Technological sources of productivity growth in Germany, Japan and the U.S.[1]

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Abstract. In this paper, we use a dynamic general equilibrium growth model to quantify the contribution of different technological sources to productivity growth in the three leading economies: Germany, Japan, and the U.S. The sources of technology are classified as representing either neutral progress or investment-specific progress. The latter can be split into two different types of equipment: information and communication technologies (ICT) and non-ICT equipment. We find that in the long run, neutral technological change is the main source of productivity growth in Germany. For Japan and the U.S., the main source of productivity growth is investment-specific technological change, mainly associated with ICT. We also find that a non negligible part of productivity growth has been due to technology specific to non-ICT equipment; this is mainly true after 1995.

Keywords: Productivity growth; Investment-specific progress; Neutral progress; Information and communication technology.

JEL classification: O3; O4.

Field: (4) Growth, Development and Population Policy

1 Introduction

In this paper, we investigate the contribution of different sources of technology to labor productivity growth in three leading economies, i.e., those of Germany, Japan and the United States, for the period 1977-2006 using a general equilibrium approach. Technological change is composed of two sources: (i) neutral change and (ii) investment-specific technological change. While the former is associated with total factor productivity (TFP), the latter represents the amount of technology that can be acquired using one unit of a particular capital asset. The aims of the paper are twofold. First, we seek to quantify the contribution to labor productivity growth of the three sources of technological progress, i.e., neutral technological change, change with non-ICT equipment and change with ICT equipment. Second, we aim to study the differences between the technological sources of productivity growth among these countries.

In our model economy, capital input is separated into three assets: structures, information and communication (ICT) equipment and non-ICT equipment. The term ICT equipment refers to hardware, software and communication networks while the term non-ICT equipment refers to machinery and transport equipment. We assume that investment-specific technology can be embedded within both forms of equipment but not in structures. The distinction between non-ICT and ICT equipment is justified by the fact that investment-specific technology can vary widely from one asset to another.

In the literature, we find two different approaches to identifying technological progress: (i) the standard growth accounting decomposition method and (ii) the calibration of a general equilibrium model.[1] Whereas most previous works, e.g., Timmer and van Ark (2005), used the "growth accounting" approach, we use the alternative "general equilibrium" approach in this paper. Greenwood and Krusell (2007) show that traditional growth accounting and equilibrium growth accounting generate very different findings concerning the empirical importance of investment-specific technological progress

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[1] The debate about the correct approach to quantifying the contribution of technological progress to growth was initiated in the opposition between Solow (1960) and Jorgenson (1966). Both authors introduce the concept of "embodied" technological change but use different frameworks. The difference is that Solow (1960) assumes "embodied" technological change but only in the production of investment goods, whereas Jorgenson (1966) assumes that such change also affects output. A review of the Solow-Jorgenson controversy can be found in Hercowitz (1998). This debate has been recently updated through criticism from Greenwood, Hercowitz and Krusell (1997) to Hulten (1992), with further related work being done more recently (see, for instance, Oulton, 2007 and Greenwood and Krusell, 2007).

for the growth process, with equilibrium growth accounting providing better results. The reason is that whereas the use of a general equilibrium model can isolate technological progress from other sources of output growth such as capital accumulation, the traditional growth accounting method cannot. Output growth is derived from both technological progress and capital accumulation. Traditional growth accounting considers both components of growth independent of one other. The problem is that capital accumulation is affected by technological progress. Thus, in reality, traditional growth accounting is not able to quantify the importance of technological change because it is not possible to know the proportion of capital accumulation that is due to technological progress. Only a fully articulated general equilibrium model can perform this function. In the same vein as the arguments of Greenwood and Krusell (2007), Cummins and Violante (2002) pointed out that the main disadvantage of traditional or statistical growth accounting is that it does not isolate the underlying sources of capital accumulation. In contrast, Oulton (2007) claims that the general equilibrium growth model with embodied technological change is a particular instance of Jorgenson's approach, where the concept of investment-specific technological change is closely related to the concept of total factor productivity and TFP growth occurs at different rates in a two-sector model.

To carry out this exercise, we combine two databases: the EU KLEMS database and the quality-adjusted investment prices estimated by Gordon (1990) and extended by Cummins and Violante (2002) (henceforth the GCV database). From the EU KLEMS, we download data on output, hours worked and nominal investment. The quality adjusted prices of the GCV database serve to deflate the EU KLEMS investment series and to provide valid measures of investment specific technological change associated with both ICT and non-ICT equipment. The GCV prices were estimated for the U.S. economy, and we adjust these deflators for Germany and Japan by applying the methodology proposed by Schreyer (2002). In fact, the EU KLEMS database uses Schreyer's methodology to quality adjust the ICT investment using the corresponding NIPA prices. However, the non-ICT equipment is not quality adjusted in the EU KLEMS database. This is a key contribution of this paper because both investment in equipment will be adjusted in the three countries. It is worth noting that when only ICT assets are subjected to this adjustment, growth accounting exercises tend to overstress the importance of ICT equipment as a factor behind the 1995 upsurge in U.S. productivity growth (see, for example, Collechia and Schreyer, 2001; Jorgenson and Stiroh, 2000).

