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Investment-Specific Technical Change and Growth around the World

Roberto M. SAMANIEGO
George Washington University

Juliana Yu SUN
Singapore Management University, YUSUN@smu.edu.sg

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Roberto M Samaniego*   Juliana Yu Sun†

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Abstract

Investment-specific technical change (ISTC) contributes little to growth in most countries. This is because in many countries the investment process does not become notably more efficient over time. Still, cross-country *differences* in the contribution of ISTC to growth are significant. Differences in the rate of ISTC appear due to cross-country variation in the use of R&D intensive capital goods, as well as trade costs.

Keywords: Price of capital, investment-specific technical change, growth accounting, sources of growth, natural resources, trade costs.

JEL Codes: F43, O11, O13, O16, O33, O41, O47.

*Department of Economics, The George Washington University, 2115 G St NW Suite 340, Washington, DC 20052. Tel: +1 (202) 994-6150. Email: roberto@gwu.edu.

†Juliana Yu Sun, School of Economics, Singapore Management University, 90 Stamford Road, Singapore 178903. Tel: (65) 6808 5456, Fax: (65) 6828 0833, Email: yusun@smu.edu.sg.

I Introduction

Investment specific technical change (ISTC) is thought to account for a significant source of economic growth. Greenwood, Hercowitz and Krusell (1997) and Cummins and Violante (2002)[1] find that about 60 percent of US post war growth can be accounted for by changes over time in the efficiency of investment. However, the contribution of ISTC to growth *around the world* is not known. Figure 1 shows that the standard measure of ISTC – the rate of decline in the relative price of capital – is positively related both to the level of GDP per capita and to its growth rate.

This paper explores the impact on economic growth of changes over time in the efficiency of investment around the world.

In order to do so, there are three issues we must confront that have been raised in the related literature.

The first issue is the approach to growth accounting. We adopt a *general equilibrium growth accounting* approach. This assigns to different sources of productivity growth a contribution that takes account of their influence on endogenous factor accumulation – see Greenwood and Jovanovic (2001). Such a framework is appropriate for two reasons. By accounting for all channels through which a given factor of growth might endogenously affect real output, it is theoretically appealing. Also, it provides an upper bound on the influence of improvements in the efficiency of investment on economic growth, providing a useful benchmark for future work.

[1] Henceforth we refer to these papers as GHK and CV respectively.

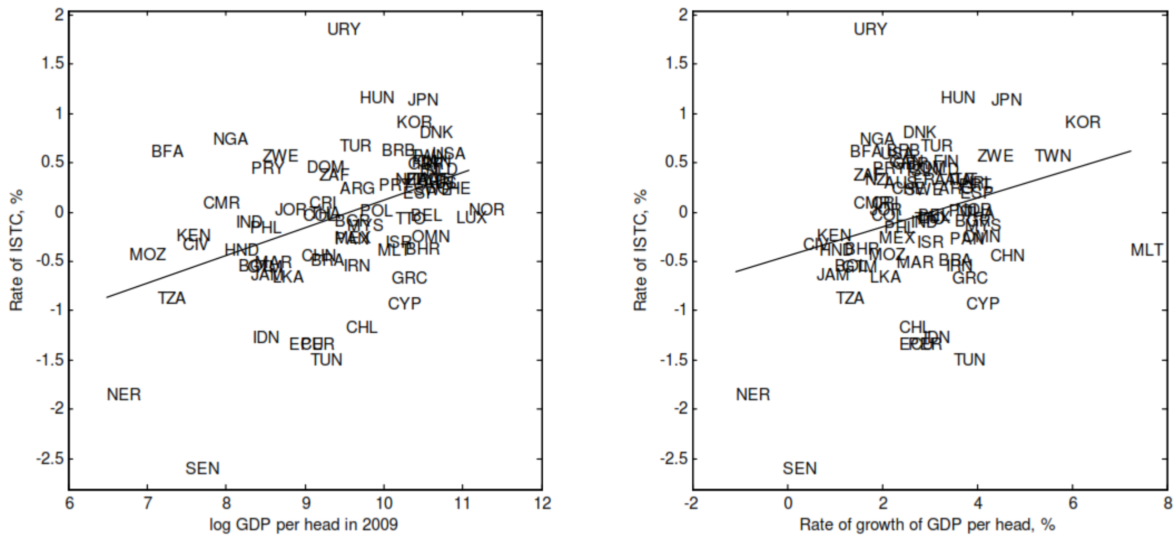

Figure 1 – Investment specific technical change (ISTC), GDP per capita and GDP growth around the world. ISTC is measured using the rate of decline in the relative price of capital as reported in the Penn World Tables 7.1. GDP per capita 2009 and GDP growth 2050 – 2011 are measured using the Penn World Tables 8.1.

The second issue has received less attention: the measurement of the capital share of income. This share is a key parameter as it determines the extent to which improvements in the efficiency of investment contribute to economic growth by stimulating capital deepening – a point raised initially by Denison (1962). The share of capital income is typically identified with one minus the labor share reported in national accounts. However, Gollin (2002) argues that capital shares are over-estimated because self-employment income is often not considered labor income when developing national accounts. Also, in some countries a substantial share of non-labor income may accrue to the extraction of natural resources, which is distinct from the accumulation of physical capital – see Caselli and Feyrer (2007) and Monge-Naranjo, Sanchez and Santaeulalia-Llopis (2015, henceforth MSS). As a result, we develop a general equilibrium growth model that extends the GHK framework to include natural resources as an input. Our model thus contains a new channel for ISTC to influence growth: when resources are replenishable, ISTC may stimulate growth via more rapid resource generation – "resource deepening".

The third issue is whether *quality adjustments* to the price of capital are necessary for measuring ISTC. For example, while a top-of-the-line laptop computer in 1995 and in 2015 both cost roughly $1,500, in terms of *quality* attributes such as storage capacity, processing speed, screen resolution and so on the two computers are vastly different, so that in quality-adjusted terms the 2015 computer may be significantly cheaper even before accounting for inflation. The rate of ISTC reflected in such quality adjusted prices will be more rapid than using prices that do not account for quality change. Gordon (1990) derives quality-adjusted prices for durable goods in the US, and GHK and CV argue that these are the relevant prices for measuring ISTC. In contrast, Whelan (2002) argues against the use of such measures, as there may be unmeasured quality improvements in consumption and services too. The bottom line is that a study of growth accounting with ISTC should attend to the potential influence of quality adjustments on any conclusions.

We find that changes over time in the efficiency of investment *are not* an important factor of growth for most countries – and, globally, the contribution of ISTC to growth is in the range $1-24$ percent. The main reason is that the rate of decline in the relative price of capital is not high in most places. The results are robust to assuming that official price data underestimate ISTC because of unmeasured quality improvements to capital goods, and to allowing for the use of capital goods as intermediates, which is shown in Ngai and Samaniego (2009) to boost the contribution of ISTC to economic growth.[2] The results are also robust to open economy extensions of the model, which is important because Eaton and Kortum (2001) argue that many developing economies import much of their capital. Thus, as a channel of growth, improvements in the efficiency of investment do not seem important in most countries.[3] The open economy extensions are also important conceptually: while some papers (such as Krusell (1998), or Wilson (2002)) identify ISTC with capital-embodied technical change, we find that trade conditions are a factor of ISTC in a world where capital is imported. While we adopt a Cobb-Douglas production function specification, we also show that trends in factor shares idenfitied in Karabarbounis and Keiman (2014) are too small to affect our conclusions.

In fact, in many low income countries, the relative price of capital actually *rises* over time according to official price data. The efficiency of the investment process has *declined* over time, so that resources have become relatively more efficient at produc-

[2] In essence, to the extent that the output of the capital goods sector is used as an intermediate, ISTC boosts efficiency in other industries by allowing them access to cheaper intermediate goods.

