Information Technology, Research & Development, or both? What really drives a nation's productivity

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Abstract

To what extent are the productivity spillovers of information technology related to R&D activity? Do these factors affect distinctly economic growth, or does the IT impact merely reflect the embodiment of R&D-induced technical progress?
Based on country-level data, this work shows that both forms of technically-advanced capital (R&D and IT) matter for long-run productivity growth. We control for either the domestic specialization in digital productions or import penetration of high-tech goods. In any case, the national endowment of IT assets emerges as a robust source of spillovers. It is also shown that the R&D base of the domestic producers of IT goods is a fundamental driver of productivity for the industrialized countries. In terms of productivity benefits, a low degree of industry specialization in information technology can be hardly compensated by a country's trade openness, i.e. importing R&D-intensive (IT) goods from abroad. This contrasts to what occurs for less advanced productions.

Keywords: Information Technology, Research & Development, Spillovers, Trade, Productivity.

JEL classification: E22, F43, O32, O47.

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1 Introduction

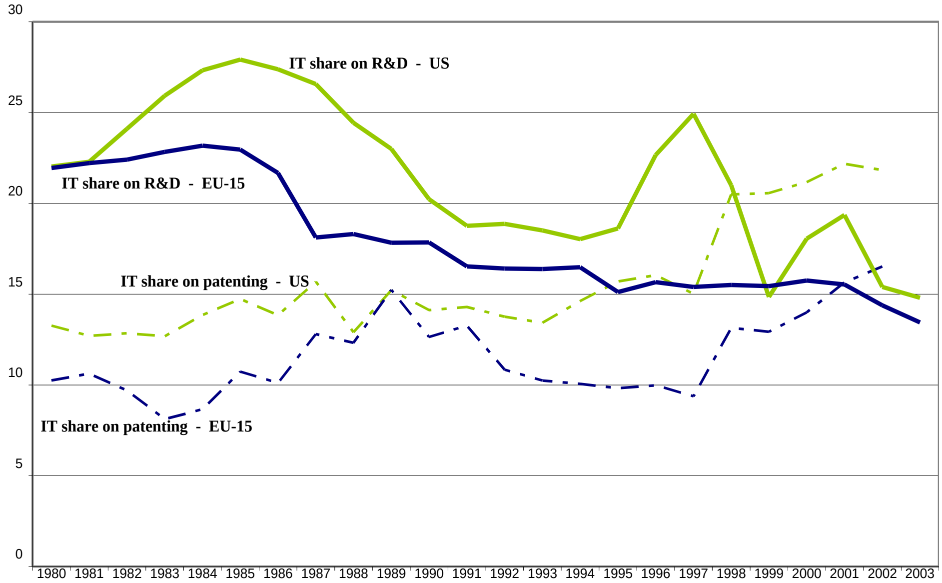
Technological change as outcome of intentional innovation activities is considered a crucial factor for the competitiveness of the modern industrial economies. R&D-based innovation is the main source of productivity, and this in turn determines a nation's well-being over the long-run. Undoubtedly, one of the most extraordinary technical achievements of the last decades are the advances made in the field of information technology (IT). IT is the driving force behind the productivity resurgence recently experienced by most countries, in the form of either firms' capital deepening or TFP growth of those sectors that manufacture these goods.

Aside few exceptions, the majority of works has investigated separately the impact of IT and R&D on economic performance. Though, these two factors are closely related, and present some similarities (and even some discrepancies) that should not be ignored in both theoretical and empirical research. First of all, they spur productivity by enabling knowledge dissemination (either R&D or IT), or creating network externalities (mainly IT). Secondly, IT producing sectors are the most intensively engaged in knowledge generation, accounting for a large fraction of both R&D and patenting activity (Figure 1). R&D-based innovation stimulates the efficiency growth in IT productions and, finally, its benefits accrue to all the purchasers of digital goods. Third, research productivity has been enormously enhanced by the application of the new generations of computers and experimental technologies to both basic and operative projects. At the top level, digital technologies have opened up new frontiers for science (genoma, high-temperature superconductors, etc.) and favored a faster circulation of ideas, as shown by the explosion of the scientific literature during the Internet age. On the other side, firm-level studies have stressed that, to be effective, IT needs complementary investment in business restructuring and human capital, and enterprises undertaking R&D projects reap larger benefits.

Given the complex relation existing between these two factors, assessing the productivity effects of IT and R&D appears a very hard task, especially in the short-run when each of them is likely to reinforce the growth impact of the other. Over a long-term horizon, instead, their social returns are more easily identifiable as the adjustment processes, learning periods and patent protection come at an end. In this respect, it seems particularly interesting to understand whether these types of technically-advanced capital are able to boost productivity distinctly, or rather whether there is a sort of double counting in their measured growth impact. The latter kind of evidence would corroborate the embodiment hypothesis concerning the mechanism through which technical change affects economic growth.

The present paper addresses such issues carrying out a regression analysis on a panel of OECD countries (the former EU-15 and US) over the period 1980-2003. It takes a long-run (cointegration) perspective to allow for the delayed ef-

Figure 1: **Percentage of IT industry on business enterprise R&D expenditure and USPTO patent grants**, 1980-2003



Source: Own calculations on MSTI, OECD (2007) and USPTO. See Data Appendix for details.

fects of IT and R&D on productivity. The analysis is developed in a threefold step. First, we estimate the elasticity of TFP to both forms of technological capital, controlling for the major issues that might undermine the consistency of the estimates. Then, we examine the industry sources of the within-country spillovers associated to R&D; this will allow us to stress the prominence of the IT-producing industry on productivity growth over the long-run. Finally, the empirical analysis is extended to an open-economy framework in order to trace the spillovers' flow related to trade of IT goods. It is found that R&D embedded in imports of computing and telecom equipment is far from promoting domestic TFP, while the reverse occurs with less technically-advanced productions. These findings confute the embodiment hypothesis for IT capital, i.e. that the significance of this factor in productivity regressions does ultimately depend on the R&D base it incorporates. Summing-up, our evidence suggests that a specialization in IT productions is either a fundamental determinant of a nation's productivity or a key factor to compete on the global market. On the other side, there is indication that IT capital provides own productivity benefits, probably due to network externalities or specific knowledge spillovers. This means that investing in this special kind of assets is highly recommendable, even though it does not offset a country's de-specialization in high-tech (IT) productions. In line with earlier studies, the knowledge spillovers of foreign non-ICT producers are found to dominate those associated to the research effort of domestic firms; it confirms that, for relatively low-tech goods, trade is an effective channel for knowledge diffusion.

The outline of the work is as follows. Section 2 surveys the literature on the impact of information technology and R&D on the dynamics of aggregate productivity; it also pays attention to those (few) studies investigating the interaction between these two forms of technically-advanced capital. Section 3 sets down the analytical framework and discusses the econometric issues featuring the regression analysis. Data description and summary statistics are presented in Section 4, the econometric analysis in Section 5. Finally, Section 6 reports some concluding remarks.

2 Overview of related literature

2.1 Productivity effects of IT

In recent years, a great attention has been paid to the contribution given to economic growth by information technology.[1] In most countries (the US ahead), the acceleration in labor productivity has been driven by the direct effects of these new technologies, through firms' capital deepening and the efficiency growth of IT producers (Jorgenson, 2005). Less rich instead is the literature on the economy-wide spillovers of information technology. These indirect benefits are considered a distinctive feature of digital goods; they take the form of network externalities, i.e. the effectiveness of IT on individual performance rises with the number of users, and of the knowledge spillovers enabled by a faster circulation of ideas and a better information management. Fuss and Wavermann (2005) find that network effects have crucially contributed to the recent dynamics of TFP in OECD countries. On the other side, Becchetti and Adriani (2005) emphasize the role of IT as enabler of knowledge dissemination, finding that its diffusion rate in the population is a good predictor for explaining cross-country differentials in income levels.

More generally, IT is regarded as general purpose technology. Its adoption entails long period of experimentation at a firm level, during which radical or incremental changes in organizational structure and in the endowment of human capital need to be finalized. The benefits of the adjustment process implemented by first-users also accrue to imitators and, at an aggregate level, the related gains show up only in a long term. Advances in information technology are claimed to shift the innovation possibility frontier of the economy, rather than directly shifting the production frontier (Bresnahan, 2001). IT uptake stimulates co-invention in users; this widens the potential for further applications, so to continually fuel

[1] See Draca *et al.* (2007) for a recent survey.

the demand for IT capital. Because of such a dynamic feedback loop, IT producers are subject to increasing returns and, finally, information technology has permanent effects on economic growth.

The 'delay hypothesis' is often advanced to explain why, at an industry-level, TFP growth is not statistically associated to contemporaneous IT investment, while it occurs with the lagged values (see respectively Stiroh, 2002 and Basu *et al.*, 2004). Yet, as shown by van Ark and Inklaar (2005), the relation may be not linear (U-shaped): 'early normal returns' stimulated by IT-production and -investment are followed by periods of 'negative spillovers', that show up when firms develop capital complementarities. An alternative strategy to fully identify the benefits of IT capital consists in working with long growth rates, as done among others by Brynjolfsson and Hitt (2003) at a firm-level and Oulton and Srinivasan (2005) on industry data.

As within the R&D context (Griliches, 1992), these arguments suggest that the estimated elasticity of TFP to IT capital is likely to be higher when a regression analysis is performed at a higher level of data aggregation as better capturing the social returns of this general purpose technology. To this end, a long-run (dynamic) perspective of analysis appears helpful for overcoming the (static) compensation existing between the performance of innovative and non-innovative firms (or industries),[2] making the economy-wide spillovers hard to single out in a short-term horizon.

2.2 Productivity effects of R&D

Since Griliches (1979) on, technological knowledge intended as either output of innovation activity or input in production of new knowledge has been a central topic in productivity literature.[3] At a country-level of analysis, Lichtenberg (1993) has first investigated the productivity effects of (privately-funded) R&D, finding an output elasticity of 7%. This evidence is interpreted against the existence of international spillovers; indeed, if knowledge did really spill over free of charge, then domestic R&D would not have a differential impact with respect to foreign knowledge. Nevertheless, it is only with the seminal paper by Coe and Helpman (1995), henceforth CH, that a focused attention has been increasingly paid

[2]See McGuckin and Stiroh (2002) for a discussion on the aggregation relations.

