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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 distinctly affect economic growth, or does the IT impact merely reflect the embodiment of R&D-driven 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 TFP gains, a low degree of industry specialization in information technology can hardly be 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.

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

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1 Introduction

Technical change as outcome of intentional innovation activity is considered a crucial factor for the competitiveness of modern industrialised economies. R&D-based innovation is the main source of productivity, and this in turn drives a nation's well-being over the long-run. Undoubtedly, one of the most extraordinary scientific achievements of the last decades are the advances made in the field of information technology (IT). IT is argued to be the key force behind the growth resurgence recently experienced by most countries.

Aside from a few exceptions, the majority of works have investigated separately the impact of IT and R&D on economic growth. Though, these two factors are closely related, and present some similarities (and even some discrepancies) that should not be ignored in both the theoretical and empirical research. First of all, they spur productivity by enabling knowledge dissemination (both R&D and IT), or creating network externalities (mainly IT). Secondly, IT producers are the most intensively involved in knowledge generation, accounting for a large fraction of R&D and patenting activity (Figure 1). R&D-based innovation stimulates the efficiency growth in the IT producing sector and, finally, its benefits accrue to all the purchasers of digital goods. Third, the application of the new generations of computers and experimental technologies has enormously enhanced the research productivity; 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

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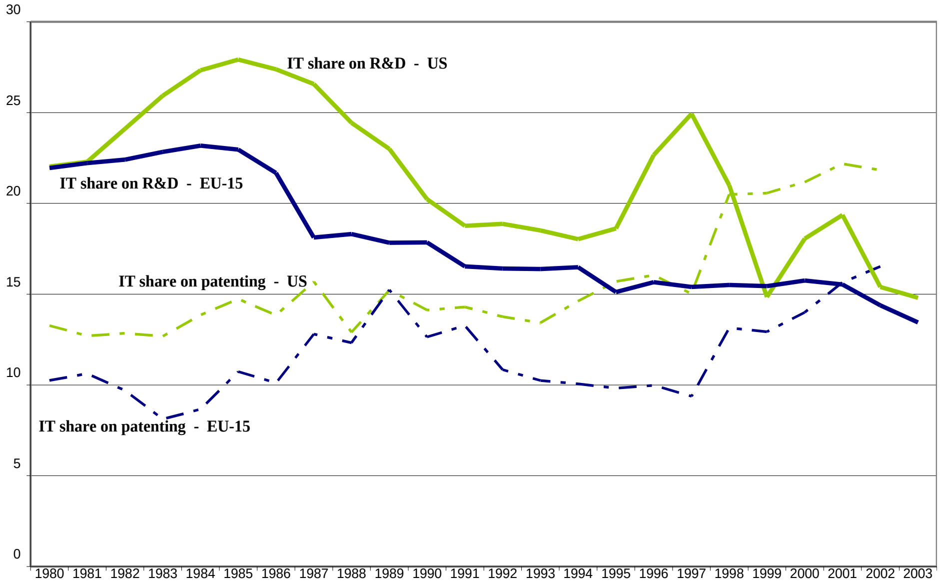
Figure 1: **Percentage of IT industry on business enterprise R&D expenditure and USPTO patent grants**, 1980-2003



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

the Internet age. On the other hand, firm-level studies have stressed that, to be effective, IT assets need complementary investment in business restructuring and human capital, and firms undertaking R&D projects are found to reap larger benefits.

Due to the complex relation between IT and R&D, assessing the productivity effects of such factors 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 period of learning and/or adjustment, as well as patent protection, come to an end. It would be then interesting to understand whether these types of technically-advanced capital are able to distinctly boost productivity, 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 technological knowledge affects economic growth.

Towards this aim, the present paper performs 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 effects of IT and R&D on productivity dynamics. 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 prominent role of the IT producing industry in productivity growth. Finally, the analysis is extended to an open-economy framework in order to trace the spillovers flow related to the international trade of IT goods. It is found that the stock of R&D embodied in imports of computing and telecom equipment is far from stimulating TFP, while the reverse occurs with less technically-advanced productions. This finding confutes 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 strong specialization in IT productions is either a key determinant of a nation's productivity or a crucial factor to compete on the global market. On the other hand, IT capital turns out to provide additional gains with respect to R&D, probably due to its ability to generate network externalities or specific knowledge spillovers. Therefore, investing in this special kind of assets appears highly recommendable, even though it is unlikely to offset a country's de-specialization in high-tech (IT) productions. In line with earlier studies, the knowledge spillovers of foreign non-IT 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 paper is as follows. Section 2 illustrates the theoretical background of the work and surveys the empirical literature on the productivity effects of IT and R&D. Section 3 defines the analytical framework and discusses some econometric issues. Data description and summary statistics are provided in Section 4, while the econometric results are presented in Section 5. Finally, Section 6 reports some concluding remarks.

2 Overview of related literature

2.1 Theoretical background

In recent years, a great attention has been paid to the contribution given to economic growth by information technology,[1] and an increasing effort has specifically been devoted to formally describing the mechanism at the roots of this process. Venturini (2007) develops a growth model where the learning process associated to the usage of IT assets by firms and households positively affects productivity along the equilibrium path. Vourvachaki (2006) endogenousizes the forces underlying the growth effect of information technology, making it dependent on the R&D effort of IT producers. Krusell (1998) constructs instead a general (one-sector) model where R&D is designed to improve the efficiency of new capital

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

vintages; investment-specific technical change pulls down the relative prices of new assets whose diffusion permanently stimulates economic growth. Recently, Ngai and Samaniego (2008) have developed a multi-sector endogenous growth framework characterised by cross-industry heterogeneity in research intensity and steady equilibrium growth.[2]

