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Technological Progress and Growth in Selected Pacific Countries

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Abstract

This paper assess the sources of technological progress that determined GDP and labor productivity growth across a group of leading Pacific economies – Australia, Japan, South Korea, and the U.S. – during the period 1980-2006. We consider three alternative sources of technological progress: disembodied and factor-embodied technical change to capital and labor. The contribution to growth of each of these sources is evaluated using both traditional and equilibrium growth accounting procedures. We find that capital accumulation is the main determinant of GDP growth in Australia, Japan and the U.S., whereas the main contribution in South Korea is given by Total Factor Productivity (disembodied technology). In all the considered economies, about half of the contribution to growth of capital-embodied technical change comes from Information and Communication Technologies.

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1 Introduction

Technological progress is a key factor driving the growth of output and labor productivity. Starting from the seminal neoclassical growth theory, a large branch of theoretical and empirical literature investigated how technical change determines economic growth, reaching a wide consensus about its primary importance for growth in contemporaneous economies. Along this line of research, we analyze more in details the effect of technology on growth by identifying different origins of technological progress and assessing which of them mostly affect and determine the growth rate of output and labor productivity. As a matter of fact, the primary sources of technological progress are various and heterogenous. Technical change may occur as neutral progress, investment-specific progress, or labor efficiency progress. While the first is intended as improvements in multifactor productivity, e.g. improvements in business organization or in institutional factors,[1] the second represents improvements in the efficiency of capital due to the technical innovations embodied in new capital assets. Finally, the third form of progress refers to every possible sources of improvement in the efficiency of labor services, e.g. an higher fraction of skilled workers, learning-by-doing tasks, an enhanced accumulation of common productive knowledge in the society (social capital). We refer to all these types of labor efficiency progress as the accumulation of human capital embedded in workers. It is worth underlying that this paper does *not* aim at developing a new theory of human capital, but rather to account for the effect of human capital on labor services. We therefore treat the level of human capital as exogenous to agents' decisions and we incorporate it in the model as technical change embodied in labor.

Although a large branch of literature emphasized the importance of human capital as source of output and productivity growth,[2] still growth decomposition exercises rarely account for the effect of human capital improvement on the efficiency of labor services [henceforth, HCI], thus imputing to Total Factor Productivity [henceforth, TFP] its contribution to growth. In our opinion, such miscalculation is not a minor issue because, insofar as the policies targeted to TFP improvements are different from the ones targeted to human capital enhancements, it has costly implications for the policy maker. To overcome this issue, we propose a simple way to incorporate HCI into both the traditional growth accounting and equilibrium models. A process for HCI is extracted from data on productivity and quality of labor services following the approach of Jorgenson, Gallop, and Fraumeni (1987). Then, the growth of HCI this process is accounted for as extra source of

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[1] In the rest of the paper we refer to this source indistinctly as *disembodied* or *neutral* technical change.

[2] There is a countless literature on the importance of human capital as determinant of growth, starting with the seminal works of Schultz (1961) and Becker (1964), among others.

technical change in the models.

About capital-embodied technical change, or investment-specific technical change [henceforth, ISTC] as it is usually referred to, we isolate it and account for its effect on growth by extracting a process of ISTC from data on quality-adjusted prices of investment. As in Greenwood, Hercowitz and Krusell (1997), a decrease of the quality-adjusted price of investment is interpreted as a technical innovation that lowered the average cost of producing that investment good with respect to the cost of producing consumption goods. Data on quality-adjusted prices of investment are constructed combining the information contained in EU KLEMS database[3] with the series of quality-adjusted prices for U.S. investment aggregates constructed by Cummins and Violante (2002) up to year 2000. For present analysis, we the series of Cummins and Violante are first extended to the period 2000-2006, and then employed to obtain their counterparts for Australia, Japan, and South Korea using the methodology of Schreyer (2002).[4] To scrutinize the marginal effect of each investment asset, we compute ISTC processes for each asset category given in the EU KLEMS database, namely: (i) hardware, (ii) software, (iii) communication equipment – these three typically referred to as Information and Communication Technology [henceforth, ICT] equipment –, (iv) transport, (v) machinery and (vi) other equipment – traditional assets or non-ICT equipment –, and (vii) structures. Technical change turns out to widely differ among these categories: ICT assets have bolstered productivity more effectively than earlier technologies, and have had a definite impact on the economy. Numerous studies have pointed to the special role played by these technologies in the recovery of productivity growth since the mid-1990s in the United States and some European countries (see among others Colecchia and Schreyer, 2001; Stiroh, 2002; Timmer, Ypma and van Ark, 2003-2005).

Finally, once we identified technical change embodied in factors (ISTC and HCI), we use two different approaches to estimate the disembodied one: (i) the traditional growth accounting decomposition and (ii) a calibrated general equilibrium model. There is a long-standing debate in the literature about which of these two approaches better identifies the determinants of growth, e.g. Greenwood, Hercowitz and Krusell (1997), Hulten (1992), Oulton (2007), Greenwood and

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[3] All details about EU KLEMS project can be found at `http://www.euklems.net`.

[4] In fact, the EU KLEMS database uses Schreyer's methodology to construct quality-adjust prices of ICT equipment starting from the corresponding NIPA prices. However, EU KLEMS only adjusts for quality the series of ICT prices. We use Cummins and Violante data to adjust for quality also the prices of traditional assets (non-ICT equipment and machinery). The resulting up-to-date series of quality-adjusted prices for all EU KLEMS asset categories is a key contribution of our paper. It is worth noting that if only quality-adjusted ICT prices are used, then growth accounting exercises tend to overweight the importance of ICT as a factor of growth behind the 1995 U.S. productivity growth upsurge (see, for example, Collechia and Schreyer, 2001; Jorgenson and Stiroh, 2000).

Krusell (2007). We take a neutral stance in this debate by performing our analysis using both approaches. For the traditional growth accounting, we estimate the three mainstream versions of it: the traditional one proposed by Solow (1956), the one suggested by Jorgenson (1966) and the later refinement put forward by Hulten (1992). Regarding the general equilibrium approach, we use an extension of the model developed in Rodríguez-López and Torres (2012) that accounts for multiple capital assets, idiosyncratic ISTC processes to each capital, and finally for the effect of HCI on labor services.