[3]Traditionally, a threefold effect is ascribed to R&D-based innovation. First, it raises the efficiency of the economic entities engaging in such activities. Furthermore, given its non-rival and non-excludible nature, technological knowledge also spills over across firms, industries and countries (or regions). Finally, R&D activity eases the absorption of technology developed elsewhere (technology transfer). This paper deals with the former two types of spillovers, referring for technology transfer to Cohen and Levinthal (1989) and subsequent works (Griffith *et al.*, 2003, and 2004).

to international technology spillovers. The main results of this literature are summarized in Table 1.[4] Under the assumption that knowledge is embodied in traded intermediate goods, CH show that larger advantages accrue to countries that import intensively from technically-advanced economies (*direction effect*). Foreign knowledge is gauged by averaging out the R&D stock owned by trading partners through bilateral import shares. Moreover, productivity is found to rise in proportion to a country's trade openness, measured by multiplying the foreign R&D with the import intensity of the recipient economies (*intensity effect*).[5] According to Keller (1998) however, this type of evidence does not corroborate the hypothesis that technological knowledge flow across countries through trade, since identical results arise whatever weights are adopted, even randomly generated. On the other side, Lichtenberg and van Pottelsberghe (1998, LP) stress that the CH's weighting scheme is subject to an *aggregation bias*, and that opportunely correcting it yields better outcomes on international spillovers.

Nowadays, there is large agreement that international spillovers contribute crucially to the productivity growth of the modern industrialised economies and, for technically following countries, even more than domestic R&D. It has been recently confirmed by examining either alternative channels of transmission or different measures of foreign knowledge. For instance, Madsen (2007) and Bottazzi and Peri (2007) exploit patent data. The former finds that trade-related spillovers amount to a 90% of the innovation impact on productivity; the latter shows that the contribution provided by foreign (un-weighted) patents to the domestic patenting ability (i.e. technological productivity) is larger than domestic R&D for the non-G7 countries, but not for the biggest economies. Using recursive weights, Lumenga-Neso *et al.* (2005) detect that the indirect R&D spillovers coming from the backward trade relations of commercial partners are in absolute the major drivers of productivity. Lee (2006) examines simultaneously a wide array of tools through which innovation may spill over internationally, finding that only inward FDI and disembodied technical change are knowledge conduits. Similarly, using technology balance of payments, Mendi (2007) shows that disembodied technology has mainly benefited backward countries, especially at the earlier phases of their take-off. Guellec and van Pottelsberghe (2004) investigate instead the interaction among the different forms (and funding) of R&D; both public basic research and foreign knowledge account more than the innovation performed internally by the business sector, despite the gap has been reducing over time. Among the factors complementary to R&D in raising the productivity levels, human capital turns out to be particularly effective (Engelbrecht, 1997 and Frantzen, 2000).

[4] See Keller (2004) for an extended survey.

[5] Kao *et al.* (1999) were first to warn against the estimation bias of earlier works, while Edmond (2001) to study cross-country heterogeneity in slope coefficients.

Table 1: **Summary of econometric evidence on international technology spillovers**

	Weighting scheme	type	DRD	DRD for G7	FRD	$m*FRD$	*Additional regressors* parameter	description	Table; pag.; # regression
Country-level studies									
Coe and Helpman (1995)	CH	IMP	0.097		0.092				3; 869; i
”	CH	IMP	0.078	0.156		0.294			3; 869; iii
Lichtenberg and van Pottel. (1998)	LP	IMP	0.059	0.086	0.109				2; 1488; v
Frantzen (2000)	CH	IMP	0.091	0.092	0.170		0.150	Human capital	3; 68; iv
Engelbrecht (1997)	CH	IMP	0.072	0.170		0.198	0.136	Human capital	1; 1483; v
Keller (1998)	RS		0.048	0.159		0.329			2; 1475; iii
Edmond (2001)	UW		0.088	0.124	0.149				3; 254; vii
Lumenga-Neso *et al.* (2005)[1]	LP	IMP	n.s.	n.s.	.208		0.995	Indirect FRD	1; 1791; iii
Madsen (2007)[2]	LP	IMP	0.050	0.290					1; 474; ix
Bottazzi and Peri (2007)[3]	UW		n.s.		0.749				4; 501; vi
”	UW			0.699	-0.300				”
Lee (2006)	LP	IMP, TP, FDI	n.s.		n.s.		0.028; 0.184	Inward FDI; disembodied technical change	5; 2085; x ”
Guellec and van Pottel. (2004)[4]	CH	TP	0.130		0.450		0.170	Public R&D	3; 365; i
Mendi (2007)	LP	IMP	0.113	0.236	0.074		0.057; -0.168 for G7	Technology balance payments	5; 130, iv
*Industry- and Country-level studies**									
Frantzen (2002)[5]	CH	IO, TP, m	0.158 [0.163]	n.s. [0.207]	0.045 [0.181]				3; 291; viii
Keller (2002b)[6]	CH	IO, IOM	0.607 [0.571]		0.092 [0.294]				6; 15; iv
Keller (2002a)	CH	DD	0.078		0.853		1.005	Distance decay parameter	2; 129; i
Acharya and Keller (2007)[5,7]	UW		0.159		0.450	0.697			13; 39; iv

Notes DRD: domestic R&D stock. FRD: foreign R&D stock. $m = \frac{M_i}{Y_i}$, M_i and Y_i are total import and GDP of domestic country (in current prices).

Scheme. CH:$FRD_i = \sum_{j \neq i} \frac{M_{ij}}{M_i} DRD_j$, M_{ij} are imports of country i from country j. LP:$FRD = \sum_j \frac{M_{ij}}{Y_j} DRD_j$, M_j is nominal GDP of the exporting country j. RS= randomly simulated shares. UW=un-weighted.

Type. IMP= bilateral imports; TP: Technological proximity; FDI: Foreign direct investments; IO: inter-sectoral input-output total flows; IOM: inter-sectoral input-output total import flows; DD: Distance deflated foreign R&D stock (only G-5 countries considered).

IO: $DRD_i^{\tau} = \sum_{\tau \neq \upsilon} \frac{m_i^{\tau\upsilon}}{m_i^{\tau}} DRD_i^{\upsilon}$, where $m_i^{\tau\upsilon}$ is the flow of intermediate inputs from industry υ to industry τ in country i, and m_i^{τ} is the total sum of domestic intermediate purchases.

IOM: $FRD_i^{\tau} = \sum_{i \neq j} \frac{M_i^{\tau\upsilon}}{M^{\tau}} FRD_j^{\upsilon}$, where $M_{ij}^{\tau\upsilon}/M_i^{\tau\upsilon}$ is the share of country's imports of intermediate inputs of the kind υ by industry τ.

* In squared brackets the estimated spillovers on productivity of the recipient industry τ in country i coming from the other industries of the same country (υi) and from those of the trading partners (υj).

1. Based on recursive weights and a grid search estimation.
2. Based on a stock-based variant of LP scheme; see section 3.1.
3. Domestic stock of patents is used as dependent variable, the foreign stock as a proxy for FRD; results are obtained from separate regressions.
4. Long-run parameters inferred from an ECM regression.
5. Based on an extended output production function framework.
6. Parameters estimated from a non-linear regression; the coefficient of DRD_{υ}, FRD_{τ} and FRD_{υ} represent the marginal effect with respect to DRD_{τ}.
7. FRD and m*FRD are the sum of the statistically significant coefficients relative to foreign R&D of G-6 countries.

Recently, aggregate evidence has been enriched by several industry-level studies, where intermediate transactions from input-output tables are used to gauge the within-country spillovers (Keller, 2002b).[6] Among others, this approach has been adopted by Acharya and Keller (2007) to assess the extent to which the R&D effort of the OECD technological leaders influences the economic performance of the other member states.

2.3 Interaction between IT and R&D

Although the co-invention process between information technology and R&D has been long recognized,[7] empirical literature on the interaction between these two factors is still unsatisfactory. Greenan *et al.* (2001) estimate some productivity regressions on French micro data (up to 1994); computing equipment and research engagement are jointly significant in cross-sectional specifications, but not in time-series regressions. A similar (cross-sectional) result is found by Matteucci and Sterlacchini (2004) studying a sample of Italian manufacturing firms during the golden years of the 'Information age' (1998-2000); the coefficient of R&D intensity is stably significant across various specifications, while that of IT investment only if taken with a lag, confirming the well-known 'delay hypothesis'. At an economy-wide level of analysis, Lee (2005) employs the CH's framework to understand the extent to which international spillovers are related to the development of telecom infrastructures, proxied by the telephone penetration rate. This effect is shown to be sizeable, especially after the advent of the Internet. This evidence is consistent with the findings (up to the mid-1990s) earlier provided by Madden and Savage (2000), exploiting a measure of foreign knowledge interacted with the import share of IT goods and an utilization index of telecommunications.

[6] In place of intermediate transactions, Frantzen (2002) employs a patent-based indicator for assessing the technological proximity among industries; Keller (2002a) examines instead the role of geographical distance. In this strand of literature, the most generalized procedure has been implemented by Brandt (2007) by estimating a dual cost function.

[7] See Allen (1986) for a discussion on the potential of information technology for research productivity.

3 Empirical setting

3.1 Analytical framework

We start by considering the following closed-economy framework (model 1):

$$\ln TFP_{it} = \alpha_{0i} + \alpha_1 \ln IT_{it} + \alpha_2 \ln DRD_{it} + \alpha_3 C_{it} + \epsilon_{it}, \quad (1)$$

where TFP_{it} is the index of total factor productivity, IT is the stock of information and communication technology capital, DRD_{it} is the cumulative (domestic) expenditure in research and development. C_{it} instead comprises a set of common time dummies and some control variables (expressed in logs) that will be introduced below. α_{0i} are the country fixed-effects, ϵ_{it} the usual stationary errors. i denotes countries ($i = 1, ..., 15$), and t the time period ($t = 1980, ..., 2003$). Initially, we consider gross expenditure on R&D as measure of knowledge capital (GERD). Then, to avoid any distortion related to the heterogeneity in the growth impact exerted by the different forms of research, we distinguish between business enterprise and public R&D (BERD and PRD), assuming a log-additivity form in their effects on productivity.

In model 2, we examine the importance of the productivity spillovers associated to R&D carried out by the IT sector relatively to that of non-IT firms. The specification to be estimated is thus shaped:

$$\ln TFP_{it} = \alpha_{0i} + \alpha_1 \ln IT_{it} + \alpha_2 \ln DRD^I_{it} + \alpha_3 \ln DRD^{NI}_{it} + \alpha_4 C_{it} + \epsilon_{it}. \quad (2)$$

DRD^I is the stock of domestic R&D cumulated by the IT-producing industry, while DRD^{NI} the one developed by the (non-IT) remaining part of the market economy. Model 2 is helpful for excluding the possibility that the TFP-enhancing effect of the knowledge cumulated by IT producers is taken up by the coefficient of IT assets when adopting an aggregate measure of R&D capital.