[3] Caselli (2005) too argues that ISTC is unlikely have much impact on growth accounting exercises, although without a general equilibrium growth accounting framework and without using relative prices of capital. Instead Caselli (2005) reaches this conclusion by examining a regression of income attributed to capital on a distributed lag of depreciated investment, with inconclusive results. This approach is likely inconclusive because, as shown below, the rate at which the efficiency of investment changes over time varies significantly across countries with a mean close to zero, so pooling country data without accounting for this heterogeneity obscures any "vintage" effects, positive or negative. Of course these data suggest that on average there are no vintage effects – however, it could still be that vintage effects related to improvements or deterioration in the efficiency of investment are in fact important for some countries.

ing consumption goods than capital goods. This could occur if there is a capital goods sector and a consumption goods sector, with both sectors experiencing productivity improvements, but where productivity improvements are most rapid in the consumption sector. However, this interpretation seems unlikely: the developing economies where ISTC contributes little to growth mostly experience particularly slow rates of income growth. This suggests instead that in many developing economies productivity growth in all sectors is slow, and it is particularly slow in the capital goods sector. Hsieh and Klenow (2007) find that the relative price of capital tends to be higher in less developed economies, arguing this is because they are particularly unproductive at producing capital or at producing goods they can exchange for capital: we find that these productivity issues are in fact *exacerbated over time*. See Figure 1. Thus, even though changes in the efficiency of investment are not an important factor contributing positively to economic growth in many countries, the significant *differences* across countries in the rate of ISTC (and its correlation with income per capita) underline the importance of this factor of growth. A contribution of the paper is the finding that ISTC is a factor contributing to a failure of convergence in income levels across countries.

Our findings beg the question: what is behind the observed cross-country variation in the rate of ISTC? Recalling that CV show that the rate of ISTC varies dramatically across types of capital good, a possible explanation is that low-income countries simply do not use the types of capital that experience noticeable price declines. Indeed we find evidence that, in countries with slow aggregate ISTC, the composition of capital is skewed towards goods that experience slower ISTC. An implication is that, if the composition of capital (and hence the rate of ISTC) is sensitive to policy, as suggested in Samaniego (2006), then the potential impact on growth rates in some developing countries of adopting policies that accelerate ISTC could be significant. We also find that ISTC measures, both with and without quality adjustment, are related to the measures of R&D directed towards capital introduced in Caselli and Wilson (2004). Thus, cross country differences in ISTC can be interpreted as differences in the amount of R&D embodied in the capital goods used by different countries. We also find that rates of ISTC correlate with certain institutional variables, particularly measures of financial development and of intellectual property rights enforcement intensity, suggesting important directions for future work on the determinants of country differences in ISTC. We also find a link between trade costs and ISTC, consistent with the findings of Parro (2013). Thus, our results contribute to the literature on the link between trade and growth by providing evidence that reductions in trade costs promote growth by lowering the cost of capital goods, as well as by promoting the use of high-tech capital goods.

The results also contribute to a long-standing debate about whether or not changes in the efficiency of investment are an important factor of growth. This debate goes back at least to Solow (1962), who argues that almost all technical progress is likely embodied in capital, and Denison (1962, 1964), who argues that the impact of ISTC on growth could be tempered by a small capital share, and that empirically unreasonable investment rates would be required for ISTC to be an important factor of growth. Hulten (1992) considers that ISTC might be underestimated because of unmeasured quality change, but argues that its impact is small nonetheless (around 20 percent), in large part by not performing a general equilibrium growth accounting exercise. In contrast, GHK find that in the US more than half of economic growth can be accounted for by ISTC in a general equilibrium growth accounting framework. For the US, our results are similar to those of GHK when we apply quality adjustments to our ISTC measures, and similar to Hulten (1992) when we do not. The reason that in most other countries ISTC is not a significant contributor to growth is simply because the rate of ISTC is low there, and quality adjustments much larger than what appear to be empirically relevant would be required to overturn this conclusion.

Section II develops the model economy. Section III presents the data and Section IV performs the general equilibrium growth accounting exercise using data on the price of capital for different countries. Section V discusses what might be behind country differences in ISTC. Section VI suggests directions for future research.

II Economic Environment

The model economy uses capital k_t, labor n_t and natural resources h_t to produce output y_t:

$$y_t = z_t h_t^{\alpha_h} k_t^{\alpha_k} n_t^{1-\alpha_h-\alpha_k} \tag{1}$$

where $z_t = z_0 g_z^t$. This production function is as in Stiglitz (1974). Following GHK, capital is accumulated according to:

$$k_{t+1} = k_t (1 - \delta_k) + q_{kt} i_{kt} \tag{2}$$

where i_{kt} is investment in capital goods measured in terms of foregone consumption, and q_{kt} is the efficiency of the investment process – i.e. the number of capital goods obtained by converting a unit of consumption into capital. We abstract from transitory changes in q_{kt} in what remains of the paper so as to focus on growth implications, and assume that $q_{kt} = q_{k0} g_q^t$. Here $g_q = q_{t+1}/q_t$ is the growth factor of ISTC, so $\log g_q$ is the rate of ISTC.

We will consider two alternative models of the resource h_t. One model assumes that the resource is exhaustible. The other assumes that the resource is renewable. It turns out that the two models have different implications for general equilibrium growth accounting. However, quantitatively, the differences turn out to be small. Since some natural resources are exhaustible and others are renewable, these two models provide upper and lower bounds for the contribution of improvements in the efficiency of investment to growth.[4]

A Exhaustible resource

Suppose that there is a finite resource. In each period there is a remaining stock X_t of the resource, where

[4] It would be straightforward to write down one model with both kinds of resources, in which case the relative shares of the two kinds of resources would lead to growth implications somewhere between the two cases considered here. However, such a model would be notationally cumbersome, which is why we choose to focus on the polar cases below.

$$X_{t+1} = X_t - h_t/q_{ht} \tag{3}$$

Here h_t is the number of efficiency units of the resource used in production, and q_{ht} is the efficiency of use of the resource. If q_{ht} is high then a given level of h_t is achievable with little depletion of the resource X_t. For example, if X_t is fossil fuels, then advances in engineering might allow the same task to be achieved with less fossil fuel. An alternative interpretation of q_{ht} is that it is an indicator of the efficiency of the extraction process itself, as in André and Smulders (2014). We set $q_{ht} = q_{h0}g_h^t$. This allows for the possibility of resource-specific technical change. Thus, in the model economy there are three factors of growth: neutral productivity growth g_z, resource-specific technical change g_h and ISTC g_q. Our goal is to assess the extent to which growth around the world depends on g_q, rather than on g_z and g_h.

Output has two uses, investment and consumption, so that

$$y_t \geq c_t + i_{kt}. \tag{4}$$

Agent preferences are defined over the discounted utility from consumption:

$$\sum_{t=0}^{\infty} \beta^t \log(c_t), \ 0 < \beta < 1. \tag{5}$$

A planner maximizes preferences (5) subject to constraints (2) and (3), as well as the feasibility constraint (4). Let $g \equiv y_{t+1}/y_t$ be the growth factor of output, which along a balanced growth path (BGP) will equal the growth factors of consumption and of investment.

It is straightforward to show that the general equilibrium relationship between output and the factors of growth is (see Appendix):

$$g = \left(g_z g_h^{\alpha_h} \beta^{\alpha_h} g_q^{a_k}\right)^{\frac{1}{1-\alpha_k}} . \tag{6}$$

In this expression, the discount factor affects the optimal growth rate of output in this economy. This is because an important aspect of an exhaustible resource is that the optimal rate of extraction is linked to the discount factor β, as known since the seminal work of Hotelling (1931). In the absence of technical progress, $g_h = g_q = 1$ and the economy would optimally shrink, at a rate related to β and also to α_k because resource depletion optimally results in capital depletion also. Instead, when $g_h \neq 1$, so that there is resource-specific technical progress (or regress), the extraction pattern in the model follows a generalized version of the "Hotelling rule".