This class of works indicates that both information technology and research and development may act as determinants of TFP $(Z_t$, where $Y_t = Z_t F(K_t, L_t))$, and that the effect of the latter factor may be differentiated across industries because of a different attitude towards knowledge-generating activities. Accordingly, the R&D impact on TFP can be distinguished between the research performed by IT producers and that of non-IT firms (respectively denoted by I_t and NI_t):

$$\begin{aligned} Z_t &= Z(IT_t, RD_t) = Z\big(IT_t, RD(I_t, NI_t)\big) \\ &= Z\big(IT_t, RD(I_t, NI_t)^D, RD(I_t, NI_t)^F\big). \end{aligned}$$

All these works however assume a closed economy and, hence, neglect the portion of technological knowledge affecting productivity that comes from abroad. From Grossman and Helpman (1991) onwards, numerous open-economy models have been developed to trace the benefits that technological laggards reap by interacting with frontier countries; such contributions have triggered the thriving branch of empirical research on international technology spillovers (Coe and Helpman, 1995). Among others, Caselli and Wilson (2004) shape cross-country productivity differences as dependent on the (exogenously-defined) content of R&D embodied in equipment imports. A fully endogenous growth model with trade of capital goods (even though without R&D) can be found in Eaton and Kortum (2001). In light of this second strand of theoretical literature, it is a standard practice to take account of foreign research, along with domestic R&D, in assessing the extent of knowledge spillovers $\big(RD(\cdot)^F$ and $RD(\cdot)^D\big)$.

2.2 Empirical evidence

Productivity effects of IT. Most studies show that labor productivity has increasingly been driven by the *direct effects* of information technology, i.e. IT capital deepening and TFP growth in IT producing industries (Jorgenson, 2005). By contrast, economy-wide evidence on the spillovers produced by these technologies is still poor, albeit they are considered a distinctive property of digital goods. The *indirect effects* of IT take the form of network externalities (i.e. the effectiveness on individual performance rises with the number of users) and of the knowledge

[2] In a multi-sector exogenous framework, cross-industry differences may reside either in TFP dynamics or factor inputs' intensity (see Whelan, 2003, Ngai and Pissarides, 2007 and Acemoglu and Guerrieri, 2007).

spillovers enabled by a faster circulation of ideas and a better information management. Fuss and Wavermann (2005) find that network effects have sizeably contributed to TFP growth in OECD countries since the mid-1990s. On the other hand, Becchetti and Adriani (2005) stress the role of IT as enabler of knowledge diffusion, finding that the adoption rate of computers is a good predictor of income differentials across countries.

More generally, IT is regarded as a general purpose technology. Its adoption entails long period of experimentation at a firm level, during which significant changes in both the organizational structure and 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 the long-run (*delay hypothesis*). Advances in information technology are claimed to shift the innovation possibility frontier of the economy, rather than directly shifting the production frontier (Bresnahan, 2001). The uptake of IT stimulates co-invention in users; this widens the potential for further applications, so to continually fuel 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 TFP growth is not statistically associated to the contemporaneous level of IT investment, while it occurs with its lagged values (see respectively Stiroh, 2002 and Basu *et al.*, 2004). Though, as shown by van Ark and Inklaar (2005), the relation may be non-linear (U-shaped): the 'early normal returns' which are caused by IT-production and -investment are followed by periods of 'negative spillovers', that show up when firms develop capital complementarities. An alternative strategy to properly gauge the benefits of IT capital consists in working with long growth rates, as done by Brynjolfsson and Hitt (2003) and Oulton and Srinivasan (2005).

As within the R&D context (Griliches, 1992), the elasticity of TFP to IT capital is likely to be higher when estimated at higher levels of data aggregation, as allowing to better capture the social return of this factor. To this end, a long-run (dynamic) perspective of analysis appears particularly helpful to overcome the (static) compensation between the performance of innovative firms (or industries) and that of the less innovative ones, which makes aggregate spillovers hard to measure in a short-term horizon.[3]

Productivity effects of R&D. Since Griliches (1979), technological knowledge intended either as output of innovation activity or as input in production of new knowledge has been a central topic in productivity literature.[4] At a country-

[3]See McGuckin and Stiroh (2002) for a discussion on the aggregation relations, and O'Mahony and Vecchi (2005) for a long-run estimation of the IT impact on output growth.

[4]Traditionally, a threefold effect is ascribed to R&D-based innovation. First, it raises the ef-

level of analysis, Lichtenberg (1993) first investigated the TFP-enhancing effects of (privately-funded) R&D, finding an elasticity of 7%. This evidence was interpreted against the existence of cross-country spillovers; indeed, if knowledge did really spill over free of charge, then domestic R&D would not have a differential impact on productivity with respect to foreign knowledge. Nevertheless, it is only with Coe and Helpman (1995), henceforth CH, that a focused attention has increasingly been paid to international technology spillovers.[5] Under the assumption that knowledge is embodied in traded (intermediate) goods, CH show that larger advantages accrue to the economies that intensively import from technically-advanced countries (*direction effect*), and that such benefits are proportional to a nation's trade openness (*intensity effect*).[6] According to Keller (1998), however, this type of evidence does not corroborate the hypothesis that knowledge flow across countries through trade, since identical results arise whatever type of weights is adopted, even randomly generated.[7] On the other hand, Lichtenberg and van Pottelsberghe (1998) stress that the CH's weighting scheme is subject to an *aggregation bias,* and that opportunely correcting it yields better outcomes on trade-related spillovers.