Our main result is that the growth rate of output has a similar composition in Australia, Japan and the U.S., while it has an opposite composition in South Korea. We find that factors accumulation explains about 60-70% of output growth in Australia, Japan and the U.S., whereas technological progress explains about 30-40%. In the case of South Korea, factors accumulation only explains approximately 36% of output growth, while technology explains 64%. We show that this difference is explained by the neutral technical change. Whereas in the three developed countries, TFP contribution to output growth is close to zero or even negative (with Hulten's decomposition), in South Korea neutral technology alone explains approximately 40% of output growth, being the most important determinant of growth in that country. This finding bring evidence to support the theory of TFP as indicator of institutional factors, whose effect on growth is saturated in developed economies, but still strong in developing economies. Similar results are obtained in terms of labor productivity growth. The general equilibrium approach confirms these results, showing that in Australia, Japan and the U.S. the main factor of labor productivity growth in the long-run is ISTC. In the case of South Korea the main contribution comes from TFP, followed by human capital. Additionally, we obtain that TFP contribution to productivity is positive for South Korea and Japan, but negative for the U.S. and Australia. Getting to a more detailed analysis, we show that ISTC contribution to growth is similar in Japan and South Korea, 0.79 and 0.70 percentage points, respectively, 0.96 percentage points in Australia and 1.09 percentage points in the U.S. However, using the Jorgenson (1966) approach, the larger contribution to output growth from ISTC corresponds to South Korea (0.71 percentage points), whereas for the other three countries the contributions is lower (0.58 for Australia, 0.46 for Japan and 0.49 for the U.S.). The differences between the two approaches are explained by the much higher capital investment process in South Korea compared to the other countries.

The reminder of the paper is structured as follows. Section 2 presents a growth model with several types assets of capital with different levels of technology embedded. Section 3 introduces the different statistical growth accounting approaches. Section 4 describes the data set and the logic of the calibration. Estimates of the contribution to output and labor productivity growth are presented in Section 5. Finally, Section 6 summarizes and concludes.

2 Data

Although it was originally created to keep track of economic growth in European countries, the EU KLEMS Database reports data on several non-European countries. In particular, we use it to collect Australian, Japanese, South Korean, and U.S. data on nominal output and productive factors compensations, on the amount (measured as total worked hours) and quality of labor services, and finally on nominal investment in physical capital break up in seven categories: (i) hardware and office equipment, (ii) communication equipment, (iii) software, (iv) transport equipment, (v) machinery, (vi) other equipment, (vii) structures. Data on investment are then used to construct the series of capital stock by the mean of the permanent inventory method.

[Insert here Table 1]

The upper panel of Table 1 reports the mean value over the period 1980-2006 of annual growth rates for the set of considered variables. The average growth rate of real output has been fairly similar across Australia, Japan, and the U.S. (around 3%), while it has been sensibly higher in the case of South Korea (approximately 7.70%). This higher rate in South Korea went along with an enhanced accumulation of physical capital, which has grown almost three times faster than in the other three countries, i.e., 8.2% on annual basis against around 3.5%. The growth of labor appears more stable over the period, with a similar 1.5% annual increase of worked hours in U.S., Australia, and South Korea. Japan constitutes an exception, showing a negative average growth rate in the considered period (column 3).[5] The growth rate of labor productivity has been similar in Australia and U.S., but relatively higher in South Korea and Japan, in the first case clearly due to the enhanced growth of output, and in the second case to the negative growth of labor.

The lower panel of Table 1 reports the averaged annual growth rate of technological progress in human and physical capital. The index of Human Capital Improvement [henceforth, HCI] is constructed using the Jorgenson, Gollop and Fraumeni (1987) approach. This index measures improvements in the productivity of labor services due to higher or better quality of human capital

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[5] A detailed analysis about the behavior of worked hours in Japan can be found in Hayashi and Prescott (2002).

embedded in workers. Its advantage with respect to other measures of human capital is that it washes out any effect of labor composition from the measure of HCI. This result is achieved by splitting the labor force into different clusters according to its educational attainment, age, industry, and gender, and then following the evolution of labor quality in each cluster separately. All the information needed to pursue the Jorgenson et al. approach are provided in EU KLEMS database. During the considered period, we find that the average annual growth rate of HCI in South Korea has been of 1.53%, indicating a strong rise in labor efficiency. Australia and Japan show a similar pattern of HCI, with an average annual growth rate of 0.70%, while U.S. shows a significantly lower growth rate (0.30%), which is possibly explained by an higher initial level of HCI to which the other countries have been converging.

To pin down the growth rate of technical change embodied in capital, we construct a series of ISTC using data on quality-adjusted prices of investment. As in Greenwood, Hercowitz and Krusell (1997), a variation in the real price of quality-adjusted investment goods is interpreted as a technology improvement specific to that good, which affects its average cost of production. EU KLEMS does not provide all the information to construct the ISTC because it only reports data on quality-adjusted prices for ICT assets but not for non-ICT assets. To overcome this issue, we combine EU KLEMS data with the series of quality-adjusted price of equipment and machinery provided by Cummins and Violante (2002) for the U.S. Using a Törnqvist index weighted with nominal investment shares, Cummins and Violante data are first extended to our sample interval, and then used to construct i category-specific annual deflator indexes for the U.S., $q_{i,t}^{US}$, one for each category of nominal investment present in EU KLEMS. Finally, similar harmonized deflator indexes for Australia, Japan, and South Korea are obtained applying the Schreyer's (2002) methodology to U.S. data.[6] ISTC are finally obtained using the expression $Q_{i,t}^{j} = PC_t / q_{i,t}^{j}$ for $i \in \{1, \ldots, 7\}$ and $j \in \{Australia,\ Japan,\ South\ Korea,\ U.S.\}$, where PC_t is the price index for consumption of non durables and services less housing, and $q_{i,t}^{j}$ are the quality-adjusted price indexes. This expression represents the amount of capital that can be purchased by one unit of output at time t, and we interpret an increase of $Q_{i,t}^{j}$ as a positive technology innovation that reduces the average cost of production of investment good i expressed in units of consumption good. We assume that all assets *but structures* are subject to efficiency improvements from ISTC, i.e., $Q_{str,t}^{j} = 1$ for $\forall\ t, j$. As in the case of HCI, the annual growth rate of ISTC also exhibits significant differences across countries. It is higher in U.S. and Australia (above 3% on average), and lower in South

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[6] A detailed explanation of the construction of series can be found in the technical Appendix of this paper. A similar application of the Schreyer's methodology to obtain harmonized deflators is given in Basu, Fernald, Oulton and Srinivasan (2003), who compare the evolution of productivity in U.K. and U.S.