Comparing the levels of technological progress in these countries is particularly interesting for several reasons. First, these are the three leading economies in the world, and their dynamics are taken as a point of reference for the overall state of the world economy. Second, economic performance has been different in each of these three countries, especially during the past decade; while the Japanese economy experienced a slowdown during the 1990s, the U.S. economy showed a resurgence of productivity and German productivity growth evolved with a more stable pattern. Third, it seems important to quantify the contribution of investment specific technological change derived from the two forms of equipment (ICT versus non-ICT) because the portfolio choice of assets differs from one country to another.

Our results show some important differences in the performance of these economies. We find that neutral technological change is the force that drives productivity in Germany, accounting for 72% of its growth. For the Japanese and the U.S. economies, productivity growth is mainly due to investment-specific technological change. Neutral technological change accounts for 46% of productivity growth in Japan and only 8.4% of that in the U.S. The contribution of investment-specific technological change to average productivity growth is only 0.67 percentage points for Germany, whereas it is about 1.4 percentage points for Japan and the U.S. The main finding of the paper is that diversity of capital portfolio composition is relevant in explaining productivity dynamics across countries. The contribution of ICT technological progress to average productivity growth is only 0.38 percentage points for Germany, 0.91 percentage points for Japan and 0.93 percentage points for the U.S. In particular, for the U.S. economy, ICT technological progress explains about 60% of total labor productivity growth.

The remainder of the paper is organized as follows. In the following section, we present a theoretical dynamic general equilibrium growth model with embodied technological progress and describe a balanced growth path. Section 3 presents a description of the data set and the calibration exercise. Section 4 estimates the contribution of each type of technological change to labor productivity growth in the long run. Finally, Section 5 summarizes and concludes.

2 The model

Following Greenwood, Hercowitz and Krusell (1997), we use a dynamic general equilibrium neoclassical growth model in which two key elements are present: the existence of different types of capital and the presence of technological change specific to the capital equipment. We use a simplification of the model developed in Martínez, Rodríguez and Torres (2008) that distinguishes between non-ICT and ICT equipment capital assets. Output is therefore produced as a combination of four inputs: L is labor in hours worked, K_{str} is non residential structures, K_{nict} is non-ICT equipment and K_{ict} is ICT equipment.

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

$$E_0 \sum_{t=0}^{\infty} \beta^t C_t^{\gamma} O_t^{1-\gamma}, \tag{1}$$

where β is the discount factor, E_0 is the conditional expectation operator at time 0, and $\gamma \in (0,1)$ is the participation of consumption on total income. Private consumption is denoted by C_t, and leisure is $O_t = N_t H - L_t$, where H is the number of effective hours in the year, times the population at the age for making labor-leisure decisions (N_t), minus the aggregate number of hours worked per year ($L_t = N_t h_t$, with h_t representing annual hours worked per worker).

The budget constraints faced by the consumer indicate that consumption and investment cannot exceed the sum of labor and capital rental income net of taxes and lump-sum transfers:

$$\begin{aligned} & (1+\tau_c) C_t + I_{str,t} + I_{nict,t} + I_{ict,t} \\ = \; & T_t + (1-\tau_\ell) W_t L_t \\ & + (1-\tau_k)\left(R_{str,t}K_{str,t} + R_{nict,t}K_{nict,t} + R_{ict,t}K_{ict,t}\right), \end{aligned} \tag{2}$$

where T_t is the transfer that consumers receive from the government, W_t is wages, $R_{i,t}$ is the rental price of asset type i, and $\tau_c, \tau_\ell, \tau_k$ are the consumption tax, the labor income tax and the capital income tax, respectively.

Capital holdings evolve according to:

$$K_{nict,t+1} = (1-\delta_{nict}) K_{nict,t} + Q_{nict,t} I_{nict,t}, \tag{3}$$

$$K_{ict,t+1} = (1-\delta_{ict}) K_{ict,t} + Q_{ict,t} I_{ict,t}, \tag{4}$$

$$K_{str,t+1} = (1-\delta_{str}) K_{str,t} + I_{str,t}, \tag{5}$$

where δ_i is the depreciation rate. $Q_{i,t}$ determines the amount of asset $i \in \{nict, ict\}$ that can be purchased by one unit of the consumption good, representing the current state of technology for producing capital i. In the standard neoclassical one-sector growth model $Q_{i,t} = 1$ for all t. In our model $Q_{i,t}$ may increase or decrease over time depending on the type of capital we consider, representing technological change specific to the production of each amount of capital. In fact, an increase in $Q_{i,t}$ reduces the average cost of producing investment goods in units of final goods. Note that the expression (5) for structures implies the standard assumption where there is no investment-specific technological change in structures.[2]

The investment specific technological change is assumed to evolve according to

$$Q_{i,t} = \eta_i Q_{i,t-1}, \tag{6}$$

for $i \in \{nict, ict\}$, where $\eta_i > 1$ is the technological growth rate specific to asset i.