Nowadays, there is large agreement that international spillovers substantially contribute to productivity growth and, for technological laggards, even more than domestic R&D. This type of findings has recently been confirmed by examining alternative channels of transmission or proxies of knowledge capital as shown, among others, by Madsen (2007) and Bottazzi and Peri (2007) with patent data or Lumenga-Neso *et al.* (2005) using a recursive weighting scheme for foreign R&D. On the other side, Lee (2006) examines a wide array of tools through which innovation may spill over internationally, finding that only inward FDI and disembodied technical change are truly knowledge conduits. Exploiting data on technology balance of payments, Mendi (2007) illustrates 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

ficiency of the economic entities involved 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 enables the absorption of technology developed elsewhere (technology transfers). This paper deals with the former two types of spillovers, referring to Cohen and Levinthal (1989) and subsequent works (Griffith *et al.*, 2003, and 2004) for the relation between absorptive capacity and technology transfers.

[5]The main results of this literature are summarized in Table A.1 of the Appendix. See Keller (2004) for an extended survey.

[6]Foreign knowledge is gauged by averaging the R&D stock owned by trading partners through bilateral import shares; the degree of trade openness is measured by multiplying the foreign R&D with the import intensity of the recipient countries.

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

among the different forms (and funding) of R&D; the effect of both public basic research and foreign knowledge are found to exceed that of domestic business R&D, despite this differential has been reducing over time. For explaining the patterns of national productivity, human capital also appears a relevant factor, being complementary to R&D (Engelbrecht, 1997 and Frantzen, 2000). Recently, this large body of evidence has been enriched by most industry-level studies, where intermediate transactions from input-output tables are used to gauge within-country spillovers (Keller, 2002a).[8] Among others, this approach has been adopted by Acharya and Keller (2007) to assess the extent to which the R&D activity of each frontier country affects the performance of technological laggards.

Interaction between IT and R&D. Although the process of co-invention between IT and R&D has long been recognized,[9] there is scarce evidence on the interaction between these two factors in productivity growth. Using French micro data (up to 1994), Greenan *et al.* (2001) find that computing equipment and research inputs are jointly significant within the cross-section dimension, but not along the time-series one. A similar (cross-sectional) result is found by Matteucci and Sterlacchini (2004) by studying a large sample of Italian firms during the golden years of the 'Information age' (1998-2000); R&D intensity is shown to be stably significant, while IT investment only if taken with a lag, confirming for this factor the 'delay hypothesis'. At an economy-wide level, Lee (2005) illustrates that international spillovers have been enhanced by the development of telecom infrastructures, especially after the advent of the Internet; on the other side, Madden and Savage (2000) and Lee (2008) point out that imports of IT commodities are particularly conducive of knowledge spillovers.

3 Empirical setting

3.1 Analytical framework

In line with the theoretical background, we start by considering the following closed-economy specification (model 1):

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

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

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

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 country fixed-effects, ϵ_{it} the usual stationary errors. i denotes countries ($i = 1, ..., 15$), and t time periods ($t = 1980, ..., 2003$). Initially, we consider gross expenditure on R&D as measure of knowledge capital (GERD). Later, to avoid any distortions due to the heterogeneous impact of 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 productivity spillovers associated to the R&D base of the IT-producing sector, relatively to those 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 R&D stock of IT firms, while DRD^{NI} the one developed by the (non-IT) remaining part of the market economy. Model 2 is helpful for excluding that the TFP-enhancing effect of the knowledge related to IT production is taken up by the coefficient of IT assets, as it may occur when one adopts an aggregate measure of R&D capital (eq. 1).

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

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

Equation (3) eliminates the risk for IT capital to be biased because of the omission of R&D carried out abroad by IT producers.

The external stock of technological knowledge is computed using the weighting method devised by Lichtenberg and van Pottelsberghe (1998, hereinafter LP). Unlike the CH's scheme, this procedure is invariant to the level of data aggregation, as the size of foreign knowledge does not rise by merging two (or more) exporting countries, yielding thus more robust results. Foreign knowledge owned by each type of firms is computed by weighting R&D capital with the current prices ratio between the flow of exports towards the recipient countries and its value-added (FRD^λ and $\lambda = I, NI$):

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

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, and the latter are proportional to the level of data disaggregation on commodity flows, 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 TFP. First, we build a smoothed LP indicator using a 3-year moving average of the flows of exports and value added ($\overline{M}_{jit}^{\lambda,F}$ and $\overline{Y}_{jit}^{\lambda,F}$):

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

Secondly, we construct the stocks-based version 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 $Y_{jt}^{\lambda,S}$):

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

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 knowledge capital ($\delta = 0.15$). 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 earlier been 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, in order to eliminate the endogeneity bias. Albeit based on the hypothesis of errors' independence, panel dynamic OLS performs well even for low degree of cross-section dependence; this effect can be easily allowed for by working with cross-sectionally demeaned variables, which 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 the 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 panel individuals. Mark *et al.* (2005) demonstrate that there is little difference in the size distortion of panel DOLS relatively to dynamic SUR, although 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. The $CIPS$ statistic tests the non-stationarity of the series. 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; such additional regressors remove the effect of cross dependence which is assumed to be shaped as a one-factor model.[10]

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 country specific (short-run) dynamics, intercepts and slope coefficients. However, by construction, VR_G accommodates a larger degree of heterogeneity, lowering the risk of accepting the null hypothesis of no cointegration in small samples because of a few individuals. By contrast, the rejection of the null hypothesis by the VR_P test provides strong evidence in favor of cointegration. It should finally be remarked that both VR statistics hinge on the assumption of errors' 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 distortion is inferior to that emerging with other popular tests

[10] Serial correlation is controlled for by including lagged first-differences of the dependent variable and their cross-section mean.