Korea and Japan (2.4% and 1.95%, respectively). While it is reasonable to expect a lower figure in South Korea as compared to the U.S. one, such low number for Japan comes at a surprise. By analyzing the composition of capital, however, we find that the fraction of traditional capital assets (non-ICT) over total assets is sensibly larger in Japan than in the other countries, which could explain the lower aggregate figure, given that the technical change associated with non-ICT assets is typically lower than that of ICT.

3 Growth Decomposition

The first and still widely employed methodology to study the determinants of output growth is the Traditional or Statistical Growth Accounting.[7] This approach identifies the unobservable contribution of technological progress to growth as the unexplained residual of actual output growth rate after controlling for the growth rates of production factors. In other words, the observed growth of output is either imputed to the increasing amount of factors employed in production, or to the development of better technologies to produce. A subsequent literature, starting with the seminal paper of Greenwood et al., proposed to use the general equilibrium growth model to obtain a structural decomposition of growth. It argued that there are several advantages in pursuing this approach against the traditional growth accounting method. First, the general equilibrium growth model is the workhorse of modern economics and the accepted paradigm for studying most macroeconomic phenomena. Second, it provides a growth decomposition which is consistent with an optimization based model. Third, it features several desirable properties in accordance with the predictions of economic theory, like yielding a balanced growth path and having the property that only technological progress explains labor productivity growth in the long run. As pointed out by Greenwood et al. and Cummins and Violante, this last property better fits the determinants of productivity growth in the long-run, given that part of the observed growth in capital is the result of technical change and therefore endogenous.

3.1 Statistical Growth Accounting

In this paper we employ three versions of the traditional or statistical growth accounting approach: (i) the original one developed by Solow (1956), (ii) the refinement of that theory proposed by Jorgenson (1966), and (iii) the subsequent refinement of Hulten (1992). Jorgenson criticized Solow's theory on the ground that it considers only TFP as source of technical change, thus

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[7] The term *traditional or statistical* to refer to Solow-alike Growth Accounting method was firstly used in Cummings and Violante.

neglecting efficiency improvements in capital assets due to investment-specific technical change. He argues that Solow erroneously accounted ISTC as neutral technology, thus distorting the true dynamics of TFP. Later on, Hulten (1992) proposed a refinement of Jorgenson's approach to better identify the contribution of ISTC to growth. We employ two extended versions of Jorgenson's and Hulten's theories that incorporate the observed progress in human capital as additional source of growth. Specifically, we add an extra term to their Growth Accounting equations to capture the efficiency improvement of labor services generated by the accumulation of human capital embedded in workers. We leave the original Solow's method untouched, and we use it as benchmark to identify the effect on growth of factors-embedded technological progress.

According to Solow (1956), the (log of) actual growth rate of output, labeled γ_Y, can be decomposed into:

$$\gamma_Y = \underbrace{\gamma_A^S}_{\text{Neutral}} + \underbrace{\textstyle\sum_i v_i \gamma_{K_i}}_{\text{Capital accumulation}} + \underbrace{v_l \gamma_L}_{\text{Labor accumulation}} \tag{1}$$

where γ_{K_i} is the growth rate of capital K_i, γ_L is the growth rate of worked hours L_t, and A_t is the Total Factor Productivity [henceforth, TFP or Solow's residual]. The coefficient γ_A^S thus measures the contribution of neutral technology to output growth as identified by Solow. The weights v_i are the elasticities of output with respect to capital asset i, usually measured as the ratio of the marginal to the average product of capital, and v_l is the elasticity of output with respect to labor measured as the ratio of the marginal to the average product of labor. Using the same approach, the (log of) growth of labor productivity, $\gamma_{\frac{Y}{L}}$ labeled g, can be decomposed as follows:

$$\gamma_{\frac{Y}{L}} \equiv \gamma_Y - \gamma_L = \underbrace{\gamma_A^S}_{\text{Neutral}} + \underbrace{\textstyle\sum_i v_i \left(\gamma_{K_i} - \gamma_L\right)}_{\text{Capital deepening}} \tag{2}$$

where the second equality uses the fact that $v_l = 1 - \sum_i v_i$.[8]

Our version of Jorgenson's (1966) approach explicitly takes into account the existence of both ISTC and enhanced human capital [henceforth, HCI] that improve the efficiency of, respectively, capital and labor services. Accordingly, output growth is decomposed into:

$$\gamma_Y = \underbrace{\gamma_A^J}_{\text{Neutral}} + \underbrace{\textstyle\sum_i v_i \gamma_{K_i}}_{\text{Capital accumulation}} + \underbrace{\textstyle\sum_i z_i \gamma_i}_{\text{ISTC}} + \underbrace{v_l \gamma_L}_{\text{Labor accumulation}} + \underbrace{v_l \gamma_H}_{\text{HCI}} \tag{3}$$

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[8] We restrict our analysis to the case of constant returns to scale which implies that the sum of ratios of the marginal to the average product of capitals plus the one of labor must sum to one, i.e. $v_l + \sum_i v_i = 1$.

where γ_A^J is the neutral technological progress as defined by Jorgenson and γ_i is country-specific growth rate of ISTC in capital i. The weights z_i measure the ratio of nominal investment in asset i to nominal GDP. Similarly, labor productivity growth is decomposed as follows:

$$\gamma_{\frac{Y}{L}} \equiv \gamma_Y - \gamma_L = \underbrace{\gamma_A^J}_{\text{Neutral}} + \underbrace{\textstyle\sum_i v_i \left(\gamma_{K_i} - \gamma_L\right)}_{\text{Capital deepening}} + \underbrace{\textstyle\sum_i z_i \gamma_i}_{\text{ISTC}} + \underbrace{v_l \gamma_H}_{\text{HCI}} \tag{4}$$