The problem faced by the consumer is that of choosing a sequence

$$\{C_t, O_t, I_{nict,t}, I_{ict,t}, I_{str,t}\}_{t=0}^{\infty},$$

to maximize the utility (1), subject to the budget constraints (2) and the laws of motion (3)-(5) and given taxes $\{\tau_c, \tau_k, \tau_\ell\}$ as well as the initial conditions $K_{i,0}$ for $i \in \{str, nict, ict\}$.

Firms. The problem for the firm is to find optimal values for the utilization of labor and the different types of capital. The production of the final output Y requires services from labor L and services from three types of capital K_i, $i \in \{str, nict, ict\}$. The firm rents capital and employs labor to maximize profits during period t, taking factor prices as given. The technology is given by a constant return to scale Cobb-Douglas production function,

$$Y_t = A_t L_t^{\alpha_L} K_{str,t}^{\alpha_{str}} K_{nict,t}^{\alpha_{nict}} K_{ict,t}^{\alpha_{ict}} \tag{7}$$

where A_t is total factor productivity and

$$\begin{aligned} 0 &\leq \alpha_i < 1 \\ \alpha_{str} + \alpha_{nict} + \alpha_{ict} &< 1, \\ \alpha_L + \alpha_{str} + \alpha_{nict} + \alpha_{ict} &= 1. \end{aligned}$$

Final output can be used for four purposes, i.e., consumption or investment in three types of capital:

$$Y_t = C_t + I_{str,t} + I_{nict,t} + I_{ict,t} \tag{8}$$

Both output and investment are measured in units of consumption.

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[2] Gort, Greenwood and Rupert (1999) estimate that the NIPA price of nonresidential structures should be quality adjusted by 1% yearly.

Government. Finally, we consider the existence of a tax-levying government to account for the effects of taxation on capital accumulation. The government taxes consumption and income from labor and capital. We assume that the government balances its budget period-by-period by returning revenues from distortionary taxes to the agents via lump-sum transfers, T_t:

$$\tau_c C_t + \tau_\ell W_t L_t + \tau_k \left(R_{str,t} K_{str,t} + R_{nict,t} K_{nict,t} + R_{ict,t} K_{ict,t} \right) = T_t. \tag{9}$$

Equilibrium. The following expressions summarize the first order conditions for the consumer and the firm:

$$\frac{1-\gamma}{\gamma} \frac{C_t}{N_t H - L_t} = \frac{1-\tau_\ell}{1+\tau_c} W_t, \tag{10}$$

$$E_t \left[\frac{C_t}{C_{t+1}} \frac{Q_{nict,t}}{Q_{nict,t+1}} \left(\left(1-\tau_k\right) Q_{nict,t+1} R_{nict,t+1} + \left(1-\delta_{nict}\right) \right) \right] = \frac{1}{\beta}, \tag{11}$$

$$E_t \left[\frac{C_t}{C_{t+1}} \frac{Q_{ict,t}}{Q_{ict,t+1}} \left(\left(1-\tau_k\right) Q_{ict,t+1} R_{ict,t+1} + \left(1-\delta_{ict}\right) \right) \right] = \frac{1}{\beta}, \tag{12}$$

$$E_t \left[\frac{C_t}{C_{t+1}} \left(\left(1-\tau_k\right) R_{str,t+1} + \left(1-\delta_{str}\right) \right) \right] = \frac{1}{\beta}, \tag{13}$$

$$\alpha_i \frac{Y_t}{K_{i,t}} = R_{i,t}, \tag{14}$$

$$\alpha_L \frac{Y_t}{L_t} = W_t, \tag{15}$$

for $i \in \{str, nict, ict\}$. The condition (10) equals the marginal rate of substitution between consumption and leisure to the opportunity cost of one additional unit of leisure. The conditions (11)-(13) mean that the intertemporal marginal rate of consumption equals the after-tax rates of return of the three investment assets. Finally, conditions (14) and (15) mean that the firm hires capital and labor so that the marginal contribution of these factors equates their competitive rental prices.

Additionally, the economy satisfies the feasibility constraint:

$$\begin{aligned} & C_t + I_{str,t} + I_{nict,t} + I_{ict,t} \qquad (16) \\ = \; & R_{str,t} K_{str,t} + R_{nict,t} K_{nict,t} + R_{ict,t} K_{ict,t} + W_t L_t = Y_t. \end{aligned}$$

First order conditions for the household (10)-(13), together with the first order conditions for the firm (14) and (15), the budget constraint of the government (9), and the feasibility constraint of the economy (16), characterize a competitive equilibrium for the economy.