(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 the GGDC Total Economy Growth Accounting database.[11] 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 hand, 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 a translog. 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 the OECD Main Science and Technology Indicators and ANBERD database.[12] Below, we carry out separate regressions using either gross expenditure in research and development (GERD) or business enterprise R&D (BERD) as measure of knowledge capital. Along with BERD, the former includes the expenses of public research labs, of the 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 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 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 also be disentangled into the one performed

[11] Groningen Growth and Development Centre. Details can be found in Timmer *et al.* (2003).
[12] OECD (2007, and 2002a).

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.2).[13] The stock of foreign R&D is constructed employing data on bilateral trade by commodity and industry, expressed in current dollars, respectively taken from the OECD International Trade by Commodities Statistics and STAN Bilateral Trade database.[14]

In robustness checks, as control variables we employ the average number of schooling years, and an alternative indicator of knowledge capital based on patent data. The former is extracted from the data set recently developed by Cohen and Soto (2007); 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 data construction is provided in the Appendix.

4.2 Descriptive analysis

Table 1 reports the dynamics of productivity and that of the various types of technically-advanced capital, expressed as average annual percentages of change. TFP grew by a 1.3% per year in our sample, showing however a remarkable variation among countries. It rose particularly fast in Ireland and Finland, while being rather sluggish in Greece and Spain, where it contributed only marginally to the convergence of these countries towards the income levels of the richest economies.

The accumulation of IT capital has been relatively more homogenous across countries, amounting to an annual 14%; the best performance are shown by Ireland and UK (about 17%). For this indicator, the relatively modest range of variation is consequence of the harmonization in investment deflators implemented at

[13] This classification slightly differs from the official one adopted by OECD (2006b, Annex A). Among IT manufacturing industries, the latter also includes insulated wires (313) and scientific instruments (332 and 333 ISIC rev. 3). 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.

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

GGDC; indeed, in order to consistently treat the quality improvement of high-tech goods, IT expenditure has been deflated by the hedonic price index developed by the Bureau of Economic Analysis for the US, corrected for cross-country differences in general inflation (see also Schreyer, 2002).

Looking at knowledge capital, it can be observed how the broadest measure of R&D 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 the countries less involved in research activity at the beginning of the period; among them, business sector played a driving role in knowledge generation especially in Ireland and Finland (11%). On the other tail of the distribution, the growth rates in the BERD stock have been considerably lower, except than for the US. This country reinforced its leadership in R&D-based innovation, especially from the late 1990s when it outpaced the knowledge accumulation of the other large-sized economies. Business R&D grew particularly slowly in the UK, closely followed by Germany and Italy; note that the latter country is the unique case in which the rise in the stock of public R&D exceeds that of private sector.

A detailed outline on knowledge accumulation can be traced by 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 industry (11.6% against 5.9%);[15] only in the UK, did the knowledge stock expand more rapidly in the non-IT part of the economy, even though this tendency has recently reversed. A specular pattern can be found in Germany and Italy where the research effort of IT firms was sizeable up to the mid-1990s, since when it sharply deteriorated.[16]

The last two columns of Table 1 report the dynamics of foreign R&D distinguished by industry types (based on standard LP weights). FRD is the portion of knowledge built abroad which is potentially relevant for the productivity growth of recipient countries, being embodied in imported goods. In open economies, trade might act as tool for offsetting the inadequateness of R&D carried out by domestic firms, in particular in those productions characterised by an on-going concentration in knowledge generation (opposed to a geographical fragmentation of manufacturing), as in the field of information technology. As a mirror of the increase in both international trade and the research of IT producers, FRD^{I} grew faster than domestic R&D (13.8 vs 11.6%). It should be noted that, for this in-

[15]At an industry-level, R&D expenditure has been deflated by the price index for value-added. These series are taken from EU KLEMS where no harmonization is done for the IT sector, implying that only a minority of countries employ price indexes adjusted to control for quality growth in IT output (Timmer *et al.*, 2007). These methodological issues will further be discussed below, and shown to unaffect the key results of the paper. Table A.2 of the Appendix reports the level of the variables at the beginning and at the end of the period examined.

[16]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 1: **Dynamics of TFP and technically-advanced capital**, 1980-2003
(average annual percentages of change)

	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 standard LP weights.

dicator, the highest rate of growth is shown by the UK (16.3%), i.e. the country characterized by a flat dynamics of IT-related knowledge (-0.6%). On the other hand, the average rate of expansion in FRD^{NI} is remarkably slower, and only Spain stands out for a brilliant performance.

Table 2 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 productivity is significantly correlated with the accumulation of both IT assets (0.31) and knowledge capital (0.31 for GERD and 0.29 for BERD). Breaking down the knowledge stock into the R&D endowment of IT and non-IT firms, distinguished by domestic and foreign industries, we find a lower degree of correlation between knowledge capital and TFP. The dynamics of productivity turns out to be statistically un-related to the R&D stock of foreign IT firms (FRD^I); by contrast, IT capital is correlated with FRD^I (0.26) but not with DRD^I.

Table 2: **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 standard LP weights. **, * significant respectively at 5 and 10%.

5 Econometric results

Closed-economy framework (Model 1). This section starts by showing the estimation of equation 1. Along with the estimated elasticities, Table 3 reports the value of the panel unit roots test on the right, and that of panel cointegration tests on the bottom. The CIPS statistic tests 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. In light of the different treatment of cross-section dependence, the panel unit roots test is carried out on original variables, while both cointegration tests on cross-sectionally demeaned series.