Finally, Hulten (1992) argued that technical innovations as the ones which are usually referred to as ISTC in the literature, would ideally affect the whole stock of capital and not just new investments, and their contributions to growth should therefore be weighted accordingly. As a result, in our version of Hulten approach output growth is decomposed into:

$$\gamma_Y = \underbrace{\gamma_A^U}_{\text{Neutral}} + \underbrace{\textstyle\sum_i v_i \gamma_{K_i}}_{\text{Capital accumulation}} + \underbrace{\textstyle\sum_i v_i \gamma_i}_{\text{ISTC}} + \underbrace{v_l \gamma_L}_{\text{Labor accumulation}} + \underbrace{v_l \gamma_H}_{\text{HCI}} \tag{5}$$

and labor productivity as follows:

$$\gamma_{\frac{Y}{L}} \equiv \gamma_Y - \gamma_L = \underbrace{\gamma_A^U}_{\text{Neutral}} + \underbrace{\textstyle\sum_i v_i \left(\gamma_{K_i} - \gamma_L\right)}_{\text{Capital deepening}} + \underbrace{\textstyle\sum_i v_i \gamma_i}_{\text{ISTC}} + \underbrace{v_l \gamma_H}_{\text{HCI}} \tag{6}$$

From a direct comparison of equations (3) and (5), it appears clear where Hulten (1992) differs from Jorgenson (1966). While he uses capital shares v_i to weigh for the contributions of ISTC, the second uses investment ratios z_i, and the difference between γ_A^J and γ_A^U can thus be used as a measure of the effect of different weights of ISTC on the implied contribution of neutral technology to growth.

3.2 Equilibrium Growth Accounting

Building on Rodríguez-Lopez and Torres (2012), we develop a general equilibrium growth model in which three key elements are present: (i) the existence of different types of capital, (ii) the presence of technical change specific to each capital equipment, (iii) the presence of Human Capital that enhances the efficiency of labor services in the production function. According to this model, output is produced with a combination of eight productive factors: worked hours L_t, and seven different capital types, K_i for $i = \{(i), \ldots, (vii)\}$, which replicates EU KLEMS categories of investment assets (hardware, software, communication networks, transport equipment, machinery, other equipment, and structures). We assume that ISTC and HCI affect only the productivity of the corresponding factor, and that both processes are exogenous to agents' optimal decisions.

Household. The economy is inhabited by an infinitely lived, representative household who has time-separable preferences in terms of consumption of final goods and leisure. Preferences are represented by the following utility function:

$$E_0 \sum_{t=0}^{\infty} \beta^t U\left(C_t, L_t\right) \tag{7}$$

where β is the subjective discount factor, E_0 is the conditional expectation operator at time 0, C_t is private consumption, and L_t is the total number of worked hours provided by the household. The budget constraint faced by the consumer says that consumption and investment cannot exceed the sum of labor and capital rental income:

$$C_t + \sum_i I_{i,t} = W_t L_t + \sum_i R_{i,t} K_{i,t} \tag{8}$$

where W_t is the wage, and $R_{i,t}$ is the rental price of asset type i.

Capital holdings evolve according to:

$$K_{i,t+1} = \left(1 - \delta_i\right) K_{i,t} + Q_{i,t} I_{i,t} \tag{9}$$

where δ_i is the depreciation rate. As mentioned in Section 2, $Q_{i,t}$ represents the amount of asset i than can be purchased with one unit of consumption good. We interpret this relative price as a measure of the current state of technology to produce i. In fact, when a technical innovation in the production of asset i occurs it either increases the quality of the good or adds new characteristics or it lowers its average cost of production. In either case, such innovation is reflected in a variation of the quality-adjusted relative price $Q_{i,t}$, which therefore can be used to represent the technical change specific to the investment good i. In general, $Q_{i,t}$ may increase or decrease over time according to the technical change actually occurred. In this paper, however, we neglect the cyclical behavior of ISTC, and we only focus on its long run trend by assuming that ISTC evolves according to:

$$Q_{i,t} = \left(1 + \gamma_{Q,i}\right) Q_{i,t-1} \tag{10}$$

where $\gamma_i > 1$ is the exogenous growth rate specific to asset i. Finally, we incorporate in the model the standard assumption of no investment-specific technical change in structures, i.e., $Q_{str,t} = 1$

$\forall\ t$.[9]

The problem faced by the household is to choose a sequence $\left\{C_t, L_t, (I_{i,t})_i\right\}_{t=0}^{\infty}$ for to maximize utility (7), subject to the budget constraints (8) and the laws of motion (9), given some initial conditions $\{K_{i,0}, Q_{i,0}\}$.

Firms. There exists a single representative firm in the economy, who produces and sells whichever quantity of output demanded by the household in a perfectly competitive goods market. The problem of this firm is to find the optimal values for the utilization of labor and of the different types of capital assets to maximize its profits at each period t. Both capital and labor services are hired in perfectly competitive factors' markets. The technology to produce is given by a constant return to scale Cobb-Douglas production function,

$$Y_t = A_t \cdot \prod_i K_{i,t}^{\alpha_i} \cdot (H_t L_t)^{\alpha_l} \tag{11}$$

where A_t is total factor productivity and $0 \leq \alpha_l, : \alpha_i < 1$. In equation (11), the services from labor are expressed in efficiency units. This last is controlled by the amount of human capital embedded in workers, with the standard assumption that a higher level of human capital entails a better ability to workers and, therefore, a higher quality of labor. Human Capital Accumulation is also assumed to evolve according to:

$$H_t = (1 + \gamma_H)\, H_{t-1} \tag{12}$$

where $\gamma_H > 1$ is the exogenous growth rate of HCI.

Equilibrium. A standard market clearing condition is used to close the model. Output Y_t can be purchased to consume or to invest in each capital asset,

$$Y_t = C_t + \sum_i I_{i,t} \tag{13}$$

Notice that both output and investment are measured in units of consumption. The equilibrium outcome for this model economy is then derived using the First Order Conditions of the household and the firm, together with the law of motion of capital assets (9), the production function (11), and the market clearing condition (13).

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[9] In the literature on ISTC, structures are typically used as the benchmark capital where no technical change occurs. Gort, Greenwood and Rupert (1999), however, estimated that NIPA prices for nonresidential structures should be quality-adjusted by a 1% on annual basis.