Define C_1 as the contribution of g_q to growth. We measure this contribution by comparing the growth rate of the economy $\log g$ with the counterfactual growth rate if ISTC were absent, so that q_{kt} is constant over time (i.e. $g_q = 1$). If C_1 is the proportional decline in $\log g$ assuming that ISTC is absent, then using (6) we have

$$\begin{aligned} C_1 &\equiv 1 - \frac{\log\left(g_z g_h^{\alpha_h} \beta^{\alpha_h}\right)^{\frac{1}{1-\alpha_k}}}{\log g} \\ &= \frac{\alpha_k}{1-\alpha_k} \times \frac{\log g_q}{\log g}. \end{aligned} \tag{7}$$

B Renewable resource

Suppose instead that the resource is renewable. A certain amount of output is spent on generating (or renewing) the resource, with some efficiency parameter q_{ht}. Thus, the resource accumulates according to:

$$h_{t+1} = h_t (1 - \delta_h) + q_{ht} i_{ht} \tag{8}$$

where h_t is the quantity of the resource, i_{ht} is output devoted to renewing the resource, $q_{ht} = q_{h0} g_h^t$ is the efficiency of the renewal process, and δ_h is the rate of depletion. In this case, output has three uses (consumption, investment in capital and investment in resource renewal) so that

$$y_t \geq c_t + i_{kt} + i_{ht} \tag{9}$$

For example, if h_t is agricultural land, then δ_h reflects the extent to which the quality of the soil deteriorates through use, i_{ht} is spending on improving the soil (e.g. fertilizers, pesticides, etc.) and q_{ht} is the efficiency of the improvement process. If h_t is electricity, then i_{ht} is spending on generation and q_{ht} is the efficiency of the generation process. As shown in GHK, an environment like this one with two accumulable inputs is interpretable as a multi-sector model in which there are separate sectors for consumption, capital and (in our case) the renewable resource, where factor shares are similar but the productivity term in the three sectors is z_t, $z_t q_{kt}$ and $z_t q_{ht}$ respectively. Moreover, this model is isomorphic to that in GHK except that both accumulable resources (k_t and h_t) may experience resource-specific technical progress. As a result we have that, in equilibrium, along a balanced growth path the growth factor of output g equals

$$g = \left(g_z g_h^{\alpha_h} g_q^{\alpha_k}\right)^{\frac{1}{1-\alpha_h-\alpha_k}} \tag{10}$$

This equation takes account of the fact that improvements in the efficiency of investment result in capital deepening, and also in "resource deepening": there is endogenous growth over time in both capital intensity and resource intensity due to ISTC.

Define the contribution of g_q to growth C_2 in this model as the percentage decline in the growth rate $\log g$ when g_q is set to one in this framework. Then, using (10),

$$\begin{aligned} C_2 &\equiv 1 - \frac{\log \left(g_z g_h^{\alpha_h}\right)^{\frac{1}{1-\alpha_h-\alpha_k}}}{\log g} \\ &= \frac{\alpha_k}{1-\alpha_h-\alpha_k} \times \frac{\log g_q}{\log g}. \end{aligned} \tag{11}$$

Notice that $C_1 = C_2 \Leftrightarrow \alpha_h = 0$. Also, if $\alpha_h > 0$, $\|C_2\| > \|C_1\|$ so that

$$C_2 > C_1 \Leftrightarrow g_q > 1.$$

Thus, to the extent that there are improvements in the efficiency of the investment process, C_2 will provide an upper bound on the contribution of ISTC to growth. This is because in the renewable resource model ISTC results endogenously in "resource deepening", boosting the impact of ISTC on growth. When the resource is exhaustible this effect is not present.

Notice also that in both cases we do not need to know any parameters related to efficiency improvements *outside* of the capital sector (g_z and g_h) to assess the contribution of the capital goods sector to growth. All we need are measures of g, g_q and factor shares. This is not to say that g_z and g_h are not of interest: however, the contribution of g_q to growth can be assessed without knowing these values.

C Intermediate goods

Ngai and Samaniego (2009) find that models with intermediate goods deliver a greater impact of ISTC on growth. This is because the output of the capital goods industry is used as an intermediate good in the production of other goods, so that technical progress in the production of capital goods results in lower prices for the intermediates used to make other goods, i.e. fewer resources are required to produce a given quantity of non-capital goods because of ISTC.[5] How would allowing for intermediate goods affect the measured growth contribution of ISTC?

Let us focus on the model with reproducible resources, which is the one most likely to yield high contributions of ISTC to growth (C_2). Suppose that the production function is augmented to allow for intermediates. Now there are three sectors producing consumption c, capital k and the natural resource h respectively. We have that in each industry $i \in \{c, k, h\}$, the production function is:

$$y_{it} = z_{it} \left(h_{it}^{\alpha_h} k_{it}^{\alpha_k} n_{it}^{1-\alpha_h-\alpha_k} \right)^{1-\alpha_m} m_{it}^{\alpha_m}$$

where y_{it} is the gross output of industry i and m_{it} is the quantity of the intermediate good used in industry i. If $\gamma_i = \frac{z_{i,t+1}}{z_{it}}$ is the growth factor of productivity in industry i, define $g_z = \gamma_c$, $g_q = \frac{\gamma_k}{\gamma_c}$ and $g_h = \frac{\gamma_h}{\gamma_c}$. Thus, as before, g_q is the rate of ISTC

[5] For example, technical progress in the production of transistors results in cheaper transistors, resulting in the increased efficiency of resources devoted to the production of transistors. It also results in cheaper toy Lamborghinis that *embody* transistors – even without any technical progress in the production of toy cars – resulting in the increased efficiency of resources devoted to the production of toys also.

(the extent to which productivity improvements in the production of capital goods outstrip those in consumption).

The intermediate good $m_t = \sum_{i\in\{c,k,h\}} m_{it}$ is a composite of the natural resource and the goods of the other sectors, and is produced using the constant returns to scale technology

$$m_t = \prod_{i\in\{c,k,h\}} l_{it}^{\phi_i}, \sum_{i\in\{c,k,h\}} \phi_i = 1, \, \phi_i \geq 0.$$

where l_{it} is the quantity of the output of industry i that is used as an intermediate at date t. This constant returns to scale technology for intermediates is as in Horvath (1998, 2000), Ngai and Pissarides (2007) and Ngai and Samaniego (2009).

In fact, this model is isomorphic to that in Ngai and Samaniego (2009), since the reproducible resource behaves like a type of capital stock. The growth accounting equation becomes:

$$g = \left(g_z g_h^{\alpha_h + \phi_h \alpha_m/(1-\alpha_m)} g_q^{\alpha_k + \phi_k \alpha_m/(1-\alpha_m)} \right)^{\frac{1}{1-\alpha_h-\alpha_k}}$$

This equation takes into account the fact that, when goods may also be used as intermediates, technical progress in industry i results in cheaper intermediates, which results in cheaper production of any good j that uses i as an intermediate. The term $\alpha_m / (1-\alpha_m)$ reflects the fact that technical progress that affects intermediates optimally results in an increased use of intermediates to an extent that depends on the intermediate share of gross output α_m.[6]

[6] It is also worth noting that, in this version of the model, g_k can be measured using the rate of decline in the relative price of capital, as before. See equations 59, 67 and 68 in Ngai and Samaniego (2009).