Initially, productivity is regressed on IT capital and the total economy measure of R&D (column i). These elasticities are found to amount to 0.063 and 0.107;[17] the latter stands in the range of values found in earlier works (see Table A.1), while the former is more conservative than the (average) value found by Ketteni *et al.* (2007) investigating the complementarity between IT and human capital (0.22). Regression (ii) shows however that the business sector is the sole source of R&D spill-overs over the period examined (0.118). In fact, public research is not significant, and this is consistent with Park (1995). The finding for PRD might depend on a compensation between the research impact of the 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. Thereby,

[17] In the regression analysis, one-year lags and leads of the regressors' first-differences are inserted into the log-level specifications. Including either a heterogenous trend or two-year leads and lags yield less robust results. The GAUSS codes used in the analysis are available at the Donggyu Sul' homepage (http://homes.eco.auckland.ac.nz/dsul013/).

Table 3: **Estimates of productivity spillovers in closed economies**

	(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)	$CIPS$
TFP (dep.)								*-0.27*
IT	0.063**	0.060**	0.047**	0.049**	0.069**	0.051**	0.050**	*-0.91*
	(0.012)	(0.011)	(0.014)	(0.020)	(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**	0.125**	0.088**	0.161**	0.101**	*0.01*
		(0.048)	(0.041)	(0.049)	(0.020)	(0.030)	(0.035)	
Human capital				-0.010				*-0.66*
				(0.044)				
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	*-2.24***	*-2.40***	*-2.05***	*-1.72***	*-1.23*	*-2.46***	*-2.43***	
VR_P	*-2.07***	*-1.55**	*-1.88***	*-1.32**	*-0.92*	*-1.52**	*-1.60**	

Notes: All variables are expressed in log-levels. Any specification includes country fixed-effects and common time dummies. Standard errors based on Andrews and Monahan's pre-whitening method in parentheses. TFP: total factory productivity; IT: IT capital; DRD: domestic R&D; Patents$_{epo}$: patent applications at EPO; Patents$_{uspto}$: patent grants at USPTO. CIPS tests checks that all series are non-stationary, VR_P that there is no cointegration for all panel individuals, while VR_G that it occurs for a positive fraction. Critical values (5 and 10%): CIPS: -2.25 and -2.14. VR$_G$-VR$_P$: -1.64 and -1.28.

both types of technically-advanced capital appear to be featured by excess of returns.[18] The estimated elasticity of TFP to business R&D is likely to gauge the social returns of knowledge-generating processes, i.e. inter-firm and inter-industry (non-pecuniary) externalities; 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 discussed in Section 2, the impact of technically-advanced capital is usually enhanced by the upgrading of workforce skills or level of education. Both R&D and IT capital are correlated with human capital, implying that the elasticities so far estimated may be influenced by the omission of such a factor.[19] To control for this possible bias, we add to the specification a measure of human capital constructed adopting the Mincherian approach, $H_t = e^{\phi * ys_t}$. ys_t are the average years of schooling for people aged 25 and over, whilst ϕ is a positive parame-

[18]Note that the direct 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 into capital and labour costs.

[19]It should be reminded that the measure of labour input used in computing TFP is based on hours worked.

ter assumed common across countries and over time (Cohen and Soto, 2007).[20] Since equation (1) is expressed in logs, the control variable used in regression (iv) is the absolute number of school years (ys_t). Such a regressor is far from being significant, and thus the coefficients of IT and business R&D capital change only fractionally.

In column (v), the amount of hours worked is used as explanatory variable to exclude any distortion 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, the coefficient of R&D or IT capital might be oversized due to presence of increasing returns, rather than reflecting that of genuine technological spillovers.[21] This possibility is however ruled out by the fact that labour elasticity is negative (-0.224), indicating the presence of decreasing returns to scale; in comparison to the previous estimates, the elasticity of IT capital now 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, equation (1) is estimated by introducing the cumulative value of patented ideas. Notoriously, R&D expenditure is only an input of the knowledge-generating process, turning out to be an imperfect measure of innovation being relevant for economic growth. In principle, this kind of mis-measurement may lead the coefficient of IT capital to be upward biased. In column (vi), we use the stock of patent applications at the European Patents Office. Probably, it is the most exhaustive indicator of the output of inventive processes occurring in Europe. Though, it should be kept in mind that only a fraction of applications are accepted at the end of the 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 for our robustness' checks. Regression (vii) seeks 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 patent stock

[20] See the Appendix for details on how the annual series on school attainment have been extrapolated.

[21] To make clear this point, consider the definition of the *true* TFP, expressed in terms of growth rates: $g_z^* = g_Y - \alpha g_K - \beta g_H$, where α and β are the *true* factor elasticities. On the other hand, 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 the other correlates.

turn out to be insignificant. Now, the coefficient of IT capital is slightly higher than shown in column (ii), and remains stable across the two specifications; by contrast, 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 3 provide sufficient guarantee of the existence of cointegration between productivity and technically-advanced assets. The variance ratio tests fail to reject the null hypothesis of no cointegration only for the specification using hours worked as control; the fact that VR_G always indicates the presence of cointegration in data, while VR_P falling at the limit of significance, suggests that heterogeneity is confined in a few countries.

IT specialisation within a closed-economy framework (Model 2). The focus of the analysis is now shifted on the role of industry specialization in IT productions. This step appears interesting for a twofold reason. First, it provides an econometric contribution to the literature on the growth impact of *IT usage* and *production* which, thus far, has mainly been investigated through growth accounts. Second, following the body of studies on R&D spillovers, the maximum emphasis is placed upon the sector most involved in innovation activities and that, as such, is considered the engine of the emergent knowledge-based economy.