The Balanced Growth Path and Growth Decomposition. We restrict out attention to equilibria that exhibit a balanced growth path, defined as an equilibrium where all variables grow at constant rates. According to our model, output, consumption, and investment all share the same long run growth rate $\gamma_Y = \gamma_C = \{\gamma_{I,i}\}_{i=1}$. Worked hours grow by the population growth rate, which is normalized to zero in this model, while the balanced growth rate of capital i depend on the growth rate of its idiosyncratic process of technical change. Using the law of motion (9), it is straightforward to show that this growth rate is equal to the common growth rate of the economy γ_Y multiplied by the growth rate of technological progress in asset i, i.e.

$$\left(1+\gamma_{K,i}\right) = \left(1+\gamma_{Q,i}\right)\left(1+\gamma_Y\right) \tag{14}$$

Combining the production function (11) and the growth rates obtained in (14), the first order Taylor approximation of the balanced growth rate of labor productivity is:

$$\gamma_{Y/L} = \underbrace{\frac{\gamma_A}{\alpha_l}}_{\text{Neutral}} + \underbrace{\sum\nolimits_i \frac{\alpha_i}{\alpha_l}\gamma_{Q,i}}_{\text{ISTC}} + \underbrace{\gamma_H}_{\text{HCI}} \tag{15}$$

where γ_A is the growth of TFP.

Expression (15) states that the long run growth rate of labor productivity can be decomposed into a combination of (i) the growth rate of neutral technology, (ii) the growth rates of ISTC, (iii) the growth rate of HCI. Note that in the long run the growth rate of output coincides with the growth rate of labor productivity, i.e. $\gamma_Y = \gamma_{Y/L}$. Thus, the model predicts that only technological progress explains output growth in the long run, which is the most remarkable difference between the equilibrium and the traditional growth accounting.

3.3 Calibration

The parameters that appear in the Growth Accounting procedures presented in Section 3.1 and 3.2 are calibrated matching some long run empirical facts of our set of countries. In particular, the elasticities of output with respect to capital i and labor, $\{v_i, v_l\}$, are measured with the ratio of the marginal to the average product of the corresponding factor. Given the national accounting rules and under the hypothesis of perfectly competitive factor markets, these elasticities coincide with the cost shares *per* factor. As regards the cost shares of capital, we follow the recommendations of OECD (2001) to construct the series of capital, which are based on the concept of *capital services*. The idea is to capture the productive services embedded in the stock of capital. Productive capital is then seen as a volume index of capital services. The expression driving the concept of capital services for the asset i is as follows:

$$VCS_{i,t} = \mu_{i,t} K_{i,t} \tag{16}$$

where $K_{i,t}$ is the stock of physical capital and $\mu_{i,t}$ is the nominal usage cost of capital. Let RE_t be the remuneration of employees. Then, cost shares are given by the following expressions:

$$v_{i,t} = \frac{VCS_{i,t}}{RE_t + \sum_i VCS_{i,t}}$$

Accordingly, we use the average values of cost shares over the sample 1980-2006 to calibrate the weights v_i, i.e. $v_i = T^{-1} \sum_t v_{i,t}$. The cost share of labor is obtained residually using the property of constant return to scale in production. That is: $v_l = 1 - \sum_i v_i$.

Regarding the Equilibrium Growth Accounting, we calibrate the coefficients α's in equation (15) exploiting the steady state relationship of the model, which imply that $\forall\ i$

$$\alpha_i = \frac{R_i K_i}{Y} \tag{17}$$

According to equation (17), α_i then corresponds to the capital-income share, which according to our calibration coincides with the cost share. Thus, $\alpha_i = v_i$. Consistently with this measure, we calibrate $\alpha_l = v_l$.

[Insert here Table 2]

Table 2 shows the cost shares of capital together with investment shares, which in Hulten's approach replace capital shares as weighting coefficients of ISTC. Investment and capital income shares appear fairly similar in the case of South Korea, while there are significant differences in Australia, Japan, and the U.S. In general, capital income shares are higher than investment shares as expected, and accordingly Hulten's approach will assign an higher weight to the contribution of ISTC to growth than Jorgenson's. Table 2 also reports the rates of depreciation, which are calibrated using the ratio of EU KLEMS estimates of capital stock over the gross formation of fixed capital. These estimates are stable across years and similar across countries. Across all considered countries, structures depreciate at the lowest rate, approximately 2.8% on annual basis, while ICT equipment depreciates much faster. For instance, a software license fully depreciates in about two years, implying a depreciation rates of 42%. This time length is four years for hardware equipment.[10]

4 Results

We begin the quantitative analysis by providing the output growth decomposition obtained using the Traditional Growth Accounting. The contributions of embodied technical progresses (ISTC and HCI), disembodied technical progress, and factors accumulation in the four selected countries are reported in Table 3. Several results are worth noticing, we shall explore them in turn. First, all the three alternative models (Solow, Jorgenson, Hulten) impute to technology the same fraction of growth. The contribution of overall technological progress to growth therefore is *not* sensitive to the model used. As apparent by inspecting expressions (1), (3),(5), this result is due to the coefficients $\{v_i,\ v_l\}_i$ used in the three models to weight for the relative contributions of factors accumulation, which are always the same. Important differences, however, exist in the relative contribution to growth of the various sources of technological progress. As expected, the impact of neutral technical change is highest in Solow's than in the other two models, given that Solow's TFP incorporates the effects of ISTC and HCI thus upward biasing the results. In general, neutral technical change contributes more to output growth in Jorgenson's than in Hulten's model. This finding is reasonable because Jorgenson only recognizes the existence of embedded technological progress in new capital assets (investment), while Hulten considers that ISTC affect the productivity of the whole stock of existing capital, thus shifting production more heavily.

Second, we find that factors accumulation is the main driving force of output growth in Australia, Japan and the U.S., explaining more than two-third of output growth, while technological progress explains the remaining one-third. In detail, capital accumulation explains approximately 42% of total output growth in the U.S., 36% in Australia, and 67% in Japan, while the growth of worked hours contributes to approximately 28% of output growth in the U.S., 30% in Australia but has a negative contribution in Japan (-6.8%), being a good candidate to explain the lower output growth in Japan with respect to U.S. and Australia. In the case of South Korea, the results are opposite. Approximately 64% of output growth is accounted for by technological progress and only 35% by factors accumulation. This finding broadly confirms that Korean economy is still at a different stage of economic development than the other three countries.