In model 3, we assess the relevance of imported technology spillovers. It is done by adding to the previous specification the R&D stock developed abroad by either IT or non-IT sectors (FRD^I and FRD^{NI}):

$$\ln TFP_{it} = \alpha_{0i} + \alpha_1 \ln IT_{it} + \alpha_2 \ln DRD^I_{it} + \alpha_3 \ln DRD^{NI}_{it} + \alpha_4 \ln FRD^I_{it} + \alpha_5 \ln FRD^{NI}_{it} + \alpha_6 C_{it} + \epsilon_{it}. \quad (3)$$

The main objective of this specification is of eliminating the risk that IT capital be upward biased because of the omission of R&D carried out abroad by IT producers.

The foreign stock of technological knowledge is computed using the method devised by Lichtenberg and van Pottelsberghe (1998). Unlike the CH's weighting scheme, this procedure is invariant to the level of data aggregation, i.e. the amount of foreign knowledge which is relevant for an importing country does not rise by merging two (or more) exporters. This paper is aimed at examining the knowledge spillovers engendered by foreign producers of IT goods, in comparison to those activated by non-IT sector ($FRD^{\lambda},\ \lambda = I, NI$). To this end, the external stock of knowledge owned by each type of industry is computed by weighting its R&D capital with the sectoral value of exports towards the recipient countries over value-added (both in current prices):

$$FRD_{it}^{\lambda,F} = \sum_{j=1}^{15} \frac{M_{jit}^{\lambda,F}}{Y_{jt}^{\lambda,F}} DRD_{jt}^{\lambda}, \quad i \neq j \quad \lambda = I, NI, \quad t = 1980, ..., 2003.$$

DRD_{jt}^{λ} is the knowledge stock of sector λ at time t in country j, $M_{jit}^{\lambda,F}$ the exports' flow of industry λ in country j towards the recipient country i, $Y_{jt}^{\lambda,F}$ is nominal value-added of the exporting industry.

Since imports exhibit large variations over time, in particular for IT goods, two additional types of weights are used to validate the results' robustness. By construction, they are less sensitive to temporary changes in trade figures and, consequently, should more accurately reflect the permanent effects of external knowledge on domestic TFP. First, we build a smoothed LP indicator using a 3-year moving average of flows of both exports and value added ($\overline{M}_{jit}^{\lambda,F}$ and $\overline{Y}_{jit}^{\lambda,F}$):

$$FRD^{\lambda,\overline{F}} = \sum_{j=1}^{15} \frac{\overline{M}_{jit}^{\lambda,F}}{\overline{Y}_{jt}^{\lambda,F}} DRD_{jt}^{\lambda}, \quad i \neq j \quad \lambda = I, NI, \quad t = 1980, ..., 2003.$$

Secondly, we construct the stocks-based variant of the LP's weights proposed by Madsen (2007); it rests on the current price ratio between the cumulative value of exports and that of value added ($M_{jit}^{\lambda,S}$ and $Y_{jt}^{\lambda,S}$):

$$FRD_{it}^{\lambda,S} = \sum_{j=1}^{15} \frac{M_{jit}^{\lambda,S}}{Y_{jt}^{\lambda,S}} DRD_{jt}^{\lambda}, \quad i \neq j \quad \lambda = I, NI, \quad t = 1980, ..., 2003,$$

where

$$M_{jit}^{\lambda,S} = M_{jit}^{\lambda,F} + (1-\delta) M_{jit-1}^{\lambda,S} \qquad Y_{jt}^{\lambda,S} = Y_{jt}^{\lambda,F} + (1-\delta) Y_{jt-1}^{\lambda,S},$$

and δ is the depreciation rate utilized to build the knowledge stock ($\delta = 0.15$). As evident, the stocks-based measure of foreign R&D collapses into the original one proposed by Lichtenberg and van Pottelsberghe (1998) when there is full depreciation for imported knowledge ($\delta = 1$).

3.2 Econometric issues

In this paper we use the panel dynamic OLS estimator developed by Mark and Sul (2003). It represents the panel extension of the single-equation procedure devised by Saikkonen (1991), whose properties have been earlier studied by Kao and Chiang (2000) under more restrictive conditions. Assuming homogenous coefficients among individuals, panel DOLS estimates the cointegration relation by introducing into each country equation lags and leads of the first-differenced regressors, eliminating thus the endogeneity bias. Albeit it rests on the hypothesis of errors' independence, panel dynamic OLS is effective even for low degree of cross-section dependence, which can be easily allowed for by working with cross-sectionally demeaned variables; this procedure is equivalent to using common time dummies. Such properties make panel DOLS a valid alternative to panel fully-modified OLS estimators. Recently, Mark *et al.* (2005) have also studied the asymptotic distribution and small-sample performance of panel DOLS under cross sectional dependence; this type of bias can be removed by also adding to each specification lags and leads of the first-differenced regressors of the other individuals. Mark *et al.* (2005) demonstrate that there is little difference in the size distortion of panel DOLS relatively to dynamic SUR, despite the latter estimator achieves substantially higher efficiency gains in presence of moderate to strong levels of cross-section dependence.

The dynamic properties of the variables are studied through the panel unit roots test developed by Pesaran (2007), $CIPS$, and the cointegration tests devised by Westerlund (2005), VR_g and VR_p. $CIPS$ checks that the all series are non-stationary. It consists in the mean of the t-ratio statistics yielded by cross-sectionally augmented Dickey-Fuller regressions (CADF); these are standard DF specifications enriched with the lagged value of cross-section mean and its contemporaneous first difference so to remove cross dependence.[8]

The variance ratio statistics developed by Westerlund (2005) consist in stationarity tests on the residuals of the potentially cointegrated relation and, accordingly, their null hypothesis is of no cointegration. These tests are defined as the sum over both the time- and cross-section dimension of the product between the square of the residuals' partial sum and the total sum of the residuals' square. The panel mean variance statistics, VR_p, is built by summing the separate terms over the cross sections prior to multiplying them together, the group mean variance statistics, VR_g, by first multiplying the various terms and then summing over the cross-sectional dimension. The alternative hypothesis of VR_p is that the panel is cointegrated as a whole, for VR_g that there is a positive fraction of cointegrated individuals. Both statistics admit individual specific (short-run) dynamics, inter-

[8]Serial correlation is controlled for by including into each specifition lagged first-differences of either single variable or their cross-section mean.

cepts and slope coefficients. However, by construction, VR_g accommodates a larger degree of heterogeneity, lowering the risk in small samples of accepting the null hypothesis of no cointegration because of few individuals. By contrast, the rejection of the null hypothesis by the VR_p test provides strong evidence in favor of the cointegration. It should be finally remarked that both VR statistics hinge on the assumption of error terms' independence. Though, they perform optimally even in presence of a low degree of cross-section dependence (i.e. the case with common time dummies), and moderately well for higher levels of correlation. In any case, their small-sample distortions is inferior to that emerging with other popular cointegration tests (Pedroni, 2004).

4 Data description

4.1 Data sources and methodology

This study examines a sample of OECD countries composed by the United States and the EU-15 members (excluding Luxembourg) over the period 1980-2003. As economy-wide measure of efficiency, total factory productivity (TFP) is calculated as residual growth of GDP over the income share-weighted rise of factors, hypothesizing perfectly competitive markets and constant returns to scale. TFP is indexed to 100 in a benchmark year (2000).

National Accounts series are taken from GGDC Total Economy Growth Accounting database.[9] It collects (and integrates) data on GDP, hours worked and various types of capital assets (IT and non-IT) from national statistical offices. IT capital includes office machinery and information equipment, communication equipment and software. On the other side, non-IT capital comprises non-residential buildings, transport equipment and non-IT equipment. These series are constructed using the Tornqvist index formula; it aggregates sub-categories with continuously updated shares, turning out to be the exact formula (superlative index) when the underlying (flexible) production function is of the translog form. These properties make the Tornqvist index more appropriate for productivity estimates than base-year (Laspeyres) indexes, usually applied to a Cobb-Douglas production function framework (Griffith *et al.*, 2004).

The stock of knowledge capital is built from R&D expenditure series reported in OECD Main Science and Technology Indicators and ANBERD database.[10] Below, we carry out separate regressions using either gross expenditure in research and development (GERD) or business enterprise R&D (BERD) as measure of

[9] Groningen Growth and Development Centre. Details can be found in Timmer *et al.* (2003).

[10] OECD (2007, and 2002a).

knowledge capital. Along with BERD, the former includes expenditure of public research labs, of higher education sector and other non-profits institutions; for simplicity, we label public research and development the difference between GERD and BERD (PRD). The broadest indicator of knowledge capital (GERD) is utilized as more consistent with data on IT assets, which refer to the total economy. Though, the focus will be later restricted on innovation activity of business sector. Indeed, the main goal of this study is of checking whether IT and R&D exert a separate effect on productivity, and it is well-known how the scientific advances in the field of digital technologies are strictly related to the initiative of privately-owned firms. In this respect, business R&D will be also disentangled into the one performed by the IT-producing industry and that carried out by the remaining market industries, labelled as non-IT producers. IT (manufacturing) industry includes office machinery and communication equipment (categories 30 and 32, ISIC Rev.1).[11] Foreign stocks of R&D are constructed employing data on bilateral trade by commodity and industry, expressed in current dollars, respectively taken from OECD International Trade by Commodities Statistics and STAN Bilateral trade database.[12]

In robustness checks, we employ as control variables the average number of schooling years, and an alternative indicator of knowledge capital based on patent data. The former is extracted from the Barro and Lee (2000)'s data set; for the latter, we rest on patent applications at the European Patent Office and patent grants at the US Trademark and Patent Office, collected in OECD Main Science and Technology Indicators and in NBER Patent Data files (Hall *et al.,* 2001).

Finally, it remains to be said that each monetary variable has been converted into US purchasing power parities, expressed in 2000 constant dollars; capital stocks have been calculated from series on real expenditure (or patent counts) through the permanent inventory method, adopting an appropriate geometric rate of depreciation. A detailed description of the statistical sources and the methodology followed in building series is provided in the Data Appendix.

[11] This classification slightly differs from the official one adopted by OECD (2006b, Annex A). Among IT manufacturing industries, the latter includes insulated wires (313) and scientific instruments (332 and 333 ISIC Rev. 1) in addition to the categories 30 and 32. Among service industries, OECD considers firms trading IT goods as wholesale of machinery, equipment and supplies (5150), renting of office machinery and equipment (7123), as well as such IT intangibles as telecommunications (642) and computer and related activities (72). These categories are excluded from the analysis due to severe limitations in R&D data.

[12] OECD (2002b, 2006a and 2006c).

4.2 Descriptive analysis

Table 2 reports the dynamics of productivity and the various types of technically-advanced capital over the period 1980-2003, expressed as average annual percentages of change. In our sample, TFP grew on average by a 1.3% per year, showing however a remarkable variation among countries. It increased particularly fast in Ireland and Finland that, as a consequence, reduced sizeably their technological gap from the leading economies. By contrast, productivity has been rather sluggish in Greece and Spain where it contributed marginally to the process of convergence towards the income levels of the richest countries.

