relates initial investment, investment growth rate at the steady state and the depreciation rate of capital. This therefore requires the assumption that all countries are the steady state at the initial period. With this methodology, the physical capital stock each year is then computed as the capital stock of last period net of depreciation rate of capital and increased by the investment flows observed for the same period. This capital stock is then divided by the deflator to be measured in constant prices.

Depreciation rate of physical capital stock

The rate of capital depreciation used in the analysis are the official depreciation rates used by the BEA with a methodology described in Fraumeni (1997). The methodology relies on assuming a geometric depreciation rates to compute rates of depreciation for capital by asset classes.

Real GDP

Real GDP from the PWT used in the analysis is computed with two main methodologies: the expenditure approach and the output approach. The PWT also provides a real GDP measure from national accounts in constant price of 2005. We use the latter measure, as it is the standard and pure measure of GDP that is not affected by computations of the authors. Summer and Heston in particular indicate that this measure is also the more consistent to take into account GDP growth rates in cross-country growth regressions. We compute GDP per capita by dividing the measure of real GDP by the measure of the population that is also provided by the PWT database.

Our dependent variable approximates GDP growth using log transformation. The GDP per capita growth is therefore computed as the log difference between the GDP per capita of t+1 and t.

Proximity to the technological frontier

We compute the proximity to the technological frontier as the difference between the log of TFP in this country in 1980 and the log of TFP in the US the same year, following the methodology of Aghion and al (2006). This variable is thus 0 by construction for the US. Log of TFP is computed following a standard growth accountting methodology that takes the log of GDP per capita minus the log of physical capital stock multiplied by the capital share in the economy.

Openess ratio

This variable is built by using the measure of the share of imports and exports in countries' GDP. We add these two variables in absolute value to obtain the share of imports and exports in total GDP.

Government consumption

This variable measures the share of government spending in total GDP expressed in current prices. Government spending are taken from national accounts.

Price level of household consumption

This variable from the PWT on the price level of household is based on national accounts and takes the USA in 2011 as 1 for reference.

Human Capital Stock

Our measure of human capital stock comes from the Barro and Lee database on initial education levels across countries. We proxy the human capital stock by the number of years of schooling per adult.

Human Capital Accumulation

We measure human capital accumulation as the percentage change in the human capital stock between two periods. The human capital accumulation variable is the rate of variation in percent between the two periods.