For comparative aims, Table 4 displays in column (i) the key results found above. In column (ii), we separate the productivity effects of business R&D into the spillovers related to the 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 (column i). On the other side, there is a marked reduction in the coefficient of IT capital, that now is significant at a 10% level; it confirms that the impact of this factor is likely to be overstated when one does not explicitly consider the R&D spillovers associated to the (domestic) production of IT goods. It might simply occur as IT firms are the most intensive users of computing equipment or, alternatively, depend on the high level of data aggregation that leads the positive spillovers produced by one or a few industries to be obscured by the performance of the rest of the economy. Regression (ii) highlights the prominent role of the knowledge base of IT producers for the modern growth process; although this industry only accounts for between 1 and 3% of business-sector employment (or value added), it performs about a 20% of private research, delivering large productivity gains to the aggregate economy.

In column (iii), we use a wider definition of IT industry, which now includes computer services as well (cat. 72, ISIC rev. 3). This sector has expanded exponentially during the last decade and, in terms of R&D effort, has overcome IT manufactures in most countries. As a consequence, the spillovers related to the IT industry might be even larger than found above due to the omission of such

Table 4. **Estimates of spillovers in closed economies: 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**						0.01
	(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**	*-1.35*
		(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	*-2.05***	*-2.45***	*-2.01***	*-2.53***	*-2.40***	*-2.56***	
VR_P	*-1.88***	*-1.48**	*-1.23*	*-1.60**	*-1.30**	*-1.52**	

Notes: All variables are expressed in log-levels. Any specification includes country fixed-effects and common time dummies. Standard errors based on Andrews and Monahan's pre-whitening method in parentheses. a) includes computer services among IT producers. b) uses variables built on non-hedonic deflators. c) refers to the period 1980-2002. TFP: total factory productivity; IT: IT capital; DRD: domestic R&D; DRD^I: domestic R&D of IT industry; DRD^{NI}: domestic R&D of non-IT industry; Patents$^I_{epo}$:patent applications at EPO by IT industry; Patents$^I_{epo}$: patent 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 a positive fraction. Critical values (5 and 10%): CIPS: -2.25 and -2.14. VR$_G$-VR$_P$: -1.64 and -1.28. **, * significant respectively at 5 and 10%.

intangibles, with the risk of an upward bias for IT capital. However, these additional series have the drawback of presenting many missing values, especially for the 1980s; such data have been interpolated as described in the Appendix. As shown in column (iii), the new classification yields sizeable differences in the estimated elasticities.[22] On one hand, the knowledge stock of the IT industry turns out to be insignificant, whilst the R&D coefficient of non-IT firms rises marginally (0.133); on the other hand, the elasticity of TFP to IT capital recovers approximately the original value of column (i). Taken rigorously, this finding indicates that the knowledge spillovers of the IT industry are associated to the production of hardware rather than software; as the research effort of the latter kind of firms has risen only recently, the related benefits are far from materializing, even though this does not preclude that it may occur in the near future. Nevertheless, in light of the heavy interpolation needed to build the new R&D stock, it might also depend on larger noise in data, that attenuates towards zero the coefficient of DRD^I. For such reasons, the next steps of the analysis will be performed by employing the narrow definition of IT industry, based on office machinery and communication equipment.

Another concern with IT, intended either as investment goods or as industry

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

output, are the measurement errors of quality improvement. As explained above, the constant-price value of IT investment has been calculated by applying the harmonized indexes developed at GGDC on the basis of the US hedonic prices. On the other side, real R&D expenditure has been computed by applying the industry deflators for value-added; for the IT sector, only a handful of countries employ hedonic methods to allow for the rising quality of output, while most of them still hinge on matching models. This creates an artificial disparity in the dynamics of research expenses; at the same time, for the majority of countries, there is an uneven treatment between the quality of IT assets and that of the knowledge stock of IT producers, that may be a further source of distortion. Since these measurement errors involve both the dependent and explanatory variables, we do not know a priori which effect prevails (Stiroh, 2002). Therefore, to understand the relevance of such issues, we re-estimate model 2 using a measure of the variables obtained with quality-unadjusted deflators (column iv).[23] This tentative exercise yields a non-trivial change only in the coefficient of IT capital, that now rises up to 0.097, indicating however that price harmonisation is source of a conservative elasticity for this factor.

The last two regressions of Table 4 assess the extent to which the previous findings are affected by the input-based indicator of knowledge capital. To exclude the possibility that the coefficient of IT assets does capture the unmeasured innovative output of IT producers we introduce into equation (2) the stock of ideas patented by this type of firms. Using EPO applications there is evidence that R&D expenses may not be exhaustive for assessing the spillovers of the IT-related knowledge, as the control variable turns out to be significant (0.025); in this case, DRD^I halves compared to column (ii) (from 0.037 to 0.020), while the coefficient of IT capital slightly increases. These outcomes are partially confirmed using USPTO data;[24] indeed, whereas both R&D elasticities are consistent with the values of column (v), now the stock of IT patents is not significant while IT capital soaring up to 0.061. As a whole, this evidence confirms the robustness of IT capital and domestic R&D as drivers of long-run productivity.

IT specialisation within an open-economy framework (Model 3). Now, we take account of imported R&D spillovers. The estimates of equation (3) are displayed in Table 5 where, as reference, we also report the main close-economy results (column i). A measure of foreign R&D based on the usual LP weights is employed in regressions (ii) through (v); instead, the two subsequent sections

[23] IT investment has been deflated through the price index for non-IT investment, R&D expenditure of IT industry using the value-added deflator of the non-IT part of the market economy. TFP series have also been re-calculated considering the new (quality 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.

[24] USPTO data are available up to 2002.

adopt the trade shares respectively constructed on the three-year moving average and the cumulative value of output and export flows. In each set of regressions, we first introduce the foreign stock of total business R&D to facilitate the comparison with the reference literature on international technology spillovers. In a second step, one at a time, we add to the basic specification the foreign R&D of the two industry types (IT and non-IT), with the view to check whether the internal knowledge stocks are picking up the effect of research performed abroad. Finally, the last regression of each section restricts on correlates which are found to drive productivity.