In this case, the contribution of ISTC to growth is:

$$\begin{aligned} C_3 &\equiv 1-\frac{\log\left(g_z g_h^{\alpha_h+\phi_h\alpha_m/(1-\alpha_m)}\right)^{\frac{1}{1-\alpha_h-\alpha_k}}}{\log g} \\ &= \frac{\alpha_k+\phi_k\alpha_m/\left(1-\alpha_m\right)}{1-\alpha_h-\alpha_k}\frac{\log g_q}{\log g_y} \\ &= \frac{\alpha_k+\phi_k\alpha_m/\left(1-\alpha_m\right)}{\alpha_k}\times C_2. \end{aligned} \tag{12}$$

D Closed and open economies

The related literature uses a closed economy framework where the economy produces both consumption and investment goods. In this case it is well known that a model with ISTC is equivalent to a model where the investment sector and the consumption sector produce different goods, but the production function is the same except for the productivity term – see GHK.

It is also well known, however, that many less-developed economies do not themselves produce capital goods, rather they import them – see Eaton and Kortum (2001) and Caselli and Wilson (2004). We now show that the growth accounting model above applies to a small open economy also.

Consider the case of a small open economy which takes international prices as given. The investment technology (2) is not available: instead, the country must export consumption in exchange for capital goods. Assume that trade must be balanced at each date: we impose this condition as it must hold in the long run and the focus of the paper is not on short run shocks nor on transitions.

The capital accumulation equation is

$$k_{t+1} = y_{kt} + (1 - \delta)\, k_t \tag{13}$$

where y_{kt} is new capital goods purchased from abroad (measured in efficiency units of capital, not in units of foregone consumption). The consumer's problem is the same as before, subject to

$$p_{ct}c_t + p_{kt}y_{kt} \leq r_t k_t + w_t + s_t h_t \tag{14}$$

where c_t and y_{kt} are purchases of consumption and capital goods respectively, and s_t is the return to the resource. The difference is that c_t is not equal to the output of the consumption sector: there are exports too. Let x_t equal exports of the consumption good, so that $y_t \geq c_t + x_t$.

We now have that p_{kt} is the domestic price of imported capital. Let $\tilde{p}_{kt}$ be the price of capital where it is produced, and let e_t be the exchange rate for the domestic currency. Then $p_{kt} \equiv e_t \tilde{p}_{kt}$. Instead, if (as in many trade models) there are costs τ_t such as transportation, tariffs, etc. that proportionately increase the price of traded goods, then $p_{kt} \equiv e_t \tilde{p}_{kt} \tau_t$. The case of no trading costs corresponds to $\tau_t = 1$.

Notice that with balanced trade we will have that the value of exports and imports must be equal, so that

$$p_{ct}x_t = e_t \tilde{p}_{kt} \tau_t y_{kt}$$

with the exchange rate e_t adjusting so that this condition holds at each date. Notice also that, normalizing $p_{ct} = 1$, with balanced trade the budget constraint (14) becomes in equilibrium

$$c_t + x_t \leq r_t k_t + w_t + s_t h_t \tag{15}$$

and the capital accumulation equation can be rewritten

$$k_{t+1} = k_t (1 - \delta) + x_t q_{kt} \tag{16}$$

where $q_{kt} \equiv \frac{1}{p_{kt}}$. This is the same as the closed economy setup above, except that the exports x_t are the foregone consumption that is used to generate capital goods via trade. Now suppose $\tilde{p}_{kt} = \tilde{p}_{k0} \tilde{g}_q^{-t}$. The growth factor $\tilde{g}_q$ might reflect technical progress abroad that improves the quality of capital goods, or it could be technical progress or institutional change that reduces trading costs. Thus, in the international case,

$$g_q = \tilde{g}_q / (g_e \times g_\tau) \tag{17}$$

where g_e is the growth factor of e_t and g_τ is the growth factor of trading costs. Thus, in principle the relative price of capital is affected by changes in the international price of capital, in trading costs and in the exchange rate. Of course on the basis of theory we would expect g_e to be determined by the equilibrium condition of balanced trade itself, so it should not have an independent effect on g_q.

Remark 1 *Although trade is not the focus of this paper, equation* (17) *raises a benefit of trade liberalization which to the authors' knowledge has not been identified and which is worthy of further research. Any downward trend in trade costs ($g_\tau < 1$) may imply an acceleration of ISTC when a significant portion of capital is imported. This is particularly relevant in a world where outsourcing of intermediate production* *or assembly services is common.*

Suppose now that the small open economy exports *resources* in exchange for the investment good. The capital accumulation equation is the same as (13)

$$k_{t+1} = y_{kt} + (1 - \delta)\, k_t \tag{18}$$

where y_{kt} is new capital goods purchased from abroad (measured in units of capital, not in units of foregone consumption). The consumer's problem is the same as before, subject to (14). However, not all of h is used in production. Instead, quantity x_t of the resource is exported. Thus the amount of resource used in production is $h_t - x_t$. With balanced trade we will have that the value of exports and imports must be equal, so that

$$s_t x_t = p_{kt} y_{kt}$$

and the exchange rate e_t adjusts so that this condition holds at each date as before. Normalizing $p_{ct} = 1$, with balanced trade the budget constraint (14) becomes

$$c_t + s_t x_t \leq r_t k_t + w_t + s_t h_t \tag{19}$$

Finally, define $u_t = s_t x_t$: this is exported resources valued in units of consumption. Then we have

$$c_t + u_t \leq r_t k_t + w_t + s_t h_t \tag{20}$$

and the capital accumulation equation can be rewritten

$$k_{t+1} = k_t\,(1 - \delta) + u_t q_{kt} \tag{21}$$

where $q_{kt} \equiv \frac{1}{p_{kt}}$. Again, the model is isomorphic to the closed economy model. Thus, our general equilibrium growth accounting framework is robust to an open economy extension which involves balanced trade over time.

III Quantitative Experiments: Data

Data on GDP is drawn from the Penn World Tables 8.1, see Feenstra et al (2013), $1950-2011$. We define g as the geometric average growth factor of GDP per capita.

In order to measure C_3 (the growth contribution assuming the output of the capital goods' sector is used as an intermediate in the rest of the economy), we require a measure of ϕ_k, the capital share of intermediates, and of α_m, the share of intermediates in gross output. Ngai and Samaniego (2009) find that in the US the dollar share of intermediate goods composed of the output of capital goods industries is about 10 percent, so we set $\phi_k = 0.1$. Ngai and Samaniego (2009), Jones (2011) and several others find that $\alpha_m = 0.5$ in the United States and elsewhere, and we adopt this value.

We adopt several approaches to measuring ISTC. Some of them are inputs into the main growth accounting exercise, whereas others are useful for interpreting the results.

A ISTC: Official Data

ISTC is typically measured using the inverse change in the relative price of capital. Our baseline measure of ISTC is the change in the relative price of capital as reported in the Penn World Tables version 7.1, see Heston, Summers and Aten (2012). The data sample is 1950-2010, or the subset thereof available for each country, provided at least 40 years are available.[7] Notice that this is not the latest version of the Penn World Tables: we explain this choice shortly. We measure ISTC as g_q, the geometric average factor by which the relative price of capital declines over the sample period.

As suggested by Denison (1962), we also wish for a measure of the capital share α_k. This is typically measured as one minus the labor share of GDP. However, as observed in Caselli and Feyrer (2007) and MSS, this overestimates capital shares in economies where *natural resources* are a significant share of GDP. Thus we measure capital shares as the share of income that cannot be attributed to labor (α_n) nor natural resources (α_h). Data on labor shares are the variable *labsh* in the PWT 8.1,[8] and natural resource shares are drawn from MSS. We choose the MSS data rather than the data from Caselli and Feyrer (2007) because the MSS data are based on actual flows of income rather than on estimated stocks of natural resources.[9] Data for all the above variables are available for 73 countries.