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[10] A more detailed description of depreciation rates for each capital asset can be found in the Technical Appendix of the paper.

Jorgenson's and Hulten's models allow to give a closer look at the actual sources of technology, revealing our third result. The contribution of neutral technology in Australia, Japan and the U.S. is extremely small using Jorgenson (from 2% to 6%) and even negative using Hulten (from -6% to -15%). Only in South Korea TFP plays an important role whichever is the model used to account for it, with an annual contribution to output growth that goes from about 5% with Solow to approximately 3% with Jorgenson and Hulten. This finding can be interpreted as the empirical counterpart of the theories on TFP as an indicator of institutional factors, e.g. laws and tribunals, institutions, patent protection, infrastructures. In developed economies as Japan or U.S., the space for growth from an improvement of institutional factors seems barely null, while in South Korea institutional factors may be still playing a crucial role on economic growth. Moreover, TFP contribution is negative for Australia, Japan and the U.S. under the Hulten approach. In this perspective, our fourth result indicates that the main contribution to output growth of technology in Australia, Japan, and U.S. arrives from ISTC being, respectively, 27%, 34%, and 37% using Hulten's model. It is worth noting that these numbers exceed the overall contribution of technology. This is due to the negative contribution of TFP that partially offset that of ISTC and HCI in the accounting procedure. Although the figures changes if we use Jorgenson's model, the ranking among sources does not, although in this case the contribution of ISTC to output growth is larger in South Korea (0.71 percentage points) than in the other three countries (around 0.50 percentage points). The differences in results depending on the approach is likely explained by Korean lower ratio of capital compensation and higher level of investment.

[Insert here Table 3]

Our fifth and last result is about the contribution of human capital to growth. This contribution is 1.2 percentage points in South Korea, while it gets only to approximately 0.4 percentage points in Australia and Japan, and to a mere 0.2 percentage points in U.S. The high figure of South Korea is consistent with the results of PISA survey on secondary education (see Hanushek and Woessmann, 2010 and 2011), where this country ranks among the firsts at world level for the quality of its education system. From the point of view of productive knowledge, this result may indicate that there is a process of convergence in the quality of labor services (productive knowledge embedded in workers) from a developing country as Korea to developed countries as Japan, U.S. or Australia. The interpretation of the whole set of results, however, is more complicated. Why we observe nowadays a 50% difference between the contribution of HCI to growth between Japan and U.S. is an open question. Looking at their history, at the business organization in each of the two countries, or at the evolution of their economies during the last century, it is hard to believe that Japan still pays a gap to U.S. in terms of human capital. We rather suggest an alternative explanation. Data are possibly reflecting some Asian effect about Human Capital that is generated by different cultural preferences toward labor. In Asian societies, once the mature stage of economic development is reached, the contribution of labor forces to production appears to shift from a quantitative increase (whatever is the sources, higher demand, higher supply, higher wages) to a qualitative increase of the labor services, thus resulting in a more educated (more productive) work force employed less hours. This pattern could be generated by an adjustment of preferences. If for cultural and social reasons labor traditionally entails less disutility in Asian countries, then a global alignment of preferences as the one observed in the last decades should imply a reduction of worked hours in Asian countries after controlling for wages. The higher accumulation of human capital would then be explained by the attempt of workers to maintain a constant wage level despite the reduction of working time, i.e., increasing wage per hour. Such Asian effect is consistent with empirical analysis of Serrano and Timmer (2002) on the supply of skills in South Korea, and interestingly it remains significant even across different levels of economic wealth, as apparent contrasting the cases of South Korea and Japan on one side and Australia and U.S. on the other side. It is not possible to test this conjecture given the small sample of countries analyzed in this paper, and we rather leave this line of research to future investigations.

Given its primary role on growth, we provide a further investigation on the sources of ISTC. Using the asset categories in EU KLEMS classification, we disaggregate the contribution to output growth of implicit technical change in each single category of capital. Table 4 displays the results using both Jorgenson's and Hulten's model. Using the Hulten approach, ISTC contribution to output growth is 0.70 percentage points for South Korea, 0.79 for Japan, 0.96 for Australia, arriving to 1.09 percentage points for the U.S. economy. ISTC contribution from ICT is about a half, with the other half corresponding to non-ICT equipment. With respect to ICT equipment, the larger contribution corresponds to hardware, representing this particular capital asset about 30% of total ISTC contribution. In the case of the non-ICT equipment, the larger contribution corresponds to machinery. We find important differences across countries in the case of the ICT equipment. In fact, ISTC corresponding to ICT in the U.S. is double of that in South Korea. By contrast, the Jorgenson's approach changes substantially the results. For South Korea, ISTC contribution remains similar, as there is little difference between investment ratios and capital income shares for this country. However, for the other three countries ISTC contribution to output growth is lower, as capital income shares are higher than investment shares. In fact, now is South Korea the country with a higher contribution from ISTC to output growth (0.71 percentage points). For Australia this contribution is 0.58 percentage points, 0.49 for the U.S. and 0.46 for Japan.

[Insert here Table 4]

The same accounting approach can be used to decompose the growth of labor productivity. Results are shown in table 5. The relative importance of technology on labor productivity growth is larger for the Korean economy (approximately 80% of productivity growth), but also important for the Australian economy (approximately 63% of productivity growth), despite average labor productivity growth in the two countries is very different (1.84% in Australia and 6.33% in South Korea). In U.S. technology explains about half of productivity growth. Finally, in the case of Japan, technological progress only explain around 36% of productivity growth, where the rest 64% is explained by capital deepening. Wong and Goh (2009) studied the diffusion process of science and technology in some Asian countries, including South Korea and Japan. They find that although the level of science and technology is higher in Japan than in South Korea, the velocity of the diffusion process is higher in the latter. This is consistent with our findings that technological progress is a more powerful growth enhancing factor in South Korea compared to Japan.