The cumulation of IT capital has been relatively more homogenous across countries; on average, it amounts to a 14% annually, with the best performance being shown by Ireland and UK (about 17%). For this indicator, the modest range of variation is consequence of the harmonization in investment deflators implemented at GGDC; indeed, to guarantee a consistent treatment to quality improvement, IT expenditure has been deflated by applying the hedonic prices constructed by the Bureau of Economic Analysis for the US, adjusted for the cross-country difference in general inflation (see also Schreyer, 2002).

Looking at knowledge capital, it can be observed how the broadest measure of R&D averagely expanded at a rate of 5.4% per year, while that of business sector at a 6.6%. For both indicators, the highest rates of change are exhibited by those countries less engaged in research activity at the beginning of the period. Among these economies, business sector played a driving role in the knowledge-generation process of Ireland and Finland, where BERD stock increased at a 11% rate per year. On the other tail of the distribution, the rates of change in the stock of business R&D have been considerably lower, except than for the US. In fact, this country has reinforced its leadership in R&D-based innovation, especially in the late 1990s when it outpaced the rate of knowledge cumulation registered by the other large-sized economies. The slowest rate of growth in BERD capital is shown by the UK, closely followed by Germany and Italy. Note that the latter country represents then the unique case in which the rise of public R&D stock exceeds that of business sector.

A deeper outline on the knowledge-accumulating process can be traced disentangling the performance of IT firms from the rest of the market economy. On average, R&D capital increased at a double digit rate in the former type of industry (11.6% against 5.9%), a differential which becomes considerably wider in the US and Sweden.[13] By contrast, in the UK the knowledge stock expanded

[13] At an industry-level, R&D expenditure has been deflated by the price index for value-added. These series are taken from EUKLEMS where it is not implemented any harmonization for the IT sector; it implies that only few countries employ hedonic deflators, i.e. price indexes adjusted to control for the quality growth in IT output (Timmer *et al.*, 2007). These methodological issues

Table 2: **Dynamics of TFP and Technically-advanced Capital**, 1980-2003
(average annual percentage rates of growth)

	TFP	IT	DRD-GERD	DRD-BERD	DRD^{I}	DRD^{NI}	FRD^{I}	FRD^{NI}
Austria	1.1	12.7	5.4	6.4	6.6	6.9	11.9	4.2
Belgium	1.4	15.6	3.0	3.5	5.1	3.8	13.4	3.1
Denmark	0.8	15.4	6.3	8.0	10.3	8.4	13.6	3.1
Finland	2.2	13.9	8.7	10.8	21.7	7.1	16.1	4.7
France	1.2	13.9	4.3	5.6	16.3	4.3	11.0	3.6
Germany	1.9	11.9	2.5	2.7	5.2	2.6	14.4	3.7
Greece	0.6	13.5	7.5	9.6	20.3	8.8	15.5	3.7
Ireland	2.7	17.2	8.1	10.9	14.9	10.3	14.8	4.5
Italy	0.7	12.4	3.2	2.8	4.5	2.9	12.1	3.7
Netherlands	0.9	15.6	2.8	3.4	8.6	2.6	11.2	2.7
Portugal	1.2	13.0	8.1	8.7	8.4	9.5	15.6	5.5
Spain	0.6	15.0	7.4	8.5	9.1	8.9	15.8	8.3
Sweden	1.2	14.5	6.6	8.2	21.0	5.3	11.7	3.2
United Kingdom	1.3	17.4	1.2	1.7	-0.6	3.1	16.3	5.0
United States	1.1	14.1	6.5	7.9	23.1	4.3	13.0	6.4
Total	1.3	14.4	5.4	6.6	11.6	5.9	13.8	4.4

Notes TFP: total factory productivity; IT: IT capital stock; DRD: domestic R&D stock; DRD^{I}: domestic R&D of IT industry; DRD^{NI}: domestic R&D of non-IT industry; FRD^{I}: foreign R&D of IT industry; FRD^{NI}: foreign R&D of non-IT industry. Foreign R&D is constructed using the (flows-based) LP weighting scheme.

more rapidly in the non-IT part of the economy, even though this tendency has reverted in the last years. A specular pattern in the R&D dynamics can be found in Germany and Italy where the research effort of IT firms was sizeable up to the mid-1990s, since when it deteriorated sharply.[14]

The last two columns of Table 2 report the dynamics of foreign R&D distinguished by industry types; these values represent the portion of knowledge built abroad which is potentially relevant for the productivity growth of recipient countries, being embedded in imported goods. In open economies, trade might act as tool for offsetting the inadequate innovative effort of domestic firms, in particular in those productions where there is an on-going process of international concentration in knowledge generation (opposed to a fragmentation of manufacturing), as in the field of information technology. As a mirror of the rise in both research effort of IT producers and the international trade, FRD^{I} grew faster than domestic R&D over the last quarter of century (13.8 vs 11.6). It should be noted that, for this indicator, the highest rate of growth is shown by the UK (16.3), i.e. the country characterized by a stagnant knowledge cumulation by IT producers. On the

will be further discussed below, and shown not to affect the outcomes of the paper. Table A.1 of the Appendix reports the estimated level of the variables at the beginning and at the end of the period considered.

[14]See Sterlacchini and Venturini (2007) for an industry-level examination on productivity effects of R&D across the major EU states and the US.

Table 3: **Correlation between TFP and Technically-Advanced Capital**, 1980-2003 (5-year growth rates)

	TFP	IT	DRD-GERD	DRD-BERD	DRD^{I}	DRD^{NI}	FRD^{I}	FRD^{NI}
TFP	1.00							
IT	0.31**	1.00						
DRD-GERD	0.31**	0.28**	1.00					
DRD-BERD	0.29**	0.30**	0.95**	1.00				
DRD^{I}	0.18*	0.16	0.66**	0.73**	1.00			
DRD^{NI}	0.19*	0.31**	0.83**	0.87**	0.33**	1.00		
FRD^{I}	-0.01	0.26**	0.05	0.096	-0.01	0.08	1.00	
FRD^{NI}	0.20*	0.39**	0.33**	0.28**	0.30**	0.19*	0.45**	1.00

Notes. TFP: total factory productivity; IT: IT capital stock; DRD: domestic R&D stock; DRD^{I}: domestic R&D of IT industry; DRD^{NI}: domestic R&D of non-IT industry; FRD^{I}: foreign R&D of IT industry; FRD^{NI}: foreign R&D of non-IT industry. Foreign R&D is constructed using the (flows-based) LP weighting scheme. **, * significant respectively at 5 and 10%.

other side, the average rate of expansion in FRD^{NI} appears remarkably slower, and only Spain stands out for a brilliant performance.

Table 3 completes the descriptive picture showing the correlation existing between the dynamics of TFP and that of the different measures of technically-advanced capital, based on 5-year growth rates. Long-differences seem more appropriate when one is interested in the long-run co-variation among economic variables; this is in line with the spirit of the cointegration analysis developed below. From this table, it is easy to see how the productivity dynamics is significantly correlated with the cumulation of both IT assets (0.31) and knowledge capital (0.29 for GERD and 0.31 for BERD). Separating the R&D stock between IT and non-IT firms, and between domestic and foreign industries, we find a smaller degree of correlation between knowledge capital and TFP. The dynamics of productivity is statistically un-related to that of the R&D stock of foreign IT firms (FRD^{I}). Finally, to the aim of the paper, it is interesting to note that IT capital results correlated with FRD^{I} (0.26) but not with DRD^{I}.

5 Empirical results

Productivity spillovers within a closed-economy framework (Model 1)

This section starts by showing the estimation of equation 1. Along with the estimated elasticities, Table 4 reports on the right the value of the panel unit roots test ($CIPS$), that of panel cointegration tests on the bottom (VR_g and VR_p). The former checks that all the panel units are non-stationary, and diverges towards a negative infinite under the alternative hypothesis. The latter tests assume the null hypothesis that there is no cointegration among variables, and are distributed as a negative, one-sided standard normal.

Initially, productivity is regressed on IT capital and the total economy measure of R&D (column i), whose elasticities are found to amount respectively to 0.063 and 0.107.[15] The latter coefficient stands in the range of values found in earlier works (see Table 1), while the former turns out to be more conservative than the average elasticity estimated by Ketteni *et al.* (2007), 0.22, investigating the complementary (non-linear) effects of IT and human capital on productivity.

Regression (ii) shows that business sector is the unique source of R&D spillovers for industrialized countries (0.118), being public research not significant. A consistent evidence has been provided by Park (1995). The result for PRD might depend on a compensation between the effects of research activity of higher education sector and that of government agencies. When public research is left out (column iii), business R&D soars up to 0.128, while IT capital falls to 0.047. Evidently, regression (iii) indicates that both types of technically-advanced capital are featured by excess of returns.[16] The estimated elasticity of TFP to business R&D gauges the social returns of knowledge-generating processes, i.e. inter-firm and inter-industry externalities (rent and knowledge spillovers). The coefficient of IT capital most probably captures the networking effects associated to the usage of this assets' types, as well as the spillovers enabled by a more rapid circulation of knowledge and a better information management.

As surveyed above, the growth impact of technically-advanced capital is usually enhanced by the upgrading of workforce's skills and level of education. Both R&D and IT capital are correlated with human capital, implying that the elasticities so far estimated may take the effect of such an omitted factor. To control for this issue, we add the average number of schooling years to equation (1). Regression (iv) shows that human capital is far from being significant; nonetheless, its inclusion causes the coefficient of IT capital to lower (0.023), and that of business R&D to increase (0.192).

In column (v), the amount of hours worked is used as explanatory variable to exclude any bias related to the presence of increasing returns to scale. Indeed, TFP is computed assuming perfectly competitive markets and constant returns to scale; if the latter assumption is violated, the Solow's residual overstates the true level of technical progress. As a consequence, in our productivity regression, the coefficient of R&D or IT capital could be inflated by increasing returns, rather than reflecting the presence of genuine technological spillovers.[17] This possibility

[15] In the regression analysis, one-year lags and leads of the regressors' first-differences are inserted into the log-level specification.

[16] It should be reminded that the directed contribution given by each factor to economic growth is already incorporated in output volume: IT capital as separate input, while R&D expenses being included in capital and labour costs.