The balanced growth path. The steady state is an equilibrium that satisfies the above conditions such that all variables grow at a constant rate. If we assume no unemployment, the figure for total hours worked increases with the population growth rate, which is assumed to be zero. Output, consumption and investment must all grow at the same rate, which is denoted by g. However, the different types of capital will increase at different rates depending on the evolution of their relative prices. From the production function (7) the balanced growth path implies that

$$g = g_A g_{str}^{\alpha_{str}} g_{nict}^{\alpha_{nict}} g_{ict}^{\alpha_{ict}}, \tag{17}$$

where g_A is the steady state exogenous growth of A_t. Let us denote g_i as the steady state growth rate of capital $i \in \{str, nict, ict\}$. Then, based on the laws of motion (3)-(5), the growth of each capital input is given by

$$g_i = \eta_i g, \tag{18}$$

with $i \in \{nict, ict\}$ and $g_{str} = g$, given the assumption of no specific technological progress for structures.

Therefore, the long-term growth rate of output can be accounted for by neutral technological progress and by increases in the capital stock. In addition, expression (18) indicates that capital stock growth also depends on the technology producing the capital goods. Therefore, it is possible to express output growth as a function of the exogenous growth rates of production technologies as follows:

$$g = \underbrace{g_A^{1/\alpha_L}}_{\text{Neutral}} \times \underbrace{\eta_{nict}^{\alpha_{nict}/\alpha_L} \eta_{ict}^{\alpha_{ict}/\alpha_L}}_{\text{Investment-specific}}. \tag{19}$$

Expression (19) implies that output growth can be decomposed as a linear combination of both type of progress.

The following ratios should be stationary along the balanced growth path

$$\frac{C}{Y}, \frac{I_{str}}{Y}, \frac{I_{nict}}{Y}, \frac{I_{ict}}{Y}, \frac{Y}{K_{str}}, \frac{Q_{nict}Y}{K_{nict}}, \frac{Q_{ict}Y}{K_{ict}}, \frac{L}{NH}, \tag{20}$$

where the time subscript has been removed for the sake of simplicity.

The balanced growth path can be characterized, based on the intertemporal Euler equation, as

$$\frac{g}{\beta} = (1-\tau_k)\,\alpha_{str}\frac{Y}{K_{str}} + 1 - \delta_{str}, \tag{21}$$

$$\frac{g}{\beta} = \frac{1}{\eta_{nict}}\left[(1-\tau_k)\,\alpha_{nict}\frac{YQ_{nict}}{K_{nict}} + 1 - \delta_{nict}\right], \tag{22}$$

$$\frac{g}{\beta} = \frac{1}{\eta_{ict}}\left[(1-\tau_k)\,\alpha_{ict}\frac{YQ_{ict}}{K_{ict}} + 1 - \delta_{ict}\right], \tag{23}$$

from the law of motion of capital,

$$g = \left(\frac{Y}{K_{str}}\right)\left(\frac{I_{str}}{Y}\right) + 1 - \delta_{str}, \tag{24}$$

$$\eta_{nict} g = \left(\frac{YQ_{nict}}{K_{nict}}\right)\left(\frac{I_{nict}}{Y}\right) + 1 - \delta_{nict}, \tag{25}$$

$$\eta_{ict} g = \left(\frac{YQ_{ict}}{K_{ict}}\right)\left(\frac{I_{ict}}{Y}\right) + 1 - \delta_{ict}, \tag{26}$$

and

$$1 = \frac{C}{Y} + \frac{I_{str}}{Y} + \frac{I_{nict}}{Y} + \frac{I_{ict}}{Y}, \tag{27}$$

$$1 = \alpha_L + \alpha_{str} + \alpha_{nict} + \alpha_{ict}, \tag{28}$$

$$\frac{C}{Y} = \alpha_L \frac{\gamma}{1-\gamma}\frac{1-\tau_\ell}{1+\tau_c}\left(\left(\frac{L}{NH}\right)^{-1} - 1\right). \tag{29}$$

3 Data and parameters

We combine data from the EU KLEMS database with the GCV quality-adjusted price of equipment for the U.S. From the EU-KLEMS database, we retrieve information regarding output, nominal investment, compensation for inputs, capital assets and hours worked for Germany, Japan and the U.S. for 1977-2006. EU KLEMS separates assets into seven categories: (i) structures, (ii) hardware and office equipment, (iii) communication equipment, (iv) software, (v) transport equipment, (vi) machinery, and (vii) other equipment. Note that categories (ii) through (iv) are ICT assets, while categories (v) through (vii) are non-ICT assets. The investment in residential structures is also provided by the EU KLEMS database, although it is not considered in our analysis.