For the purposes of this paper, it is important to underline that the data in the more recent Penn World Tables version 8.1 (Feenstra et al (2013)) are *not* suitable

[7] This mainly excludes countries from the former USSR and former Yugoslavia, as well as Kuwait, Qatar and Saudi Arabia, for whom under 25 years of data are available. We also exclude the city states of Hong Kong, Macao and Singapore because their land prices and structures prices are likely to be highly distorted.

[8] Labor income includes the income of the self-employed: to be precise, a portion of the income of the self-employed is attributed to capital, and the remainder is considered labor income. This portion is set to match the capital share of other income, as in Gollin (2002).

[9] MSS classify natural resources into: (a) energy and mineral (subsoil) resources, (b) timber resources, (c) crop lands and (d) pasture lands.and (e) urban land. See MSS for details of the data construction, which are a combination of World Bank data on flows of income from different resources and their own computations.

for measuring changes over time in the relative price of capital, which is the critical input into our growth accounting exercises. In versions of the PWT prior to 8.0, the database has one benchmark year for which goods prices were measured in a comparable way across countries to establish purchasing power parity (PPP), and data for other years were extrapolated using price indices reported in the national accounts. Thus, in the PWT 7.1, the *change over time* in the price level relative to the price index of new capital is exactly our notion of g_q: we are interested in the *growth* of relative prices, not in *levels* at any particular date. In contrast, PWT version 8.0 and above use several benchmark years for the price data, which renders them unsuitable for our purposes. In benchmark years, a set of comparable products is priced in each country, and the geometric mean is taken between the PPPs measured using weights based on expenditure shares in "comparable" countries in order to compute the exchange rate that would make a basket of such products *have equal value* in different countries.[10] Thus, rather than measuring the price of goods in each country at any date, the benchmark prices for any given country are actually measured using expenditure shares on various goods in *other* countries, and the sampling method focuses on goods that are comparable across countries, instead of being representative of goods purchases in any given country. As a result the price indices in versions 8.0 and above are unsuitable for our purposes of measuring g_q.

At the same time, although measuring g_q using official prices from the PWT 8.1 does not produce a measure of ISTC, it does produce a measure of the component of ISTC that is *not* influenced by country variation in the structure of the capital

[10] See the ICP 2003-2006 Handbook from the World Bank for a detailed discussion.

stock. Thus we compute a measure of g_q which we call $g_q^{8.1}$ using PWT 8.1 in order to examine the factors behind differences in ISTC that are *unrelated* to compositional variation.

The PWT report official price data. In their study of the United States, GHK argue that one should apply a quality adjustment along the lines of Gordon (1990) to official price data to take account of improvements in the quality of capital. This significantly raises the measured rate of ISTC in the US. On the other hand, Whelan (2003) argues that quality adjustments are not needed because productivity increases in services are likely understated, so that adjusting for the quality of capital only does not in his view provide a more accurate measure of g_q. In any case, the most recent national accounts guidelines adopted by the United Nations in 2008 call for quality adjustments to the price measurement of capital, although it is not clear to what extent quality adjustments are applied in practice. We will use official price data as a benchmark, as quality-adjusted measures for each country in the dataset do not exist. At the same time, we will also provide two different approaches to constructing quality-adjusted measures of g_q for the countries in our database.

B Quality adjustment: Information Technology

We will approach quality adjustment in two ways. First, we show that the penetration of information technology may serve as a proxy for the extent to which quality adjustments are necessary, and derive an adjusted measure that builds on the official data. Second, we use the composition of capital in each country and the capital good-specific estimates in Cummins and Violante (2002) to obtain a measure that isolates the impact of capital *composition* on ISTC.

Suppose that in the United States data the appropriate quality adjustment is a factor $g_{quality}$, so if g_{op}^{US} is the rate of decline in the relative price of capital in the official price data then $g_q = g_{quality} \times g_{op}^{US}$ in the US. Assume that for each country c other than the US, $g_q = g_{quality}^{\Theta(c)} \times g_{op}^{c}$, where $\Theta(c) \geq 0$ is a measure of the extent to which the quality adjustment applies in country c.

How could we measure Θ? It is well known that a key source of quality improvements in capital goods is information technology (IT), see GHK and CV among others.[11] Thus, we can measure $\Theta(c) \geq 0$ using an indicator of the penetration of information technology in the economy of each country c, relative to the US.

We measure $\Theta(c)$ using the average number of secure servers per million people in 2013 in country c, relative to the US, as reported in the World Development Indicators.[12] A secure server is defined as a computer that contains websites that may be accessed over the internet and which supports encryption. Secure servers are a good indicator of the use of information technology in production because they are essential for business use of the internet – without them users cannot encrypt information on credit card data nor blueprints, business plans nor any other con-

[11] To verify this, we took the quality-adjusted CV measures of g_k by type of capital good and aggregated them for the 63 industries for which the "Historical-Cost Investment in Private Nonresidential Fixed Assets" of the Bureau of Economic Analysis to get industry rates of ISTC over the period $1947 - 2004$ (see CV for details). We found that the correlation between industry rates of equipment ISTC and the average share in equipment investment in Computers and Peripheral Equipment over the period was 0.70^{***} (and the standard error is just 0.091). Samaniego and Sun (2016) find that capital good types are substitutes, indicating that a lack of IT is consistent with an increase in the relative use of lower-ISTC capital.

[12] We do not use earlier years because coverage deteriorates rapidly. Naturally secure server use has changed over time, as the first server CERN httpd was not introduced until 1990. The presumption going back in time is that servers were adopted where the relevant IT infrastructure was already prevalent, so the server count is an indicator of historical IT investment also.

fidential information necessary for business transactions or communication within or between firms. See Coppel (2000), Pilat and Lee (2001) and Samaniego (2006) for other papers using secure servers as a measure of the penetration of information technology in production. By this measure, Θ ranges from 0.06% in Burkina Faso and Sierra Leone to 2.2 in Iceland.[13] The measure Θ exceeds unity only in Switzerland, Denmark, Finland, Iceland, South Korea, Luxembough, Malta, Netherlands, Norway and Sweden. The measure Θ is also strongly positively correlated with log GDP per head in 2009 (0.72) so, whatever else happens, this measure exacerbates the positive link between g_q and average income in Figure 1. The correlation between Θ and g_q measured using official data is 0.20, significant at the 5 percent level.

In US official data, $g_q = 1.0058$. On the other hand, according to GHK, using quality adjusted data $g_q = 1.018$. This implies that $g_{quality} = (1.018/1.0058)$.

C Quality adjustment: Cummins and Violante (2002)

It is well known at least since the work of Gordon (1990) and Cummins and Violante (2002) that the rate of ISTC differs significantly across types of capital good – and, for the United States, the best practice for estimating ISTC has been to construct measures of ISTC by type of capital good, using quality-adjuster capital goods prices, and to compute a weighted average based on measured shares of each type. Thus, countries that use a different mix of capital goods might experience different rates of ISTC as a result.

[13] Another measure of IT penetration is the percentage of internet users in the population. We prefer secure servers because internet use does not necessarily relate to the use of information technology in production. In any case the correlation between the share of the population with internet access and the servers' measure is 0.88.