[17] Consider the definition of the *true* TFP expressed in terms of growth rates: $g_z^* = g_Y -$

Table 4: **Estimation of productivity spillovers in a closed economy**

	(i)	(ii)	(iii)	(iv)	(vi)	(vi)	(vii)	$CIPS$
TFP (dep.)								*-0.27*
IT	0.063**	0.060**	0.047**	0.023**	0.069**	0.051**	0.050**	*-0.91*
	(0.012)	(0.011)	(0.014)	(0.010)	(0.012)	(0.008)	(0.012)	
DRD-GERD	0.107**							*-1.04*
	(0.034)							
DRD-PRD		-0.005						*0.22*
		(0.041)						
DRD-BERD		0.118**	0.128**	0.192**	0.088**	0.161**	0.101**	*0.10*
		(0.048)	(0.041)	(0.024)	(0.020)	(0.030)	(0.035)	
Education				-0.043				*-0.61*
				(0.101)				
Hours worked					-0.224**			*-1.42*
					(0.097)			
Patents$_{epo}$						-0.019		*-2.70***
						(0.025)		
Patents$_{uspto}$							0.021	*-2.11*
							(0.036)	
VR_g	*-2.58***	*-2.25***	*-2.64***	*-2.11***	*-1.93***	*-2.14***	*-2.37***	
VR_p	*-1.89***	*-1.50**	*-2.02***	*-1.30*	*-1.31*	*-1.23*	*-1.44**	

Notes: All variables are expressed in log-levels. Any specification includes a country fixed-effect and common time dummies. Standard errors based on Andrews and Monahan's pre-whitening method in parentheses. TFP: total factory productivity; IT: IT capital stock; DRD: domestic R&D stock; Patents$_{epo}$: stock of patents applied at EPO; Patents$_{uspto}$: stock of patents granted at USPTO. $CIPS$ 5% critical value: -2.25; 10% critical value: -2.14. VR_g and VR_p 5% critical value: -1.64; 10% critical value: -1.32. **, * significant respectively at 5 and 10%.

is however ruled out by the the fact that labour elasticity is negative, suggesting the presence of decreasing returns to scale; in this case, the elasticity of IT capital rises up to 0.069, while that of R&D falls down to 0.088.

As further check on the joint significance of both forms of technically-advanced assets, we insert the stock of patents into equation (1). It is well-known that R&D expenditure is only an input of the knowledge-generating process, turning out to be an imperfect measure of innovation that is relevant for the economic growth. This kind of mis-measurement could lead the coefficient of IT capital to be upward biased. In column (vi), we use the cumulative value of patent applications at the European Patents Office. Probably, it is the most exhaustive indicator for the output of innovative processes occurred in the European Union over the period considered. Though, it should be kept in mind that only a fraction of patent applications are accepted at the end of examination process (about 60%), as most of them fail to satisfy the elementary requisites for granting (i.e. novelty and originality). As a consequence, the EPO indicator might not be a powerful control

$\alpha g_K - \beta g_H$, where α and β are the *true* factor elasticities. On the other side, the neoclassic measure of TFP employed here is given by $g_z^m = g_Y - \alpha g_K - (1-\alpha)g_H$, or equivalently $g_z^m = g_z^* - (1-\alpha-\beta)g_H$. As a consequence, the validity of the constant returns' assumption can be inferred by regressing TFP on labour input, along with on other correlates.

for our robustness' checks. Regression (vii) attempts to fill this lack by employing the stock of patent grants at the US Patent and Trade Office. This measure is likely to understate the extent of the commercially-exploitable ideas developed in Europe; on the other side, there is reason to believe that EU firms apply in the United States the most relevant inventions, especially in the high-tech fields because of the prominence of the US market. As shown by regressions (vi) and (vii), both measures of cumulative patents turn out to be insignificant when inserted into equation (1). Whereas the magnitude of IT coefficient remains stable across the two specifications, the elasticity of business R&D rises up to 0.161 when using EPO data, but falls to 0.101 with USPTO patents.

It should be finally noted that the auxiliary tests reported at the margins of Table 4 provide sufficient guarantee about the cointegration between productivity and technically-advanced assets. The hypothesis of non-stationarity is not accepted only for EPO patent and, accordingly, the VR_p statistics largely fails to reject the null hypothesis of no contegration for regression (vi).[18] The most robust indication in favor of the existence of a stationary long-run relation is found for the specification based on IT capital and business R&D as explanatory variables (column iii).

Productivity spillovers in a closed economy: the role of IT specialisation (Model 2)

Now, the focus of the analysis is shifted on the role of industry specialization in IT productions for long-run productivity growth. This issue appears interesting for two reasons. First, it econometrically integrates the body of growth accounts' literature on the contribution given by both *production* and *usage* of IT goods to the resurgence recently experienced by most countries (Jorgenson, 2005). Furthermore, following earlier works on R&D spillovers, it puts emphasis on the sector showing the highest rate in innovation fertility, and that is claimed to deliver huge welfare gains to modern knowledge societies.

For comparative aims, Table 5 displays in column (i) the key result found above. In column (ii), we separate the productivity effects of business R&D into spillovers related to the research effort of IT sector and those imputable to the rest of the market economy (0.037 and 0.120). It should be first noted that the sum of these coefficients exceeds the elasticity estimated for total business R&D in regression (i), 0.128. Meanwhile, there is a marked reduction in the elasticity of IT capital, that now is significant only at a 10%. This indicates that the TFP-enhancing effects of IT investment are likely to be overstated when one does not

[18]The fact that VR_g always indicates the presence of cointegration in data, while VR_p falling at the extreme of the significance's region, suggests that heterogeneity is highly concentrated in few countries.

Table 5. **Estimation of spillovers in a closed economy: the role of IT specialisation**

	(i)	(ii)	(iii)[a]	(iv)[b]	(v)	(vi)[c]	$CIPS$
TFP (dep.)							*-0.27*
IT	0.047**	0.021*	0.045**	0.097**	0.025**	0.061**	*-0.91*
	(0.014)	(0.012)	(0.004)	(0.034)	(0.008)	(0.006)	
DRD-BERD	0.128**						0.10
	(0.041)						
DRD^I		0.037**	0.003	0.038*	0.020**	0.025**	*-0.37*
		(0.009)	(0.005)	(0.023)	(0.008)	(0.010)	
DRD^{NI}		0.120**	0.133**	0.156**	0.101**	0.118**	*-1.37*
		(0.025)	(0.012)	(0.031)	(0.023)	(0.014)	
$Patents^I_{epo}$					0.025**		*-1.54*
					(0.011)		
$Patents^I_{uspto}$						-0.029	*-0.95*
						(0.015)	
VR_g	*-2.64***	*-2.30***	*-2.05***	*-2.17***	*-2.66***	*-2.55***	
VR_p	*-2.02***	*-1.33**	*-1.21*	*-1.52***	*-1.54**	*-1.47**	

Notes: All variables are expressed in log-levels. Any specification includes a country fixed-effect and common time dummies. Standard errors based on Andrews and Monahan's pre-whitening method in parentheses. a) includes computer services and related among IT producers. b) uses variables built on non-hedonic deflators. c) refers to the period 1980-2002. DRD: domestic R&D stock. TFP: total factory productivity; IT: IT capital stock. DRD^I: domestic R&D stock of IT industry; DRD^{NI}: domestic R&D stock of non-IT industry; $Patents^I_{epo}$: patent stock applied at EPO by IT industry; $Patents^I_{epo}$: patent stock granted at USPTO by IT industry. CIPS tests checks the null hypothesis that all series are non-stationary, VR_p that there is no cointegration for all panel individuals, while VR_g that it occurs for only a positive fraction. $CIPS$ 5% critical value: -2.25; 10% critical value: -2.14. VR_g and VR_p 5% critical value: -1.64; 10% critical value: -1.32. **, * significant respectively at 5 and 10%.

explicitly consider the knowledge spillovers associated to the domestic production of these technologies. This might simply occur as IT firms are the most intensively users of computing equipment. Alternatively, it may depend on the high level of data aggregation, leading the positive spillovers produced by few industries to be obscured by the negative effects exerted by the other ones. Whereas reducing the extent of IT capital as driver of productivity, regression (ii) highlights the prominence of the knowledge base of IT producers, found to account for about one quarter of total R&D spillovers. This figure exceeds the share of IT sector on BERD expenses (about 20%) and appears highly valuable in light of the fact that this industry accounts only for between 1 and 3% of business-sector employment (or value added).

In column (iii), we use a wider definition of IT industry, which now includes computer services and related as well (cat. 72, ISIC Rev. 1). This sector has expanded exponentially during the last decade, and in terms of research effort has overcome IT manufactures in most countries. The productivity effects of IT production found in column (ii) might then be downsized as we did not take explicitly account of the spillovers associated to the production of such intangibles; potentially, this can induce the coefficient of IT capital to be inflated. On the other side, these additional series have the drawback of presenting many missing values for the 1980s; such data have been estimated by the interpolation method described in the Appendix. Using the new industry classification, we find elasticities profoundly different from earlier results. On one hand, knowledge stock of IT industry turns out to be insignificant, whereas the R&D elasticity of non-IT industry rises only marginally (0.133). On the other hand, the elasticity of TFP to IT capital doubles, passing to 0.045 from 0.021 of column (ii).[19] Rigorously, this finding should be interpreted as indicating that the knowledge spillovers of IT industry are associated to the production of hardware rather than software. As the research effect of the latter kind of producers has intensified only recently, the related benefits are far from materializing, even though this does not preclude that it might occur in the near future. Yet, in light of the heavy interpolation needed to re-construct R&D series for computer services industry, this finding is more likely to depend on noise in data, that attenuates towards zero the coefficient of DRD^{I}.[20] Because of these issues, the analysis will be carried out employing the narrow definition of IT industry, based on office machinery and communication equipment.

Another concern with IT, intended either as investment goods or industry output, is the measurement of its quality improvement over time.[21] As explained above, the constant-price value of IT investment has been calculated by applying the harmonized indexes developed by GGDC on the basis of the US hedonic prices. On the other side, real R&D expenditure has been calculated using the original deflators for value-added. For IT industry, only a handful of countries employs hedonic methods to allow for the improvement in output quality, while the majority still hinges on matching models. This artificially creates a disparity in the dynamics of research expenses. At the same time, cross-country differences in quality treatment of IT assets and knowledge capital of IT producers may be source of a further distortion in estimation. In order to understand the relevance of such methodological issues, we re-estimate model 2 using a measure of the explanatory variables built on quality-unadjusted deflators.[22] In doing so, the magnitude of factor elasticities is found to be consistent with earlier figures, expect for IT capital that now exhibits a coefficient of 0.097. Roughly, this outcome stresses the importance of adopting harmonised techniques to properly evaluate the returns of this kind of assets.

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[19] The value of CIPS statistics for the variables employed in regression (iii) amounts to -1.06 for DRD^{I}, and -1.04 DRD^{NI}.

[20] Albeit cointegration techniques are less sensitive to error measurements, the latter may still affect the estimation of factor elasticities with relatively short time-series at hand.

[21] See OECD (2004) for technicalities.

[22] IT investment has been deflated by means of the price index for non-IT investment, R&D expenditure of IT industry through the value-added deflator of the non-IT part of the market economy. TFP series have also been re-calculated using the new (unadjusted) series of IT capital. For TFP, the value of CIPS is -0.02, for IT capital -1.52, and -0.73 for DRD^{I}.