As expected, introducing the business-sector stock of foreign knowledge lowers both elasticities of domestic R&D (column ii); on the other hand, the coefficient of IT capital turns out to be larger, and abundantly more significant, than in column (i). Compared to existing evidence, the spillovers of foreign R&D appear rather modest in size, and only weakly significant. As suggested by the next two regressions (col. iii and iv), a possible explanation for this finding is the diverging impact exerted by IT and non-IT producers.[25] Regressions (iii) considers the trade-weighted value of R&D accumulated abroad by the IT industry; with respect to column (i), there is a sizeable increase in the size of elasticities, in particular for IT capital. It occurs as the coefficient of FRD^{I} has a negative sign (-0.056), probably reflecting the competition effect caused by the import penetration of IT goods: the less a country produces information technology (and accordingly the more imports from abroad), the more the related benefits are eroded by the competing economies. This phenomenon has been investigated by Bitzer and Geishecker (2006) within a more general context. Thereby, maintaining a minimum level of specialization in IT productions appears essential to compete on the international market, as the knowledge base underlying these activities is not easily transferable or imitable. The negative effect of FRD^{I} might thus reflect the nature of (oligopolistic) competition featuring IT industries where the most innovative players take all the market once they develop a new frontier technology (competition *for* the market)[26]. Dynamic economies of scale in research activity may then be the driving force behind the on-going process of concentration in IT sector. By contrast, there is no evidence of a similar negative effect from the foreign non-IT sector (column iv); indeed, FRD^{NI} exhibits a strongly positive coefficient (0.087), while the R&D elasticity of the domestic non-IT industry loses significance.

[25] A problem with FRD^{F} is that it is not non-stationary for all countries, as indicated by the CIPS test (-2.15*); this clearly depends on $\mathrm{FRD}^{NI,F}$ for which the null hypothesis of non-stationarity is rejected at the highest level of significance (-2.60**). As shown below, a similar finding emerges when employing the trade shares based on the cumulative value of import propensity, but not when adopting the smoothed flows. Thereby, for regressions (vi) through (ix) the necessary conditions for the validity of the cointegration tests are fully fulfilled.

[26] See Shapiro and Varian (1999) and Shy (2001).

Table 5: **Estimates of productivity spillovers in open-economies: the role of IT specialisation**

	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		*-1.35*
	(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**				0.083**				*-2.15**
		(0.026)				(0.020)				(0.033)				
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	*-2.45***	*-2.43***	*-2.19***	*-2.38***	*-2.15***	*-2.47***	*-2.23***	*-2.47***	*-2.27***	*-2.42***	*-2.36***	*-2.55***	*-1.79***	
VR_P	*-1.48**	*-1.41**	*-1.29**	*-1.42**	*-1.46**	*-1.39**	*-1.30**	*-1.42**	*-1.47**	*-1.47**	*-1.41**	*-1.50**	*-1.31**	

Notes: All variables are expressed in log-levels. Any specification includes country fixed-effects and common time dummies. Standard errors based on Andrews and Monahan's pre-whitening method in parentheses. TFP: total factory productivity; IT: IT capital; DRD^I: domestic R&D of IT industry; DRD^{NI}: domestic R&D of non-IT industry; FRD: foreign R&D; 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 a positive fraction. Critical values (5 and 10%): CIPS: -2.25 and -2.14. VR$_G$-VR$_P$: -1.64 and -1.28. The value of the CIPS statistic 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 test amounts to -1.48 for FRD, -0.87 for FRD^I, -3.06** for FRD^{NI}. **, * significant respectively at 5 and 10%.

As a final step, column (v) reports the parsimonious version of model 3. Synthetically, it shows that the within-country spillovers are enabled only by the R&D base of the IT industry and the total-economy endowment of IT assets. International trade instead is a valid channel for transmitting the knowledge created in less advanced productions, neutralizing thus the research effort of domestic firms; in line with existing evidence, cross-country spillovers contribute to productivity growth more than any internal factor.[27]

Next we turn to assess the sensitivity of estimates to import volatility. As discussed in Section 3, temporary changes in trade figures may be source of noise in FRD series, undermining the consistency of slope parameters. Nonetheless, it can be easily observed from columns (vi) through (ix) that the use of smoothed weights yields similar outcomes.[28] The main discrepancy can be identified in the insignificance of DRD^{NI} in regression (vi), and in the high explanatory power of FRD that now is consistent with the values found in earlier works (0.108). Moreover, there is a strong confirmation of the negative (trade-related) impact exerted by the research effort of foreign IT firms (-0.064) and, finally, the elasticities of the restricted model lye very close to those obtained using standard weights (col. ix).

Finally, the open-economy model is re-estimated employing the LP procedure based on stock variables.[29] As argued above, this scheme should be particularly robust to trade volatility, and more accurately capture the (slow) learning of foreign knowledge by domestic firms. The estimates reported in columns (x)-(xiii) however are consistent with the two previous sets of regressions, aside from a relevant exception. In column (xi), neither IT capital nor the knowledge stock embodied in IT imports are significant, suggesting that such factors may be capturing the same effect on productivity. This finding would corroborate the hypothesis of the incorporated nature of technical progress, i.e. that IT capital is not a special type of assets and the related benefits derive from its content of R&D, which is mainly developed abroad. Though, it is easy to show that such a result depends on a distortion concerned with the stocks-based version of the LP method, and in particular with the formula adopted to estimate the initial stocks.[30] Indeed, whenever the depreciation rate used in building stocks approaches to the unity, the trade shares underlying FRD^F and FRD^S should virtually coincide. This means that the use of a measure of FRD^S based on rising values of δ should produce estimates coming closer to those obtained with standard weights (FRD^F). Nevertheless, in

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

[28]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}.