Data are available from 1991 to 2006 for unified Germany and from 1970 to 1990 for West Germany. Using the West Germany data, we reverse-recover the series of output and investment assets of Germany for 1977-1990.

Using a Törnqvist index weighted by the BEA nominal investment shares, the GCV series of quality adjusted investment prices is used to build U.S. deflators for the nominal investment series labeled in the previous categories (ii) through (vii): i.e., for ICT equipment and for non-ICT equipment. For Germany and Japan, we obtain harmonized deflators for the EU KLEMS investment series using Schreyer's (2002) methodology.[3] A detailed explanation of how the different series have been aggregated can be found in the technological appendix of this paper. Structures are deflated using a price index for the consumption of nondurables and services excluding housing. This strategy is justified given that the EU KLEMS database only quality-adjusts series for ICT assets using the corresponding NIPA prices and Schreyer's harmonized deflator. Non-ICT series are not quality adjusted in the EU KLEMS database, so their deflators cannot be used to measure investment specific technological change for the related assets.

Using the GCV quality adjusted investment prices, $q_{i,t}$, $i \in \{nict, ict\}$, investment specific technical change is proxied as $Q_{i,t} = PC_t/q_{i,t}$, where PC_t is the price index for the consumption of nondurables and services excluding housing. No investment specific technological change is assumed for structures. Table 1 presents the average percentage change in $Q'_{i,t}s$, for the U.S. using the GCV dataset, i.e., the investment specific technological change. The first row aggregates over all equipment (TIC and no-TIC). Across 1970-2006, investment specific change has grown by 5% in the U.S. This rate is decomposed into progress due to non-ICT equipment (3%) and that due to the ICT equipment (10.5%). The ICT assets are by far the most important contributors to this rate of progress. However, an additional non negligible source of investment specific change is also provided by non-ICT assets using measures of quality adjusted prices. In fact, the three considered assets of non-ICT equipment show an increasing role.[4]

The evolution of the levels of the $Q_{i,t}$ is depicted in Figure 1 (the base year is 1995). The investment specific technological change aggregated over both types of equipment is also represented. The three lines show an upward trend, although the slope for the ICT is higher according to the estimates of Table 1.

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[3] An application of Schreyer's harmonized deflator can be seen in Basu, Fernald, Oulton and Srinivasan (2003), which compares the evolution of productivity in the U.K. and the U.S.

[4] A similar table can be found in Cummins and Violante (2002).

Table 2 presents average labor productivity growth rates for several periods. Labor is measured in hours worked. On average, for the period 1977-2005 and according to EU-KLEMS data, the Japanese economy shows the highest productivity growth rate (2.70%), followed by Germany (2.46%) and the U.S. (1.55%). The evolution of productivity over time is different; while it is (reasonably) stable for Germany, it decreases in Japan and increases in the U.S. The Japanese growth rate during 2000-2006 is almost half that during the 1990s, while the U.S. growth rate in 2000-2006 is double that in the 1990s. This upsurge in U.S. productivity has been associated with the use of ICT assets (see Jorgenson and Stiroh, 2000; or Jorgenson, 2001).

The calibration requires the assignation of values to the following set of parameters:

$$\left\{ g, \frac{L}{NH}, \alpha_L, \left\{ \delta_i, \frac{I_i}{Y}, \eta_i \right\}_{i \in \{str, nict, ict\}}, \tau_c, \tau_\ell, \tau_k \right\}. \tag{30}$$

Table 3 shows the selected values for these parameters. The first row presents figures for gross productivity growth, g, which are backed by the results in Table 1. The model will be calibrated to ensure that labor productivity growth exactly matches the observed figures.

What follows is the fraction of hours worked over total hours, $L/(NH)$. Hours worked steady shares (L/NH) have been calculated as the average of hours worked taken from the EU-KLEMS database over total hours; the figures are calculated assuming that each worker has a time endowment of 96 hours (16 non-sleeping hours for each of 6 days) per week (therefore, $H = 96 \times 52 = 4992$) and where N is the total number of workers. This fraction ranges from 29% in Germany to 36% in Japan and the U.S. In the case of Japan, this ratio decreased from 42% in 1977 to a stable value of 35% by the middle of the 1990s (see Hayashi and Prescott, 2002). This decrease is related to institutional reforms in the labor market that have limited the workweek since the late 1980s. In the case of the U.S., this ratio is very stable when the EU-KLEMS data are used. Greenwood et al. (1997) instead use a value of $L/(NH) = 0.24$ for the U.S. economy.