The last two regressions of Table 5 assess the extent to which the previous estimates are affected by the input-based nature of the innovation indicator (R&D expenses). To this aim, we introduce into equation (2) the ideas' stock patented by IT industry. This variable should guarantee a considerably finer check to exclude that the coefficient of IT capital does capture the unmeasured innovation output of IT producers. Using EPO applications, there is evidence that the R&D stock may not be exhaustive for assessing productivity spillovers of IT-related inventions, as the control variable turns out to be significant (0.025). In this case, the elasticity of TFP to the knowledge stock of IT producers halves (from 0.037 to 0.020), while the coefficient of IT capital remains unchanged. These outcomes are only partially confirmed employing USPTO data. Indeed, whereas the R&D elasticities lie sufficiently close to the values of column (v), now the stock of IT patents is not significant, while the coefficient of IT capital soars up to 0.061. This evidence confirms the robustness of IT capital and R&D expenditure as drivers of productivity.

Productivity spillovers within an open-economy framework (Model 3)

This section takes account of imported technology spillovers. The estimates of equation (3) are displayed in Table 6 where, as reference, we also report in column (i) the elasticities of the closed-economy specification. The measure of foreign R&D based on the usual LP weighting scheme is employed in regressions (ii) through (v). The two subsequent sections adopt instead the trade-related shares constructed on the three-year moving average of output and exports' flows, and on the stocks-based variant of the LP method. In any set of regressions, we first introduce the foreign stock of total business R&D to draw a comparison with the reference literature on international technology spillovers. In a second step, we add separately to the basic specification the foreign knowledge of the two industries' types in order to check whether these internal sources of spillovers are picking up the effect of R&D carried out abroad. Finally, the last regression of each section restricts on correlates found to spur productivity in this open-economy framework.

Using the traditional weights (FRD^F), the inclusion of business-sector stock of foreign knowledge lowers the magnitude of domestic R&D elasticities (column ii). R&D investment turns out to be highly rewarding for the most advanced countries, even though the related gains are reduced by trade as acting as channel for knowledge diffusion. From the comparison with column (i) it emerges that failing to take account of the external benefits leads the coefficients of domestic R&D to be overstated. On the other side, the elasticity of IT capital is larger and strongly more significant than in the closed-economy specification. Compared to existing evidence, the knowledge spillovers of foreign R&D appear rather modest in size, and only weakly significant. A problem with this variable is that it is not non-stationary for all countries, as indicated by the CIPS test. This may explain why the value of the cointegration tests is substantially higher for regression (ii) than in the previous estimates, and now the null hypothesis of no cointegration is not rejected by the VR_p statistics. The next two regressions will demonstrate how the main factor behind the modest elasticity of foreign R&D is the diverging impact exerted by IT producers with respect to non-IT firms (columns iii and iv).

In column (iii), we insert the trade-weighted value of R&D cumulated abroad by the IT industry. There is a sizeable increase in the factor elasticities with respect to column (i), in particular for IT capital. It occurs as the coefficient of FRD^I has a negative sign (-0.056), probably reflecting the competition effect associated to the import penetration of IT goods: the less a country produces information technology by its own (and accordingly the more purchases from abroad), the more the related benefits are eroded by the competing economies. At an industry-level, this phenomenon has been investigated by Bitzer and Geishecker (2006) within a more general context. Regression (iii) suggests that maintaining a minimum level of specialization in IT productions is essential to compete on the international market, as the knowledge base underlying these activities is not easily transferable or imitable. Dynamic economies of scale in research activity may then be the driving force behind the on-going process of concentration in IT sector. What seems particularly interesting is that the same does not occur for the non-IT sector. Indeed, when used as explanatory variable (column iv), the foreign knowledge of this type of firms exhibits a positive elasticity (0.087), while the domestic R&D coefficient loses significance at all.

As a final step, we report in column (v) the parsimonious version of model 3 focused on the drivers of productivity. It points out how the R&D base of the IT producing industry and the total-economy endowment of IT assets are the sole enablers of internal spillovers. Trade instead is effective for disseminating the knowledge created in relatively less advanced productions, neutralizing thus the effort of domestic firms; in line with existing evidence,[23] international technology spillovers arise as a key determinant of a nation's productivity, more than any internal factor.

Next, we turn to assess the sensitivity of elasticities to imports' volatility. As discussed in Section 3, temporary changes in trade figures may raise noise in foreign R&D series, undermining the consistency of slope parameters. Nonetheless, we obtain similar findings using the smoothed LP weights (columns vi-ix).

[23] See in particular Lumenga-Neso *et al.* (2005), Lee (2006) and Bottazzi and Peri (2007).

Table 6: **Estimation of productivity spillovers in a open-economy framework**

		LP-Flows		(FRD^F)		LP-Smoothed Flows		(FRD$^{\overline{F}}$)		LP-Stocks		(FRD^S, $\delta = 0.15$)		$CIPS$
	(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)	(viii)	(ix)	(x)	(xi)	(xii)	(xiii)	
TFP (dep.)														*-0.27*
IT	0.021*	0.030**	0.068**	0.039**	0.050**	0.031**	0.070**	0.048**	0.049**	0.030**	0.013	0.029**	0.050**	*-0.91*
	(0.012)	(0.005)	(0.009)	(0.006)	(0.010)	(0.005)	(0.008)	(0.004)	(0.005)	(0.008)	(0.015)	(0.008)	(0.011)	
DRD^I	0.037**	0.032**	0.050**	0.025**	0.024**	0.041**	0.056**	0.037**	0.020**	0.013**	0.052**	0.028**	0.028**	*-0.37*
	(0.009)	(0.006)	(0.007)	(0.006)	(0.009)	(0.004)	(0.007)	(0.005)	(0.005)	(0.005)	(0.009)	(0.005)	(0.008)	
DRD^{NI}	0.120**	0.081**	0.142**	0.040		-0.005	0.142**	-0.035		0.073**	0.154**	-0.024		*-1.07*
	(0.025)	(0.030)	(0.020)	(0.025)		(0.022)	(0.018)	(0.020)		(0.036)	(0.037)	(0.027)		
FRD		0.043*				0.108**				0.067**				*-2.15**
		(0.026)				(0.020)				(0.026)				
FRD^I			-0.056**				-0.064**				-0.021			*-0.78*
			(0.017)				(0.015)				(0.031)			
FRD^{NI}				0.087**	0.109**			0.134**	0.106**			0.228**	0.123**	-2.60**
				(0.022)	(0.015)			(0.018)	(0.011)			(0.032)	(0.032)	
VR_g	*-2.30***	*-1.82***	*-2.00***	*-1.97***	*-2.35***	*-1.93***	*-2.07***	*-2.15***	*-2.50***	*-2.71***	*-2.13***	*-2.68***	*-2.72***	
VR_p	*-1.33**	*-0.99*	*-1.31*	*-1.23*	*-1.50**	*-1.04*	*-1.31*	*-1.33**	*-1.55**	*-1.57***	*-1.32*	*-1.62**	*-1.66***	

Notes: All variables are expressed in log-levels. Any specification includes a country fixed-effect and common time dummies. Standard errors based on Andrews and Monahan's pre-whitening method in parentheses. TFP: total factory productivity; IT: IT capital stock; DRD^I: domestic R&D of IT industry; DRD^{NI}: domestic R&D of non-IT industry; FRD: foreign R&D stock; FRD^I: foreign R&D of IT industry; FRD^{NI}: foreign R&D of non-IT industry. CIPS tests checks the null hypothesis that all series are non-stationary, VR_p that there is no cointegration for all panel individuals, while VR_g that it occurs for only a positive fraction. The value of CIPS statistics for the variables employed in regressions (vi)-(ix) is of -0.81 for FRD, -0.82 for FRD^I, and -0.95 for FRD^{NI}; for regressions (x)-(xiii) the CIPS statistics amounts to -1.48 for FRD, -0.87 for FRD^I, -3.06** for FRD^{NI}. $CIPS$ 5% critical value: -2.25; 10% critical value: -2.14. VR_g and VR_p 5% critical value: -1.64; 10% critical value: -1.32. **, * significant respectively at 5 and 10%.

The main discrepancy can be identified in the insignificance of the DRD^{NI} in regression (vi); this outcome is likely to depend on the high explanatory power shown by FRD, which now results consistent with earlier estimates (0.108). On the other side, the negative (trade-related) impact exerted by the research effort of foreign IT firms is strongly confirmed (-0.064), and finally the findings of the restricted model lie close to the values obtained using the usual LP weights (see respectively columns ix and v). A clear advantage of this weighting scheme is of providing non-stationary series for any indicator of external R&D;[24] as a consequence, one can safely conclude that the relation expressed by equation (3) is cointegrated.

As a last step, the open-economy framework is re-estimated employing the LP procedure based on stock variables, as suggested by Madsen (2007).[25] As argued above, this scheme should be particularly robust to trade volatility, and more accurately capture the (slow) learning process of foreign knowledge by domestic firms. These estimates however turn out to be perfectly lined up to those of the two previous sets of regressions, with a relevant exception. In column (xi), neither IT capital nor the knowledge stock embodied in IT imports are significant; it indicates that such factors may be capturing the same effect on productivity, i.e. the spillovers of R&D carried out abroad by IT producers and which are assimilated by the recipient countries through trade. This would corroborate the hypothesis of the embodied nature of technical progress. Though, it is easy to demonstrate how this finding is ascribable to a distortion inherent the stocks-based variant of the LP method, which is related to the formula followed to estimate the initial level of the stocks.[26] To this end, it should be reminded that the shares underlying the construction of FRD^F and FRD^S should virtually coincide when the depreciation rate adopted to capitalize the flow variables approaches to the unity (δ; see Section 3.1). As a consequence, using a measure of FRD^S based on increasingly higher values of δ should produce estimates coming closer to the elasticities obtained with the usual LP weights. Nevertheless, in doing so, we find a positive coefficient for FRD^{I,S}, whose size tends to rise as δ converges to the unity; by contrast, the elasticity of IT capital is negative and decreasing with respect to δ.[27] In presence of relatively short and volatile series, the method proposed Madsen (2007) appears inadequate, as the error done in estimating the initial stocks hardly disappears with the elapsing of time, with heavy consequences on regression results.

[24]The value of CIPS test for the measures of foreign knowledge employed in regressions (vi)-(ix) is of -0.81 for FRD, -0.82 for FRD^I, and -0.95 for FRD^{NI}.

[25]The value of CIPS test for the measures of foreign knowledge employed in regressions (x)-(xiii) is of -1.48 for FRD, -0.87 for FRD^I, -3.06** for FRD^{NI}.

[26]$K_0 = I_0/(g + \delta)$. See the Appendix for methodological details.