To explore this possibility, we use the Cummins and Violante (2002) ISTC measures by capital good type to compute the average for each country over the time period for which we have relevant data. This involves using quality-adjusted relative price data as measured in the US over the period $1947 - 2005$. These data are the Gordon (1990) quality-adjusted price data relative to the consumption and services price index, extended using forecasting methods detailed in CV.[14]

To compute detailed shares of capital good types by country, we adopt the Eaton and Kortum (2001) and Caselli and Wilson (2004) premise that all but 15 countries mostly import their equipment, so that the import shares of these goods are reasonable proxies for the actual equipment composition in these countries. It is notable that Caselli and Wilson (2004) find that investment shares and import shares are highly correlated even among the capital goods producers as well as among capital importers, however, so that import shares are in fact a reasonable proxy for capital composition in most countries.[15] Shares are computed using the data of Feenstra et al (2005) for the years $1962 - 2000$. We computed the value of g_q in this way for each year for each country, then took the geometric average. These import-based measures of g_q hold goods prices constant across countries: thus these measures focus solely on differences in composition of capital goods across countries, assuming rates of ISTC for each type of capital good are similar in different places. Certainly for

[14]The method is to estimate the relationship between the Gordon (1990) prices and the official prices, and to extrapolate the Gordon (1990) series using these estimates and subsequent official price reports. Unfortunately we cannot replicate this procedure for other countries since they generally lack a comprehensive hedonic price study along the lines of Gordon (1990). We are grateful to Gianluca Violante for providing us with quality adjusted price data for different capital good types.

[15]The only country with a correlation below 0.35 in our data is Malta, see Figure 1 in Caselli and Wilson (2004).

the types of capital that experience the most rapid rates of ISTC, draconian trade restrictions should be required for this assumption to be violated.

There are two caveats regarding the use of this measure. First, the above argument applies to equipment, not structures (which are not part of the CV measure), so we need further information on both structures ISTC and the share of equipment compared to structures in capital in order to compute this measure of ISTC. We use the share reported in the ICP data for the benchmark year 2005, which is the year that maximizes coverage.[16]

Following GHK, we also assume that there is no ISTC in the production of structures. This is because structures tend to embody high-tech goods much less frequently than equipment.

The second caveat is that, by construction, the CV-based measure of g_q never declines. For all types of equipment in the CV data, the change in the relative price of capital indicates a positive rate of ISTC. Thus, this measure of ISTC is an indicator of ISTC if it were solely based on *compositional differences.* There could be factors that affect ISTC other than composition, such as differences in productivity growth, exchange rate changes, trade cost changes and so on. Thus we will use this ISTC measure for interpretation rather than as an input into the growth accounting exercises.

To sum up, we have 4 measures of g_q. Our baseline measure is based on official data from the PWT 7.1. Second we have a measure which applies a quality adjustment based on IT intensity. Third we have a quality adjusted measure that, by

[16] In addition, revisions to the procedure for computing prices of structures mean that data from prior ICP rounds may not be comparable.

construction, focuses on compositional differences. Fourth we have a measure that abstracts from compositional differences, based on the data with multiple benchmark years in the PWT 8.1.

D Basic observations

Our focus is on *growth* accounting. However, one significant correlation worth noting regarding *levels* of economic activity is that GDP per head in 2009 and official g_q have a correlation[17] of 0.38^{***} and that the correlation between g_q and the average *level* of q_t is 0.34^{***}. See Figure 1. Thus, developing countries are falling behind developed economies on average in terms of the efficiency of investment. Recalling that Hsieh and Klenow (2007) identify important differences among countries in terms of levels in the relative price of capital, we find that these differences are in fact being *exacerbated further over time.*

[17] In what follows of the paper, one, two and three asterisks indicate statistical significance at the 10, 5 and 1 percent levels respectively.

	Correlation		
$\log g_q$	Servers	CV	$g_q^{8.1}$
Official	$.836^{***}$	$.458^{***}$	$.508^{***}$
Servers	–	$.274^{**}$	$.372^{***}$
CV	–	–	$.227^{*}$

Table 1 – Correlations between different measures of $\log g_q$. One, two and three asterisks refer to statistical significance at the $10, 5$ and 1 percent levels respectively.

Table 1 studies how the three ISTC measures are related among themselves. There are several findings. Most importantly, *all the measures are significantly positively correlated*. This is important because, while the official values are not thought to reflect the comprehensive quality adjustments of the CV measures, they do nonetheless appear to be capturing the same variation. The exception is that $g_q^{8.1}$ and the CV-based measure of g_q are not significantly related at conventional levels. This is consistent with the fact that the former focuses on the part of ISTC that is due to country differences in the composition of the capital stock – at least at the level of disaggregation in the CV industry data – whereas $g_q^{8.1}$ measures the component of ISTC which is *unrelated* to compositional differences.

It is worth noting that the average values are much higher for the CV measures than the official-based measures.[18] This is by construction: the CV measures at the

[18] The regression coefficient is 0.746^{***} (.188) indicating that the quality adjusted measures are also a bit more spread out, consistent with there being some quality adjustment in the CV measures

level of each capital good all exceed zero, so any weighted average cannot be below zero. On the other hand, the mean *official* value of $\log g_q$ is in fact zero, i.e. there are several countries where the relative price of capital *rises*. Since the *ranking* of countries is unaffected by the choice of g_q measure, this implies that an important component of country differences in g_q is the *composition of capital*. At the same time, there are significant *level* differences – the median value of official g_q is 1, whereas the median value of the CV-based g_q is 1.016. We conclude that cross-country differences in composition are an important factor of country differences in ISTC – but there are also important cross-country differences in *overall* trends in the relative price of capital – systematic differences across countries in the rate at which consumption can be transformed into capital of any kind.

Finally, Table 2 explores whether there is a *statistical* link between the rate of ISTC and the rate of economic growth. Clearly there is, with the exception of the CV-based measure. This is a key finding: although in itself it does not tell us whether ISTC is an important contributor to growth, the fact that there is a statistical link with growth (and also with GDP levels, see Table 1) suggests that variation in ISTC could be a factor of international differences in growth and development. Interestingly, Table 2 suggests that the link with growth is strongest when we measure ISTC net of differences in composition, at least differences at the level of aggregation

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that is absent from the official measures.

of the CV data.

	Correlation			
$\log g_q$	Official	Server	CV	$g_q^{8.1}$
$\log g$	0.269**	0.344***	0.007	0.276**

Table 2 – Correlations between $\log g_q$ and the rate of economic growth.

IV Quantitative Experiments: Results

We now measure C_1 and C_2 for a variety of countries. To frame our discussion, we need a criterion for what is or is not a "large" contribution to growth, based on the related literature. Hulten (1992) finds a contribution of ISTC to growth equal to 20 percent, arguing that this is "small." Thus, we follow Hulten (1992) in considering a contribution to growth of 20 percent or less to be "small", and consider a contribution to growth of 30 percent or more to be "large."

A Official Data

Figure 2 reports the contribution of changes in the efficiency of investment to rates of economic growth using measures of g_q derived from the PWT 7.1. Using official price data, the contribution of improvements in the investment process to growth are very small in almost all places. Only in 2 of 71 countries does it contribute more than 30 percent to growth using measure C_1: Turkey and Uruguay. According to C_2 and C_3 the list is the same, except for the addition of Nigeria.

In Uruguay and Nigeria the rate of ISTC is at least one standard deviation higher than the median of zero, relatively high. On the other hand, only in Turkey is the rate of GDP growth higher than the sample median of 2.4%. Thus the contribution to growth of ISTC in these countries is large not so much because ISTC is rapid in those countries, but because growth in the other fundamentals (neutral productivity change and the efficiency of resource extraction, production or use) is slow. This is also seen in that, in the case of Uruguay, the contribution of ISTC to growth is over 100%.

Again, the cross-country correlation between log GDP per head in 2009 and g_q measured without any quality adjustments is 0.38^{***}, suggesting ISTC is relevant at best for a few developed economies. Globally, using official data, the geometric average ISTC factor weighted by country GDP in 2009 is about 0.1%, accounting for 3.9% of global growth among the countries in our data according to C_1, 3.5% according to C_2 or 4.5% according to C_3.