[29]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}.

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

so doing, we find a positive coefficient for FRD^{I,S} and a negative one for IT capital, and the gap between such elasticities rapidly widens by increasing the value of δ.[31] 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.

6 Concluding Remarks

This paper has examined the role played by both IT and R&D on the economic growth of modern knowledge-based societies. The aim was of understanding whether these factors generate separate productivity spillovers, or merely embody the two sides of the same coin, i.e. the benefits produced by the R&D-led advances achieved in the field of information technology.

Our results indicate that investing in IT assets is highly recommendable to stimulate economic growth, as delivering productivity gains distinct from R&D, probably due to network externalities and specific knowledge spillovers. Though, this strategy might not be sufficient to offset a country's low specialization in the production of information technology. Indeed, in contrast to less technically-advanced industries for which trade is a robust enabler of cross-country spillovers, the type of knowledge underlying IT productions seems hardly transferable abroad, as shown by the negative effect associated to the import penetration of IT goods. This evidence suggests that, in the current technological age, extraordinary efforts should be conducted by any modern economy to retain some competitive advantage in IT productions (even though limited to very small segments) in order to improve the long-run prospects of growth.

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

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Appendix: Data 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 rise of factor inputs, using the Tornqvist index formula (individual subscripts omitted):

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

where $\bar{s}$ is a two-year average of the inputs' income on GDP (in current prices). TFP is indexed to 100 in 2000. Y is real GDP net of actual and imputed rents for housing. 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). L are hours worked. National Accounts series come from the **Groningen Growth and Development Centre Total Economy Growth Accounting Database**.[32]

Current prices series have been deflated by means of country-specific price indexes (taken from GGDC), and then converted into US GDP Power Purchasing Parities, expressed in constant dollars of 2000. Deflators for IT investment consist in the US hedonic indexes corrected for the differential in general inflation (*price harmonisation*). R&D expenditure has been converted into a constant-price base through the industry deflators for value-added; these are taken from **EU KLEMS database**.[33] 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 by geometrically interpolating the industry shares on GERD (or BERD); the percentages of 1980 are backwardly estimated from the values of 1981 using the average annual rate of change relative to the period 1981-91.

IT (manufacturing) sector is defined as the sum of office machinery and communication equipment (category 30 and 32, ISIC rev. 3). 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 the 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, we have classified as IT patents those granted to the OTAF category n. 357 (Office computing and accounting machines) and n. 365-367 (Communication equipment and electronic components). NBER Patent data cover the period 1980-2002. See Hall *et al.* (2001) for details.

Capital stocks, S^λ, have been obtained from series on real investment or patent counts, I^λ, by

[32] www.ggdc.net; release July 2005.

[33] www.euklems.net, release March, 2007.

means of the permanent inventory method and geometric depreciation:

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

g^λ is the average annual growth rate of real investment (or patents) over the period 1980-2003. δ^λ is an asset-specific depreciation rate, assumed constant over time and across countries. It is fixed to 0.150 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. For office machinery, instead, δ is variable and ranges from 0.222 to 0.312; this is due to reflect the rising weight in this category of computing equipment, which is featured by a faster physical deterioration ($\delta = 0.315$) than the other types of IT assets (printers, photocopiers terminals, etc.). Finally, capital series are adjusted to mid-year values, $K_t = (S_t + S_{t-1})/2$.

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 SITC rev. 2 and ISIC rev. 3) has been implemented through the Eurostat correspondence tables.[34] The following commodities have been attributed to the IT industry: cat. 75 and 72655 to Office machinery (cat. 30 ISIC rev. 3); categories 76 less 76483, 7722, 7723, 776 and 7786 to Communication equipment (cat. 32 ISIC rev. 3).

The level of human capital has been constructed as a Mincherian function, using Cohen and Soto (2007)'s data:

$$H_t = e^{\phi * ys_t}.$$

ys_t is the average years of schooling for people aged 25 and over, and ϕ a positive parameter assumed constant across countries and over time. Cohen and Soto (2007) have developed such a measure of educational attainment for a large sample of countries using detailed census sources; such data are available since 1960 at ten-year intervals. In contrast to what occurs using other popular measures of human capital, ys_t is found to be significant in standard (cross-section and panel) growth regressions. ys_t is defined as the average sum of the number of schooling years attained by five-year age cohorts:

$$ys_t = \sum_{g=g1}^{G} q_{gt} ys_{gt}$$

where q_{gt} is the share of each cohort on the population aged 25 and over, and ys_{gt} the corresponding school attainment ($g_1 = 25-29, ..., G$ =65 and over). The missing values between benchmark years have been calculated by means of the following (two-step) strategy. First, we run a fixed-effect regression between ys_t and the percentage shares of each five-year age cohort on the population aged 25 and over, using data at benchmark years ($t = 1960, 1970, 1980, 1990, 2000$).[35] Secondly, we use the estimated coefficients to predict the value of ys_t for intermediate years. This method guarantees a larger variability in human capital series than linearly interpolating data (see Frantzen, 2000). It should be however remarked the results reported in column (iv) of Table 3 are consistent with those yielded by using interpolated series.

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

[35] Demographic data are taken from **EUROSTAT, Demographic and migration statistics** (available at an annual base from 1960).

Table A.1: **Main results on international technology spillovers: Country- and industry-level studies**

	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 (2002a)[6]	CH	IO, IOM	0.607 [0.571]		0.092 [0.294]				6; 15; iv
Keller (2002b)	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 imports 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 version 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.

Table A.2: 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 calculations 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.