[27]Such additional regressions are not reported but available upon request from the author.

6 Concluding Remarks

This paper has examined the role played by both IT and R&D on the economic growth of the modern knowledge-based societies. The aim was of understanding whether these factors engender separate productivity spillovers, or merely embody the two opposite sides of the same coin, i.e. the benefits produced by the R&D-led advances achieved in the field of information technology. In this sense, the work relates to the rich strand of studies investigating the incorporated nature of technical change.

We have reported robust evidence indicating that both factors deliver sizeable benefits at an economy-wide level. TFP is found to be significantly influenced by investment in either IT capital or research activity. The knowledge-cumulating process of IT producing industry turns out to be particularly effective in boosting productivity, accounting for one quarter of internal R&D spillovers. As a whole, these findings stress the prominence of both IT investment and IT production for a nation's productivity, as well as for its ability to compete on the global market. Indeed, when we extend the regression framework to including international trade, there emerges a negative competition effect related to the import penetration of IT goods. The type of knowledge underlying such productions seems hardly transferable abroad; it implies that, to benefit from this form of technical progress, each country should develop the necessary competencies by its own. This sharply contrasts with the evidence found for less technically-advanced productions, for which trade is confirmed to be a valid channel to diffuse knowledge.

Summing-up, investing in IT assets is highly recommendable to stimulate economic growth as delivering gains distinct from those of R&D activity, probably related to network externalities and specific knowledge spillovers. Though, this strategy might not be sufficient to offset a country's low specialization in the field of IT productions. Hence, in the current technological age, extraordinary efforts should be conducted by any modern economy to retain some competitive advantage in the IT sector (even though limited to very small segments) in order to ensure steadily positive prospects of development and well-being.

References

ACHARYA, R. C. AND KELLER, W. (2007). *Technology Transfer Through Imports*. CEPR Discussion Paper No. 6296.

ALLEN, T. J. (1986). *Organizational Structure, Information Technology and R&D Productivity*. Paper presented at the Conference of the European Industrial Research Managers' Association, The Hague, Netherlands, June 5, 1985.

BARRO, R. J. AND LEE, J.-W. (2000). *International Data on Educational Attainment: Updates and Implications*. Center for International Development, Harvard University, Working Paper No. 42.

BASU, S., FERNALD, J., OULTON, N. AND SRINIVASAN, S. (2004). *The Case of the Missing Productivity Growth: Or, Does Information Technology Explain why Productivity Accelerated in the United States but not in the United Kingdom?* In *NBER Macroeconomics Annual 2003* (edited by GERTLER, M. AND ROGOFF, K.), pp. 9–63. The MIT Press, Cambridge, MA.

BECCHETTI, L. AND ADRIANI, F. (2005). *Does the Digital Divide Matter? The Role of Information and Communication Technology in Cross-Country Level and Growth Estimates*. Economics of Innovation and New Technology, 14(6): 435–453.

BITZER, J. AND GEISHECKER, I. (2006). *What Drives Trade-related R&D Spillovers? Decomposing Knowledge-Diffusing Trade Flows*. Economics Letters, 93(1): 52–57.

BOTTAZZI, L. AND PERI, G. (2007). *The International Dynamics of R&D and Innovation in the Short and Long Run*. Economic Journal, 117: 486–511.

BRANDT, N. (2007). *Mark-ups, Economies of Scale and the Role of Knowledge Spillovers in OECD industries*. European Economic Review, 51(7): 1708–1732.

BRESNAHAN, T. F. (2001). *The Mechanisms of Information Technology's Contribution to Economic Growth*.

BRYNJOLFSSON, E. AND HITT, L. M. (2003). *Computing Productivity: Firm-Level Evidence*. Review of Economics and Statistics, 85(4): 793–808.

COE, D. T. AND HELPMAN, E. (1995). *International R&D Spillover*. European Economic Review, 39: 859–887.

COHEN, W. AND LEVINTHAL, D. (1989). *Innovation and Learning: Two faces of R&D*. Economic Journal, 99: 569–596.

DRACA, M., SADUN, R. AND REENEN, J. V. (2007). *ICT and Productivity: A Review of the Evidence*. In *Handbook of Information and Communication Technologies* (edited by MANSELL, R., AVGEROU, C., QUAH, D. AND SILVERSTONE, R.). Oxford University Press, Oxford.

EDMOND, C. (2001). *Some Panel Cointegration Models of International R&D Spillovers*. Journal of Macroeconomics, 23(1): 241–260.

ENGELBRECHT, H.-J. (1997). *International R&D Spillover, Human Capital and Productivity in OECD Countries: An Empirical Investigation*. European Economic Review, 41: 1479–1488.

FRANTZEN, D. (2000). *R&D, Human Capital and International Technology Spillovers: A Cross-Country Analysis*. Scandinavian Journal of Economics, 102(1): 57–75.

— (2002). *Intersectoral and International R&D Knowledge Spillovers and Total Factor Productivity*. Scottish Journal of Political Economy, 49(3): 280–303.

FUSS, M. AND WAVERMANN, L. (2005). *The Networked Computers: the Contribution of Computing & Telecommunications to Economic Growth Productivity OR Why is there no New Economy in Old Europe. a Production Function Approach*. London Business School, Digital Transformations Working Paper No. 1.

GREENAN, N., MAIRESSE, J. AND TOPIOL-BENSALD, A. (2001). *Information Technology and Research and Development Impacts on Productivity and Skills: Looking for Correlations on French Level Data*. NBER Working Paper 8075.

GRIFFITH, R., REDDING, S. AND REENEN, J. V. (2003). *R&D and Absorptive Capacity: Theory and Empirical Evidence*. Scandinavian Journal of Economics, 105(1): 99–108.

— (2004). *Mapping the Two Faces of R&D Productivity Growth in a Panel of OECD Industries*. Review of Economics and Statistics.

GRILICHES, Z. (1979). *Issues in Assessing the Contribution of R&D to Productivity Growth*. Bell Journal of Economics, 10(1): 92–116.

— (1992). *The Search of R&D Spillovers*. Scandinavian Journal of Economics, 94: 29–47.

GUELLEC, D. AND VAN POTTELSBERGHE, B. (2004). *From R&D to Productivity Growth: Do the Institutional Settings and the Source of Funds of R&D matter?* Oxford Bulletin of Economics and Statistics, 66(3): 353–78.

HALL, B. H., JAFFE, A. B. AND TRAJTENBERG, M. (2001). *The NBER Citations Data File: Lessons, Insights and Methodological Tools*. NBER Working papers 8498.

JORGENSON, D. W. (2005). *Accounting for Growth in the Information Age*. In *Handbook of Economic Growth* (edited by AGHION, P. AND DURLAUF, S.), ch. 10. Elsevier, Amsterdam.

KAO, C. AND CHIANG, M.-H. (2000). *On the Estimation and Inference of a Cointegrated Regression in Panel Data*. In *Nonstationary Panels, Panel Cointegration, and Dynamic Panels, Advances in Econometrics* (edited by BALTAGI, B. H.), ch. 15, pp. 179–222. JAI Press., Amsterdam.

KAO, C., CHIANG, M.-H. AND CHEN, B. (1999). *International R&D Spillovers: An Application of Estimation and Inference in Panel Cointegration*. Oxford Bulletin of Economics and Statistics, 61(0, Special Issue November): 691–709.

KELLER, W. (1998). *Are International R&D Spillovers Trade-Related? Analyzing Spillovers Among Randomly Matched Trade Partners*. European Economic Review, 42: 1469–82.

— (2002a). *Geographic Localization of International Technology Diffusion*. American Economic Review, 92(1): 120–42.

— (2002b). *Trade and the transmission of technology*. Journal of Economic Growth, 7(1): 5–24.

— (2004). *International technology diffusion*. Journal of Economic Literature, XLII: 752–84.

KETTENI, E., MAMUNEAS, T. AND STENGOS, T. (2007). *The Effect of Information Technology and Human Capital on Economic Growth*. The Rimini Centre for Economic Analysis Working Paper 03-07.

LEE, G. (2005). *Direct versus Indirect International R&D Spillovers*. Information Economics and Policy, 17(3): 334–348.

— (2006). *The Effectiveness of International Knowledge Spillover Channels*. European Economic Review, 58(8): 2075–2088.

LICHTENBERG, F. R. (1993). *R&D Investment and International Productivity Differences*. In *Economic Growth in the World Economy. Symposium 1992* (edited by SIEBERT, H.). Tubingen.

LICHTENBERG, F. R. AND VAN POTTELSBERGHE, B. (1998). *International R&D Spillovers: A Comment*. European Economic Review, 42: 1483–91.

LUMENGA-NESO, O., OLARREAGA, M. AND SCHIFF, M. (2005). *On 'Indirect' Trade-Related R&D Spillovers*. European Economic Review, 49(7): 1785–98.

MADDEN, G. AND SAVAGE, S. J. (2000). *R&D Spillovers, Information Technology and Telecommunications, and Productivity in ASIA and the OECD*. Information Economics and Policy, 12: 367–392.

MADSEN, J. B. (2007). *Technology Spillover through Trade and TFP Convergence: 135 years of Evidence for the OECD Countries*. Journal of International Economics, 72(2): 464–480.

MARK, N. AND SUL, D. (2003). *Cointegration Vector Estimation by Panel DOLS and Long-Run Money Demand*. Oxford Bulletin of Economics and Statistics, 65(5): 655–80.

MARK, N. C., OGAKI, M. AND SUL, D. (2005). *Dynamic Seemingly Unrelated Cointegrating Regression*. Review of Economic Studies, 72: 797–820.

MATTEUCCI, N. AND STERLACCHINI, A. (2004). *ICT, R&D and Productivity Growth: Evidence from Italian Manufacturing Firms*. EPKE working paper n. 28.

MCGUCKIN, R. H. AND STIROH, K. J. (2002). *Computers and Productivity: Are Aggregation Effects Important?* Economic Inquiry, 40(1): 42–59.

MENDI, P. (2007). *Trade in Disembodied Technology and Total Factor Productivity in OECD countries*. Research Policy, 36(1): 121–133.

OECD (2002a). *ANBERD - R&D Expenditure in Industry (ISIC Rev.2)*, vol. 2002/1. OECD, Paris.

— (2002b). *International Trade by Commodities Statistics (SITC Rev.2) - Historical Series 1961-1990*, vol. 2002/1. OECD, Paris.

— (2004). *Handbook on the Quality Adjustment of Price Indices for ICT Products*. OECD, Paris.

— (2006a). *International Trade by Commodities Statistics (SITC Rev. 2)*, vol. 2006/1. OECD, Paris.

— (2006b). *OECD Information Technology Outlook*. OECD, Paris.

— (2006c). *STAN Bilateral Trade Database*, vol. 2006/1. OECD, Paris.