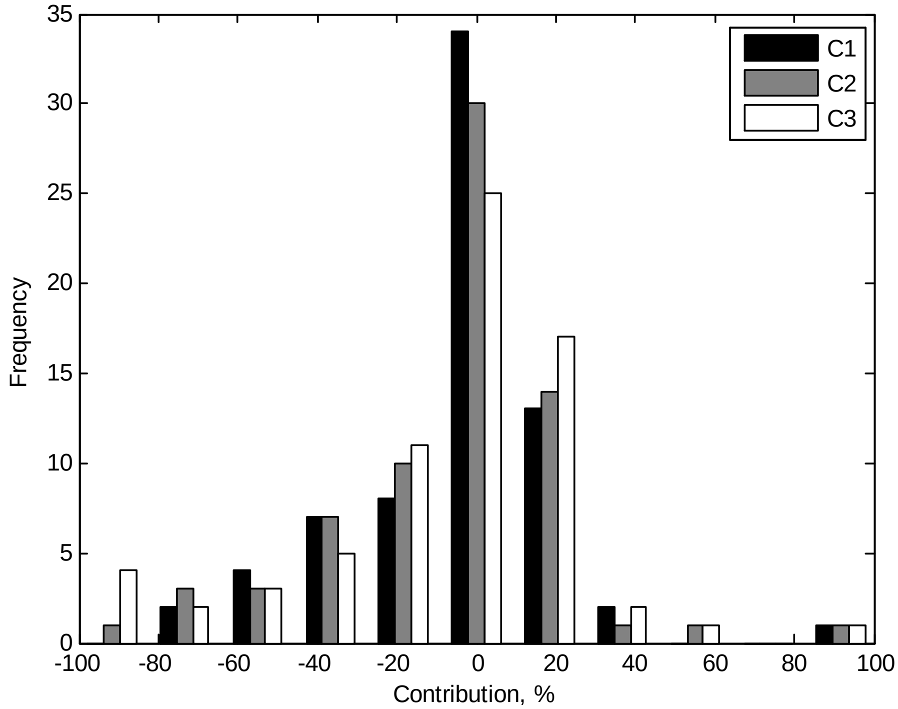

Figure 2 – Contribution of ISTC to economic growth. Authors' calculations based on PWT 7.1, 8.1, MSS and World Bank Development Indicators. C_1 assumes the resource is exhaustible, C_2 assumes it is replenished and C_3 assumes it is replenished and also allows for intermediate goods in the production function. Values above/below 100%/-100% are rounded down/up.

We conclude that investment specific technical change does not appear to be a significant factor of growth in most countries, using official price data. Reversing this conclusion would require large unmeasured quality-adjustments to capital, leading to significantly higher values of g_q than those suggested by the official price data.

B Quality adjustments

We now repeat the above exercises using the measure of g_q adjusted for quality using the IT penetration measure.

The contributions with the server-adjusted measure of g_q is obtained by replacing g_q with $g_q \times g_{quality}^{\Theta(c)}$, where g_q is the measure of ISTC computed using official prices and $\Theta(c)$ is the indicator of the extent of quality adjustment required for country c. Then it is straightforward to show that equations 7, 11 and 12 become:

$$\tilde{C}_1 = C_1 + \frac{\alpha_k}{1-\alpha_k} \times \frac{\Theta(c)\log g_{quality}}{\log g} \tag{22}$$

$$\tilde{C}_2 = C_2 + \frac{\alpha_k}{1-\alpha_h-\alpha_k} \times \frac{\Theta(c)\log g_{quality}}{\log g} \tag{23}$$

$$\tilde{C}_3 = \frac{\alpha_k + \phi_k \alpha_m / (1-\alpha_m)}{\alpha_k} \times \tilde{C}_2. \tag{24}$$

Thus the servers' adjustment unambiguously raises the contribution of growth regardless of the measure, since $\Theta(c) \geq 0$. In this case the list of countries where ISTC contributes above 30% to growth expands to include USA, New Zealand, Netherlands, Luxembourg, South Korea, Japan, Iceland, UK, Finland, Denmark, Switzerland and Canada according to the contribution measure C_1, as well as Australia according to C_2, and Ireland plus Norway according to C_3. These are all fairly advanced economies (indeed many of them are among the capital producing economies), and interestingly none of them displays a contribution above 100%, suggesting these really are "contributions" rather than a reflection of low productivity. At the same time, the histogram of contributions in Figure 3 is not obviously different from that in Figure 2 except that it is more skewed to the left: the countries that experience a positive Θ adjustment already had positive ISTC contributions before the adjustment, whereas many others still experience no benefit from ISTC.

Thus, as before, ISTC contributes significantly to growth in a handful of countries only. Indeed, in about half the countries in the data the efficiency of investment still *decreases* over time, so ISTC is not a channel of growth at all for them. Globally, using the server-adjusted data, the geometric average ISTC factor weighted by country GDP in 2009 is about 0.6%, accounting for 16% of global growth according to C_1, 16% according to C_2 or 21% according to C_3. This is larger than using only unadjusted official data, but it is still fairly small.

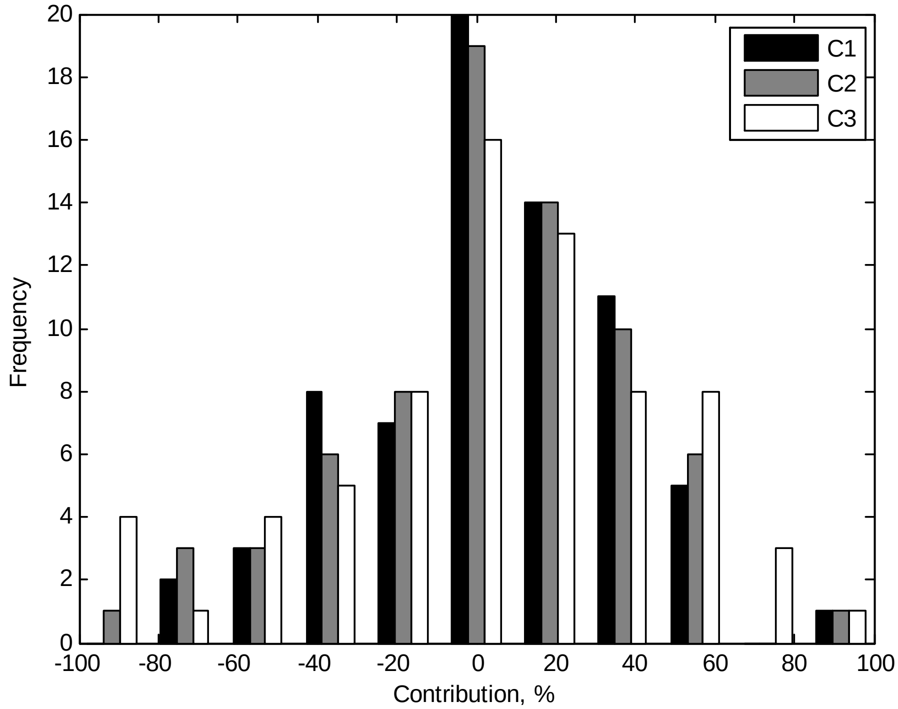

Figure 3 – Contribution of changes in the efficiency of investment to economic growth, assuming a quality adjustment the magnitude of which is set by Θ, the density of secure servers relative to the US.

C ISTC in the USA

Since the prior literature has focused on the US, it is worth seeing how the US fares in this exercise. In the US, we find that the contribution ranges from 15% to 20% using official data. Why so different from GHK? This is because in the official data $g_q = 1.0058$, and $g = 1.020$. In contrast, in GHK, $g_q = 1.018$ because of the use of quality adjusted price data, and $g = 1.0124$, because of the choice of measuring GDP per hour rather than per capita. The difference is not because of any decrease in capital shares: in fact GHK assume that $\alpha_k = 0.3$, whereas in our data $\alpha_k = 0.34$ for the US.