[Insert here Table 5]

Table 6 reports the growth decomposition of labor productivity obtained the equilibrium growth accounting. The main difference with the traditional approach of table 5 is that in this case only technological progress explains productivity growth, while the contribution of capital deepening is imposed equal to zero. The reason is that in the long run firms' supposedly converged toward the optimal utilization of factors, which therefore does not vary anymore. The general equilibrium approach show that in Australia, Japan, and U.S. the main factor explaining the growth of labor productivity is ISTC, while in South Korea the main contribution comes from TPF, followed by human capital. Additionally, we observe that the contribution of TFP to productivity is positive for Korea and Japan, but negative for U.S. and Australia. The larger contribution to productivity growth corresponds to the U.S. (1.63 percentage points). Nevertheless, results for Australia and

Japan are similar (1.42 and 1.28 percentage points, respectively). Similar results for the case of Japan are obtained by Braun and Shioji (2007). A lower contribution from ISTC is obtained for the case of Korea (about 0.86 percentage points). We also find important differences for the contribution of human capital. In this case the lower contribution corresponds to the U.S. (only 0.3 percentage points), whereas the contribution in the case of the Korea economy is 0.86 percentage points. The main differences is found in the contribution from neutral technology change. We find negative contributions for the case of Australia and the U.S., whereas is positive for Japan and Korea. It is remarkable the case of Korea, where the contribution of the neutral change to productivity growth is close to 4 percentage points. Overall, we find that differences in labor productivity growth among selected countries are explained mainly by differences in the neutral technological change. This technological factors explain why average labor productivity growth during the period is larger in South Korea with respect to the other countries. Moreover, the average labor productivity for the Japanese economy (2.55%) is also larger than the ones of Australia and the U.S. (1.84% and 1.64%, respectively), which also can be attributed to the neutral technical change.

[Insert here Table 6]

5 Concluding remarks

In the last twenty years, the identification of the sources of technological progress received a renewed attention, in particular after the economic boom caused by the expansion of Information and Communication Technologies, i.e., the so-called "new economy". This paper identifies three of those sources – technological progress generated by enhanced human capital, by an improvement of TFP, and by innovations in productive capital – and assesses their relative importance in explaining output and labor productivity growth. This analysis is performed on a group of Pacific countries observed during the period 1980-2006, and employs two different approaches to quantify the contribution of each source to growth: a traditional growth accounting approach and a general equilibrium model consistent growth decomposition. Whereas the first approach is a good explanation of the importance of technological progress in the transition, the second approach better identifies the determinants of productivity growth in the long-run.

The main conclusion of the paper is that the most important sources of growth in South Korea are different from the that of Australia, Japan and the U.S., which instead have similar composition of growth. Factors accumulation explains about 60-70% of output growth in Australia, Japan and the U.S., but only 36% in South Korea. Conversely, technological progress explains no more than 30-40% of growth in the first three countries, whereas it accounts for 64% of Korean growth. We show that the difference is determined by the importance of the neutral technological change. Whereas in the three first countries, TFP contribution to output growth is relatively low or even negative, in the case of South Korea neutral technological change plays a crucial role in explaining output growth. Similar results are obtained in terms of labor productivity growth. Our results also stress the importance of taking into account embedded technological progress to factor inputs, both labor and capital. Technical progress embedded within equipment, mainly ICT, has increases its role as a productivity contributor in the last decades which, together with human capital contribution can explain a large proportion of output and productivity growth.

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Table 1: Average Annual Growth Rates, 1980-2006

	Australia	Japan	Korea	U.S.
Variables				
Output	3.50	2.29	7.70	2.92
Labor Productivity	1.84	2.55	6.33	1.64
Worked Hours	1.66	-0.26	1.37	1.28
Capital	3.58	3.79	8.19	3.51
Technology				
HCI	0.64	0.69	1.53	0.30
ISTC	3.20	1.95	2.39	3.27

Table 2: Cross-country empirical evidence, 1980-2006

	Australia	Japan	Korea	U.S.
Capital-Income shares (v_i)				
ICT equipment (i+ii+iii)	0.046	0.043	0.027	0.062
Hardware (i)	*0.021*	*0.019*	*0.011*	*0.020*
Software (ii)	*0.015*	*0.013*	*0.008*	*0.024*
Communication equipment (iii)	*0.010*	*0.011*	*0.008*	*0.018*
Non-ICT equipment (iv+v+vi)	0.141	0.181	0.108	0.142
Transport equipment (iv)	*0.048*	*0.031*	*0.030*	*0.035*
Machinery (v)	*0.073*	*0.101*	*0.079*	*0.098*
Other equipment (vi)	*0.020*	*0.049*	*0.000*	*0.008*
Structures (vii)	0.164	0.180	0.069	0.147
Investment-Income shares (z_i)				
ICT equipment (i+ii+iii)	0.028	0.026	0.028	0.031
Hardware (i)	*0.012*	*0.011*	*0.007*	*0.009*
Software (ii)	*0.010*	*0.008*	*0.011*	*0.013*
Communication equipment (iii)	*0.006*	*0.006*	*0.010*	*0.009*
Non-ICT equipment (iv+v+vi)	0.085	0.098	0.119	0.057
Transport equipment (iv)	*0.031*	*0.021*	*0.037*	*0.016*
Machinery (v)	*0.044*	*0.051*	*0.083*	*0.038*
Other equipment (vi)	*0.010*	*0.026*	*0.000*	*0.003*
Structures (vii)	0.082	0.081	0.145	0.055