— (2007). *Main Science and Technology Indicators*, vol. 2007/1. OECD, Paris.

OULTON, N. AND SRINIVASAN, S. (2005). *Productivity Growth and the Role of ICT in the United Kingdom: an Industry View, 1970-2000*. CEP Discussion Paper No. 681.

PARK, W. (1995). *International R&D Spillovers and OECD Economic Growth*. Economic Inquiry, 33: 571–591.

PEDRONI, P. (2004). *Panel Cointegration: Asymptotic and Finite Sample Properties of Pooled Time Series Tests with an Application to the PPP Hypothesis*. Econometric Theory, 20: 507–625.

PESARAN, M. H. (2007). *A Simple Panel Unit Test in the Presence of Cross Section Dependence*. Journal of Applied Econometrics, 22(2): 265–312.

SAIKKONEN, P. (1991). *Asymptotically Efficient Estimation of Cointegration Regressions*. Econometric Theory, 7: 1–21.

SCHREYER, P. (2002). *Computer Price Index and International Growth and Productivity Comparisons*. Review of Income and Wealth, 48(1): 15–31.

STERLACCHINI, A. AND VENTURINI, F. (2007). *Boosting Manufacturing Productivity through R&D: International Comparisons with Special Focus on Italy*. Polytechnic University of Marche, Department of Economics, Working paper n. 306.

STIROH, K. J. (2002). *Are ICT Spillovers Driving the New Economy?* Review of Income and Wealth, 48(1): 33–57.

TIMMER, M., VAN MOERGASTEL, T., STUIVENWOLD, E., YPMA, G., O'MAHONY, M. AND KANGASNIEMI, M. (2007). *EU KLEMS Growth and Productivity Accounts. Part I Methodology*. EUKLEMS project.

TIMMER, M., YPMA, G. AND VAN ARK, B. (2003). *IT in the European Union: Driving Productivity Divergence?* Groningen Growth and Development Centre Research Memorandum GD-67.

VAN ARK, B. AND INKLAAR, R. C. (2005). *Catching Up or Getting Stuck? Europe's Troubles to Exploite ICT's Productivity Potential*. Groningen Growth and Development Centre Research Memorandum GD-79.

VAN ARK, B., MELKA, J., MULDER, N., TIMMER, M. AND YPMA, G. (2002). *ICT Investments and Growth Accounts for the European Union 1980-2000*. Groningen Growth and Development Centre Research Memorandum GD-56. (revised March 2003).

WESTERLUND, J. (2005). *New Simple Tests for Panel Cointegration*. Econometric Reviews, 24: 297–316.

Appendix: Sources and Methodology

Assuming perfectly competitive markets and constant returns to scale, TFP is calculated as the residual growth of output over the income share-weighted growth of factor inputs, using the Tornqvist index formula (individual subscripts omitted):

$$\Delta \ln TFP_t = \Delta \ln Y_t - \bar{s}_t^H \Delta \ln H_t - (1 - \bar{s}_t^H - \bar{s}_t^I)\Delta \ln K_t^{NI} - (1 - \bar{s}_t^H - \bar{s}_t^{NI})\Delta \ln K_t^I,$$

where $\bar{s}$ is a two-year average of each input's share on GDP. TFP is indexed to 100 in 2000. Real GDP excludes actual and imputed rents for housing (Y). Non-IT capital includes detailed series on non-IT equipment, transport equipment and non-residential buildings (K_{NI}). IT capital collects expenditure on computers and other office machinery, communication equipment and software (K_I). H are hours worked. National Accounts series comes from the **Groningen Growth and Development Centre Total Economy Growth Accounting Database**.[28]

Each monetary variable has been deflated by means of a country-specific price index, and then converted into US GDP Power Purchasing Parities, expressed in constant dollars of 2000. Price indexes used to deflate National Accounts series are taken from GGDC; for IT investment, such deflators are harmonized on US hedonic series, in order to guarantee a consistent treatment of quality growth in computing equipment. Industry series of value-added deflators are extracted from **EUKLEMS** database[29] and employed to convert into a constant-prices base R&D expenditure. For GERD, real expenses are obtained aggregating up the industry series (DRD^I, DRD^{NI} and PRD) employing the Tornqvist index formula.

R&D expenditure, expressed in current prices, come from **OECD Main Science and Technology Indicators** and **OECD ANBERD Rev. 2**. Missing values have been calculated interpolating geometrically the industry share on GERD (or BERD); the percentages of 1980 are estimated backwardly from the values of 1981 using the average annual rate of change relative to the period 1981-91.

In order to preserve a coherent industry classification among the various data sources employed, IT (manufacturing) sector is defined as the sum of office machinery and communication equipment (category 30 and 32, ISIC rev.1). This classification slightly differs from the official one adopted by OECD (2006b, Annex A); among IT manufacturers, the latter also collects insulated wires (313) and scientific instruments (332 and 333), as well as service industries trading IT goods as wholesale of machinery, equipment and supplies (5150), renting of office machinery and equipment (7123), and IT intangibles sectors like telecommunications (642) and computer services and related activities (72).

Patent applications at European Patent Office and patent grants at the US Patent and Trade Office are derived from **OECD Main Science and Technology Indicators**. For IT sector, USPTO data are taken by NBER Patent files, which are available in STATA format at the Bronwyn Hall's homepage (release October 2006). Following the SIC concordance table, IT patents have been defined as those granted to the OTAF category n. 357 (Office computing and accounting machines) and n. 365-367 (Communication equipment and electronic components), covering the period 1980-2002. See Hall *et al.* (2001) for details.

[28]www.ggdc.net; release July 2005.
[29]www.euklems.net, release March, 2007.

Each capital stock, S^λ, has been obtained from the series of real investment or patent counts, I^λ, by means of the permanent inventory method and geometric depreciation:

$$S_t^\lambda = I_t^\lambda(1-\delta^\lambda) + I_{t-1}^\lambda, \quad S_{1980}^\lambda = I_{1980}^\lambda/(g^\lambda + \delta^\lambda).$$

g^λ is the average annual growth rate of real investment over the period 1980-2003. δ^λ is an asset-specific depreciation rate, assumed constant over time and across countries. It is fixed to 0.15 for R&D and patent stocks. Following van Ark *et al.* (2002), δ amounts to 0.028 for structures, 0.191 for transport equipment, 0.132 for non-IT equipment, 0.315 for software, and 0.115 for TLC equipment. By contrast, it is assumed to variable for Office Machinery, ranging from 0.222 to 0.312; it reflects the rising weight in this category of computing equipment, which is featured by a faster physical deterioration ($\delta = 0.315$) compared to the other types of IT assets (printers, photocopiers terminals, etc.). Finally, capital series are adjusted to mid-year values, $K_t = (S_t + S_{t-1})/2$, and for the R&D stock they are also one-period lagged.

Bilateral imports by industry come from **OECD STAN Bilateral Trade Database 1988-2003**; for the period 1980-1988, trade figures are available by commodity, and are taken from **OECD Historical Statistics on International Trade by Commodities**. Both series are expressed in current US dollars. The concordance between the commodity and industry classifications (respectively SIT Rev. 2 and ISIC. Rev. 1) has been implemented through the Eurostat correspondence tables.[30] The following commodities have been attributed to the IT industry: cat. 75 and 72655 to Office machinery (cat. 30 ISIC Rev. 1); categories 76 less 76483, 7722, 7723, 776 and 7786 to Communication equipment (cat. 32 ISIC Rev. 1).

The average annual of schooling for people aged 25 and over, available at five year intervals, are extracted from **Barro and Lee (2000)**'s data set. As in Engelbrecht (1997), intermediate years have been geometrically interpolated, while the levels of 2001-03 have been estimated using the rate of change relative to the period 1995-2000.

[30] http://ec.europa.eu/eurostat/ramon/relations/.

Table A1: Estimated levels of TFP and technically-advanced capital

		TFP	IT	DRD-GERD	DRD-BERD	DRD^{I}	DRD^{NI}	FRD^{I}	FRD^{NI}
Austria	1980	78.0	1,419	6,694	3,370	857	2,493	734	2,180
	2003	100.5	26,647	25,464	16,185	3,909	12,269	11,395	5,696
Belgium	1980	72.7	1,070	13,785	8,677	989	7,672	1,037	6,787
	2003	100.3	38,824	30,501	21,524	3,194	18,371	22,845	13,755
Denmark	1980	82.3	585	4,092	1,776	79	1,726	492	1,679
	2003	98.9	20,205	19,514	12,709	837	11,905	11,206	3,422
Finland	1980	63.1	850	2,786	1,172	49	1,764	260	876
	2003	105.7	20,634	23,286	15,864	7,275	9,045	10,454	2,588
France	1980	76.3	5,246	70,036	31,272	441	42,539	3,755	9,226
	2003	101.0	129,363	208,114	128,006	18,762	113,300	47,567	21,245
Germany	1980	66.4	13,951	159,771	104,021	8,567	102,389	3,265	10,456
	2003	102.4	215,819	308,114	212,262	28,237	184,421	89,502	24,384
Greece	1980	92.9	933	1,088	176	4	191	151	833
	2003	106.5	20,908	7,071	1,837	409	1,431	5,371	1,942
Ireland	1980	55.0	134	946	335	48	308	482	1,214
	2003	102.1	7,068	6,873	4,762	1,450	3,299	14,346	3,425
Italy	1980	81.4	10,126	42,409	23,434	3,299	20,548	2,314	6,312
	2003	96.6	174,739	98,292	49,825	9,389	40,483	37,123	14,714
Netherlands	1980	81.3	1,208	23,955	11,307	877	11,777	2,274	7,326
	2003	99.7	43,244	49,715	27,317	6,370	21,237	29,631	13,532
Portugal	1980	75.2	830	1,015	243	31	207	229	655
	2003	98.8	16,630	7,483	2,044	210	1,825	8,237	2,344
Spain	1980	84.0	2,575	7,350	2,922	270	2,742	750	1,779
	2003	96.0	80,340	44,865	23,388	2,198	21,174	28,622	11,946
Sweden	1980	79.2	1,375	9,477	4,698	57	8,792	849	2,297
	2003	105.3	38,211	48,095	34,854	7,228	29,977	12,388	4,821
United Kingdom	1980	76.7	3,527	119,375	69,978	11,249	49,594	1,436	6,377
	2003	104.6	193,220	172,293	111,621	9,795	101,428	61,119	20,080
United States	1980	82.0	68,774	283,490	143,289	747	338,025	1,526	4,628
	2003	105.3	1,781,667	1,429,904	1,006,101	151,897	906,959	30,565	19,950

Notes: Own calculation on OECD Main Science Technology Indicators and GGDC Total Economy Growth Accounting Database. TFP is indexed to 100 in 2000. Monetary variables are expressed in US constant dollars of 2000, converted into GDP power purchasing parities.