We estimate the labor cost share parameter α_L, as the ratio of labor compensation over total compensation (all these series are provided by the EU-KLEMS database). Compensation for the services from residential capital has been excluded. For the U.S. and Germany, these shares are consistent with those provided by Gollin (2002), who estimates that it should be within the [0.65,0.80] interval in a wide set of countries under consideration. In particular, for the U.S. economy, Gollin estimates a range of [0.664, 0.773] that encompasses our prior guess of $\alpha_L = 0.7003$. This value is used by Greenwood et al. (1997) and Pakko (2005) in similar calibrations. However, in the case of Japan, Gollin's estimate is [0.692, 0.727], while we use a value of $\alpha_L = 0.6335$ based on the EU-KLEMS dataset. Hayashi and Prescott (2002) estimate a value of $\alpha_L = 0.638$, using data from national accounts and input-output matrices, which are similar to those that we use.

The depreciation rates, $\{\delta_{str}, \delta_{nict}, \delta_{ict}\}$, are estimated using the three aggregated series of capital. As shown in Table 3, these estimates are similar but not identical across countries, given that the weights within the portfolio of assets differ from one country to another. Further explanation regarding how we calculate this rate can be found in the technological appendix of this paper.[5]

The following rows in Table 3 report the ratio of investment in assets i to output, I_i/Y. In relative terms, the portfolio structure is similar in Germany and Japan but not in the U.S. Non-ICT equipment represents about a half of the total investment in Germany and Japan. The U.S. economy has invested 26% in ICT assets. This weight is notably higher than that observed for Germany or Japan (about 15%).

The average gross price changes for the three assets for the three countries are reported in the following rows in Table 3, 1977-2006,

$$\eta_i = T^{-1} \sum_t Q_{it}/Q_{it-1}.$$

Price variations η_i are similar in Germany and the U.S. The prices of non-ICT equipment change by 2.4% and 3.5% in the U.S. and Germany, respectively. In the case of Japan, this change is 1.9%. The investment-specific technological change, as measured by the evolution of the Q_i, is thus stronger for the ICT equipment (about 11% in the three countries).

Finally, to take into account the distortional effects of taxes, particularly on capital accumulation, realistic measures of tax rates are necessary. We use the tax rates estimated by Boscá, García and Taguas (2008), who follow the methodology proposed by Mendoza, Razin and Tesar (1994); Table 3 presents average values for the period 1980-2005. The tax structure is similar in Japan and the U.S., where labor income taxes are higher than capital

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[5] When quality improvements exist, the economic depreciation rate is different from the physical depreciation rate due to obsolescence. Cummins and Violante (2002) recommend the use of physical depreciation rather than economic depreciation rates when capital is measured in efficiency units, as in our case (the rates in Table 2 are physical). The calibration has been made using both rates of depreciation (i.e., physical and economic), but the results do not hinge on this practice.

income taxes. In Germany, the consumption tax rate is double that of Japan and the U.S., but the labor income tax is higher than the capital income tax.

[**Tables 1, 2 and 3 and figure 1 here**]

4 Productivity growth decomposition

According to the neoclassical growth model, long-term productivity growth can only be driven by the state of technology. In our framework, we can decompose long-term labor productivity growth into three different technological factors: neutral change, non-ICT equipment investment and ICT equipment investment.

In this section, we calibrate the contribution of investment-specific technological progress to long-term labor productivity growth. This calculation is driven by the expression (19), which relates long-term productivity growth to both neutral progress and investment specific technological progress. Additionally, we exploit the system of nine steady state equations (21)-(29) to solve for the following nine unknowns

$$\left\{\alpha_{str}, \alpha_{nict}, \alpha_{ict}, \frac{Y}{K_{str}}, \frac{Q_{nict}Y}{K_{nict}}, \frac{Q_{ict}Y}{K_{ict}}, \frac{C}{Y}, \beta, \gamma\right\}, \tag{31}$$

given the parameters in (30), as reported in Table 3. The right hand side of expressions (21), (22) and (23) are the real (after-tax) rate of return on each asset, which in equilibrium should equal the stationary marginal rate of substitution between future and present consumption, given by g/β. Table 4 summarizes the results obtained from the calibrated decomposition exercise for the three countries using an after tax rate of return of 4%, $g/\beta = 1.04$. These are the results.

Germany. Labor productivity growth is dominated by neutral technological change. The neutral change produces increases in total labor productivity of 1.79%; this represents 73% of productivity growth. Investment-specific technological change accounts for the remaining fraction of 27%. The contribution of the ICT equipment is 0.38 percentage points (15% of productivity growth), whereas the contribution of the non-ICT equipment is about 0.29 percentage points (explaining about 12% of productivity growth).

Japan. The neutral change produces increases in productivity of 1.25%, while specific technological progress produces increases of 1.45%. Therefore, neutral technological change accounts for around 46% of productivity growth. The remaining 54% is accounted for by investment-specific technological change. Contributions from ICT equipment and non-ICT equipment are 20% and 33.7%, respectively.

U.S. Investment specific technological change accounts for 91% of labor productivity growth, due mainly to the ICT assets (which explain about half of the total labor productivity growth). This contribution of ICT greatly exceeds that of the neutral change (0.13%). This proportion is much larger than the 60% fraction calculated by Greenwood et al. (1997) for the period 1954-1990 or that given by Cummins and Violante (2002) for 1947-2000.