Table 3: Contribution to GDP growth, 1980-2006

	Australia			**Japan**			**Korea**			**U.S.**		
GDP growth (γ_Y)	3.50			2.29			7.70			2.92		
Contribution	Sol.	Jorg.	Hul.	Sol.	Jorg.	Hul.	Sol.	Jorg.	Hul.	Sol.	Jorg.	Hul.
Capital	1.26	1.26	1.26	1.53	1.53	1.53	1.68	1.68	1.68	1.23	1.23	1.23
Labor	1.08	1.08	1.08	-0.15	-0.15	-0.15	1.09	1.09	1.09	0.83	0.83	0.83
TFP	1.17	0.17	-0.20	0.91	0.04	-0.29	4.93	3.00	3.01	0.86	0.17	-0.43
ISTC	-	0.58	0.96	-	0.46	0.79	-	0.71	0.70	-	0.49	1.09
HCI	-	0.42	0.42	-	0.41	0.41	-	1.22	1.22	-	0.19	0.19
Decomposition ($\%$)												
Capital (i)	35.9	35.9	35.9	67.0	67.0	67.0	21.8	21.8	21.8	42.2	42.2	42.2
Labor (ii)	30.8	30.8	30.8	-6.8	-6.8	-6.8	14.1	14.1	14.1	28.4	28.4	28.4
Factors (i+ii)	66.7%			60.2%			35.9%			70.6%		
TFP (iii)	33.3	5.0	-5.9	39.8	2.0	-12.6	64.1	39.0	39.1	29.4	6.0	-14.8
ISTC (iv)	-	16.5	27.3	-	19.9	34.4	-	9.3	9.1	-	16.7	37.5
HCI (v)	-	11.9	11.9	-	18.0	18.0	-	15.8	15.8	-	6.7	6.7
Technology (iii+iv+v)	33.3%			39.8%			64.1%			29.4%		

Table 4: ISTC contribution to output growth, 1980-2006

	Australia		**Japan**		**Korea**		**U.S.**	
	Jor.	**Hul.**	**Jor.**	**Hul.**	**Jor.**	**Hul.**	**Jor.**	**Hul.**
Total Contribution (a+b)	0.58	0.96	0.46	0.79	0.71	0.70	0.49	1.09
ICT capital (a=i+ii+iii)	0.30	0.50	0.26	0.43	0.28	0.31	0.30	0.62
Hardware (i)	*0.20*	*0.34*	*0.17*	*0.28*	*0.12*	*0.18*	*0.14*	*0.33*
Software (ii)	*0.04*	*0.06*	*0.02*	*0.04*	*0.05*	*0.03*	*0.05*	*0.10*
Communications (iii)	*0.06*	*0.11*	*0.06*	*0.11*	*0.11*	*0.09*	*0.10*	*0.20*
Non-ICT capital (b=iv+v+vi)	0.28	0.45	0.20	0.36	0.43	0.39	0.19	0.47
Transports (iv)	*0.12*	*0.12*	*0.06*	*0.09*	*0.15*	*0.12*	*0.06*	*0.14*
Machinery (v)	*0.13*	*0.22*	*0.10*	*0.21*	*0.29*	*0.27*	*0.12*	*0.32*
Other equipment (vi)	*0.02*	*0.05*	*0.03*	*0.06*	*0.00*	*0.00*	*0.01*	*0.02*
Decomposition (%)								
ICT capital (i+ii+iii)	52.2%	52.6%	56.7%	54.6%	39.2%	44.4%	60.6%	56.9%
Hardware (i)	*34.3*	*35.4*	*37.7*	*36.2*	*17.3*	*26.3*	*28.6*	*30.0*
Software (ii)	*6.9*	*6.0*	*5.1*	*4.6*	*6.5*	*4.8*	*10.6*	*8.7*
Communications (iii)	*10.9*	*11.3*	*13.9*	*13.9*	*15.5*	*13.3*	*21.4*	*18.2*
Non-ICT capital (iv+v+vi)	47.8%	47.4%	43.3%	45.4%	60.8%	55.6%	39.4%	43.1%
Transports (iv)	*20.4*	*19.1*	*13.0*	*11.0*	*20.8*	*17.0*	*12.6*	*12.6*
Machinery (v)	*23.4*	*23.5*	*23.0*	*26.5*	*40.0*	*38.6*	*25.1*	*28.8*
Other equipment (vi)	*4.1*	*4.8*	*7.3*	*7.9*	*0.0*	*0.0*	*1.7*	*1.7*

Table 5: Contribution to labor productivity growth, 1980-2006

	Australia			**Japan**			**Korea**			**U.S.**		
Labor productivity ($\gamma_{\frac{Y}{L}}$)	1.84			2.55			6.33			1.64		
Contribution	Sol.	Jorg.	Hul.	Sol.	Jorg.	Hul.	Sol.	Jorg.	Hul.	Sol.	Jorg.	Hul.
Capital/Hours	0.67	0.67	0.67	1.64	1.64	1.64	1.40	1.40	1.40	0.78	0.78	0.78
TFP	1.17	0.17	-0.20	0.91	0.04	-0.29	4.93	3.00	3.01	0.86	0.17	-0.43
ISTC	-	0.58	0.96	-	0.46	0.79	-	0.71	0.70	-	0.49	1.09
HCI	-	0.42	0.42	-	0.41	0.41	-	1.22	1.22	-	0.19	0.19
Decomposition (%)												
Capital/Hours	36.6	36.6	36.6	64.3	64.3	64.3	22.1	22.1	22.1	47.8	47.8	47.8
TFP (i)	63.4	9.4	-11.1	35.7	1.8	-11.3	77.9	47.4	47.6	52.2	10.7	-26.4
ISTC (ii)	-	31.4	51.9	-	17.8	30.9	-	11.3	11.1	-	29.7	66.7
HCI (iii)	-	22.6	22.6	-	16.1	16.1	-	19.2	19.2	-	11.9	11.9
Technology (i+ii+iii)	63.4%			35.7%			77.9%			52.2%		

Table 6: Contribution to labor productivity growth, 1980-2006

	Australia	**Japan**	**Korea**	**U.S.**
Labor productivity ($\gamma_{\frac{Y}{L}}$)	1.84	2.55	6.33	1.64
Contribution (i+ii+iii)	*General equilibrium approach*			
TFP (i)	-0.22	0.58	3.94	-0.29
ISTC (ii)	1.42	1.28	0.86	1.63
ICT	*0.73*	*0.68*	*0.37*	*0.91*
Non-ICT	*0.69*	*0.60*	*0.48*	*0.72*
HCI (iii)	0.64	0.69	1.53	0.30
Decomposition (%)				
TFP (i)	-12.1	22.7	62.3	-17.8
ISTC (ii)	77.3	50.3	13.5	99.5
ICT	*39.6*	*26.8*	*5.8*	*55.3*
Non-ICT	*37.4*	*23.3*	*7.7*	*43.8*
HCI (iii)	34.8	27.1	24.2	18.3