[**Table 4 here**]

In view of these results, we highlight the following facts. First, the technological nature of long-term productivity growth is very different in the Japanese and U.S. economies compared with the German economy. Neutral technological change dominates productivity growth in Germany (73%), while it accounts for 46% of labor productivity growth in Japan and only around 8% of labor productivity growth in the U.S. In contrast, investment specific technological change is the main source of productivity growth in Japan and in the U.S. The contribution of investment-specific productivity growth to technological change is around 0.7 percentage points for Germany compared to 1.85 percentage points for Japan and 1.17 percentage points for the U.S.

Second, technology embedded in the ICT assets is a very important source of investment-specific change in these economies, but there are significant quantitative differences across them. This is a standard result that is also found in other papers like that by Collechia and Schreyer (2001) or Jorgenson and Stiroh (2000), which indicate the ICT is responsible for the upsurge in U.S. productivity growth during the 1990s. We find that with only ICT investment-specific technological change, productivity growth would have increased by 0.38% in Germany, 0.91% in Japan and 0.93% in the U.S.

Third, the "traditional" non-ICT equipment also has a non negligible contribution to economic growth with some differences across countries. In Japan and the U.S., the investment specific change associated with ICT equipment is double that of the non-ICT equipment. In contrast, the contribution of non-ICT and ICT to productivity growth is fairly similar in Germany. This contribution is about 0.3 percentage points in Germany and around 0.5 percentage points in Japan and the U.S. Therefore, not only ICT specific change but also non-ICT investment-specific technological change is greater in the Japanese and U.S. economies than in the German economy.

One conclusion that seems to be reasonably derived from the previous results is that investment specific technological change contributes similarly to labor productivity growth in Japan and the U.S. as the main source of long-term labor productivity growth in both economies but the same is not true for Germany. This difference is mainly explained by the role of technological change associated with ICT equipment. Jorgenson and Motohashi (2005) study the role of ICT in the economic growth in Japan and the United States. They show that the contribution of ICT to economic growth in Japan after 1995 was similar to that in the U.S. and that more than half of Japanese output growth from the mid 1990s can be attributed to information technology.

To study how specific technological change has evolved over time, we repeat the previous analysis by splitting the sample period into two periods, 1977-1995 and 1995-2006. The results are summarized in Table 5. In both sub-periods, productivity growth is led by the neutral change in Germany. However, the contribution of specific technological change to productivity growth is 0.56 percentage points in the first subperiod and 0.85 percentage points in the second. Japan experienced a deceleration in the "lost decade" due to the contraction in neutral change (negative in the second sub-period). For the second sub-period, the average contribution to total labor productivity growth from investment specific technological change was about 2.3 percentage points, mainly due to ICT equipment (1.65 percentage points). This is consistent with the results obtained by Hayashi and Prescott (2002), in which low productivity growth in Japan in the 1990s is associated with a reduction in total factor productivity growth. Braun and Shioji (2007) extended this exercise and found that economic growth in the “lost decade” was mainly due to investment-specific technological change. Also, Fueki and Kawamoto (2009), using the EU-KLEMS industry-level database, find that the upsurge in productivity after the mid 1990s in Japan was specific to the ICT production sector. The evolution of the U.S. economy presents an improvement in neutral change, while contributions from investment specific technological change remain almost constant. In the first period, negative evolution even occurs, reflecting the change in pattern after the 1974 slowdown. However, the recovery of TFP growth was remarkable during the 1995-2006 period.

It is worth noticing that non-ICT equipment have also had a decisive participation in the growth of productivity. According to the results in Table 5, this participation has increased after 1995 in the three countries. This finding points out to the fact that, when quality is made for every type of assets, not only the ICT equipment are found as contributors of the

US productivity recovery in the “new economy” age, as growth accounting studies have widely stressed.

[**Table 5 here**]

5 Concluding remarks

This paper investigates the contribution of different sources of technological progress to productivity growth in three leading world economies, i.e., those of Germany, Japan and the United States. We use a dynamic general equilibrium growth model that allows us to decompose productivity growth into three different sources of technological progress: neutral technological change and two different investment-specific forms of technological change (non-ICT and ICT equipment). This distinction is crucial because we want to focus on quantifying the importance of both ICT and non-ICT equipment in explaining differences in productivity growth across the three economies.

The results obtained from the calibration of the model economy show that the sources of productivity growth are different among these three countries. Investment-specific technological change is more important in Japan and the U.S. than in Germany. We find that although it represents a small fraction of the total capital used by the economy, the ICT equipment explains a large fraction of productivity growth. As long as the U.S. economy is an intensive user of ICT, these differences are mainly due to the technological progress embedded in these capital assets. On the other hand, the contribution of neutral change is much more important in Germany than in the other economies, accounting for a large fraction of productivity growth. This implies that differences in long swings of productivity growth can be attributed to the relative importance of the two types of progress.

Our results indicate that the U.S. is becoming the leading economy in terms of productivity growth derived from both investment-specific and neutral technological change, whereas for the Japanese economy, investment specific technological change is becoming the only source of long-term productivity growth. For the German economy, we find that the contribution of investment specific technological change to labor productivity growth is relatively low compared to its contribution in the other two countries.

Yet the role of the investment-specific technological change from non-ICT equipment should not be neglected, as they can account for a considerable fraction of productivity, mainly after 1995. This implies that the so called "new economy age" was not a phenomenon due solely to the ICT assets.

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A Tables and figures

Table 1: Investment Specific Technical Change by Asset, U.S.A. 1977-2006

	77-06	77-80	80-90	90-00	00-06
All equipment	**5.8**	**2.6**	**5.5**	**7.0**	**5.7**
Non-ICT equipment	3.5	0.0	3.5	4.0	4.3
(i) Transport equipment	*3.8*	*2.6*	*3.3*	*4.6*	*4.1*
(ii) Machinery equipment	*3.1*	*2.0*	*2.2*	*3.7*	*4.5*
(iii) Other equipment	*2.2*	*0.1*	*2.0*	*2.5*	*2.9*
ICT equipment	10.9	14.0	10.6	12.3	7.7
(iv) Hardware equipment	*19.1*	*30.1*	*15.6*	*22.1*	*14.3*
(v) Communication equipment	*12.4*	*17.6*	*9.0*	*13.8*	*13.2*
(vi) Software	*4.2*	*5.2*	*4.9*	*4.1*	*2.6*

Table 2: Average productivity growth rates 1977-2006

	Germany	**Japan**	**U.S.A.**
1977-1980	2.92	3.86	-0.15
1980-1990	2.19	3.66	1.05
1990-2000	2.88	2.01	2.10
2000-2006	1.99	1.54	2.28
1977-2006	2.46	2.70	1.55

Table 3: Parameters values

	Germany	**Japan**	**U.S.A.**
g	1.0246	1.0270	1.0155
$L/(NH)$	0.2998	0.3530	0.3660
α_L	0.7848	0.6335	0.7003
δ_{str}	0.0240	0.0240	0.0240
δ_{nict}	0.1183	0.1116	0.1176
δ_{ict}	0.1448	0.1475	0.1566
s_{str}	0.0533	0.0673	0.0495
s_{nict}	0.0656	0.1016	0.0549
s_{ict}	0.0205	0.0309	0.0374
η_{nict}	1.0239	1.0191	1.0349
η_{ict}	1.1060	1.1140	1.1096
τ_c	0.1130	0.0510	0.0470
τ_ℓ	0.3390	0.2510	0.2300
τ_k	0.2420	0.3850	0.3300

Table 4: Sources of productivity growth, 1977-2006

	Germany	Japan	U.S.A.
Productivity g, (a)+(b)	2.46	2.70	1.55
Neutral change (a)	1.79	1.25	0.13
Specific change (b)=(b1)+(b2)	0.67	1.45	1.42
Non-ICT equipment (b1)	*0.29*	*0.54*	*0.49*
ICT equipment (b2)	*0.38*	*0.91*	*0.93*
Elasticities			
Structures, α_{str}	0.0925	0.1373	0.1384
Non-ICT equipment, α_{nict}	0.0947	0.1778	0.0982
ICT equipment, α_{ict}	0.0285	0.0522	0.0625
Decomposition of technical change			
Neutral	72.7	46.3	8.4
Investment-specific	27.3	53.7	91.6
Non-ICT	*11.8*	*20.0*	*31.6*
ICT	*15.5*	*33.7*	*60.0*

Table 5: Contribution to growth, 1977-1995 versus 1995-2006

	Germany		Japan		USA	
	77-95	95-06	77-95	95-06	77-95	95-06
Productivity, g (a+b)	2.52	2.38	3.25	1.81	1.00	2.46
Neutral change (a)	1.96	1.53	1.81	-0.47	-0.32	1.11
Specific change (b=b1+b2)	0.56	0.85	1.44	2.28	1.33	1.35
Non-ICT equipment (b1)	*0.19*	*0.46*	*0.51*	*0.63*	*0.30*	*0.55*
ICT equipment (b2)	*0.37*	*0.39*	*0.93*	*1.65*	*1.03*	*0.80*
Percentage						
Neutral	77.7	64.3	55.7	–	–	45.1
Investment-specific	22.2	35.7	44.3	–	–	54.9
Non-ICT-equipment	*7.5*	*19.3*	*15.7*	–	–	*22.4*
ICT equipment	*14.7*	*16.4*	*28.6*	–	–	*32.5*

Figure 1: Investment-specific technological change, 1977-2006