If we apply the quality adjustment implied by the GHK data, we have a contribution in the US that ranges from 46% to 61%. Thus, without a quality adjustment, the contributions are along the lines of those in Hulten (1992), whereas with quality adjustment the results are similar to those in GHK.

D Robustness

One important assumption in much of the literature is the Cobb-Douglas production function. We maintain this assumption as it is necessary for a balanced growth path when there is more than one accumulable resource with different rates of ISTC: see Ngai and Pissarides (2007). The purpose of the paper is not to examine a generalization of this assumption: it is to examine the contribution of ISTC to growth in a context comparable to that which has been used to quantify said contribution in the prior literature (i.e. for the United States by GHK). Moreover the purpose is to provide such a measurement in a long-run context; it unlikely that deviations from this technology would significantly change the conclusions below regarding what happens over a long period of time on average. Nonetheless, we check that the factor shares are not varying much over time in each country.

The capital share α_k is the critical parameter for general equilibrium growth accounting with ISTC. The standard deviation of α_k across countries is 9%, compared to a mean of 40%. We computed the standard deviation of α_k *over time* in each country, finding that it was only 3.7% on average (and the s.d of the s.d. is 3.0%). We conclude that variation over time in α_k is insufficient to affect our results.

For C_2 and C_3 the resource share α_h matters too. We find that in our sample the mean value of α_h is 5.0%, and that the standard deviation is 5.5%. We also measure the standard deviation of α_h across *time* in each country, finding that the average standard deviation value is 2.3%. This indicates that volatility or trends in α_h are likely to only be relevant for at most a few cases. In fact, only 8 countries have a standard deviation above 5%. Out of these, none have a standard deviation larger than their mean.

Finally, are patterns in g and g_q consistent with the BGP assumption? We find that a time trend in g is statistically significant only in ten countries: Japan, Jamaica, Italy, Israel, Austria, Greece, Spain, Côte d'Ivoire, India and Bolivia. Only in the last 2 is the trend positive, in the others it is negative. A time trend in g_q is statistically significant only in Japan (negative) and Israel (positive). Thus, not only is the BGP assumption empirically reasonable for most countries, but the few for which there is any suggestion of a time trend in the factors of growth are not outliers in terms of the growth contribution of ISTC.

V Discussion and Interpretation

A Economic Significance of ISTC

While ISTC may not be a significant factor of growth in many countries, it is still a significant factor of growth *differences* across countries. This begs the question: what is the impact of variation across countries in g_q, and what are its underlying causes?

For example, consider a country with median values of all the parameters, so that $g_q = 1$, $\alpha_k = 0.4$, $g = 1.026$ and $\alpha_h = 0.04$. The contribution of ISTC to growth is zero. However, if g_q were to rise to 1.0058 (the official US value), g would accelerate to 1.0299, a difference that would generate a 10% gap in GDP per capita in 25 years, and leading to a contribution to growth of between 14% and 19%. If g_q were to rise to 1.018 (the quality-adjusted US value) then g would rise to 1.0382, enough to generate a 10% gap in 8 years, and leading to a contribution between 34% and 45%. Alternatively, if we were to raise g_q to 1.018 everywhere in the world, the weighted average rate of economic growth (weighted by GDP shares in 2009) would rise by 0.84% per year, enough to generate a 10% gap in 12 years. Thus, identifying the reasons why g_q is small in some developing economies, and whether g_q is sensitive to policy, could be important for accelerating economic growth.

There are several reasons why not all countries might share the same value of g_q:

1. the composition of capital goods differs significantly across countries.

2. for a given type of capital good the rate of ISTC differs across countries.

3. since many capital goods are imported in developing economies, terms of trade conditions could matter.

4. declines in the costs of international trade – including transportation costs and formal trade barriers – could lower the price of imported capital differentially.

B Capital goods composition

There is strong evidence that the composition of capital is important because of the correlations between all the different measures of ISTC. In particular, the measures of g_q obtained using official data are highly correlated with the measure of ISTC computed using the CV data, which assumes rates of ISTC for each capital type that are constant across countries and thus vary across countries only due to compositional differences. This can be seen in Table 1.

Of course the composition of *equipment* is not the only relevant statistic for understanding the impact of composition on ISTC. One is the share of structures (as opposed to equipment) in the capital stock. In our data, we find that the correlation between our baseline measure of g_q and the share of structures in capital is -0.27^{**}, consistent with the idea in GHK that structures experience slower ISTC than equipment.

Another is the composition of consumption and services. ISTC might appear low if non-capital output is skewed towards the production of goods that also experience relatively rapid declines in the relative price of capital. In this case the appearance of slow ISTC would in fact be related to rapid technical progress in those countries. However in that case we would expect the correlation between ISTC and GDP growth to be negative. Depending on the measure of ISTC, we find that the correlation between the rate of economic growth and the rate of ISTC varies from 1% to 34%, always positive.

The question remains: what might cause significant variation in the composition of the capital stock? Also, as noted, the significant differences in the magnitudes of g_q measured using the PWT and using CV indicate that other factors are present too.

C Capital goods composition and R&D

Before proceeding with these lines of inquiry, we discuss how to *interpret* differences in ISTC across countries, particularly differences in composition. Wilson (2002) and Caselli and Wilson (2004) argue that upstream R&D may be responsible for differences in ISTC across capital goods (as suggested by the theoretical model of Krusell (1998)). This begs the question as to whether their upstream R&D measures could be related to country differences in g_q. In this case, we would conclude that an important factor behind differences in g_q across countries is differences in the *embodied knowledge* content of their capital, as manifested via differences in the composition of the capital stock.

Caselli and Wilson (2004) aggregate the R&D performed by different capital-producing industries in the 15 capital producing countries selected by Eaton and Kortum (2001). They then use these data to produce two "embodied R&D" measures. One is the "R&D stock" measure, which is the R&D stock for a given capital good type, measured using the perpetual inventory method assuming a 15 percent depreciation rate, divided by total sales by those countries of each good. The second is the "R&D flow" measure, which is the R&D flow for a given capital good type, divided by total sales by those countries of each good. For each of these measures, we compute the country average, as before using import shares of each capital good type drawn from Feenstra et al (2005).

First of all, it is notable that these measures are very closely related to the import-based g_q measures. The cross-country correlation between the R&D stock and the import-based g_q values using the CV quality adjustments is 0.61^{***}. The cross-country correlation between the R&D flow and the import based g_q values is 0.64^{***}. This suggests that the R&D measures might explain the country values of g_q measured using official data as well as the import- and CV-based measures do. In fact, we find that the correlation between g_q measured using official data and the R&D-weighted measures is also high. The correlation between g_q measured using *official data* and R&D stock is 0.43^{***}. The correlation between g_q and R&D flow is 0.44^{***}. See Table 3.

	Correlation			
$\log g_q$	Official	Server	CV	$g_q^{8.1}$
R&D stock	0.39^{***}	0.47^{***}	0.33^{***}	0.19
R&D flow	0.42^{***}	0.49^{***}	0.33^{***}	0.21^{*}

Table 3 – Correlations between $\log g_q$ and upstream R&D.

Thus, cross country differences in g_q can be at least partly interpreted as differences in the quantity of R&D embodied in the capital stock in use. This is interesting for at least 2 reasons. First, it suggests that among capital-importing countries ISTC are a particular form of technology diffusion, so that differences in g_q can be interpreted in terms of differences of rates of technology diffusion. Second, it suggests that the kind of institutions that might interfere with technology diffusion (such as weak intellectual property rights, see Ilyina and Samaniego (2011)) might explain to some extent differences across countries in g_q. We look at this below. Furthermore it is interesting to note that the upstream R&D measures are *not* related to $g_q^{8.1}$: there remains a portion of ISTC that is not explained by composition and that is not interpretable as variation in upstream R&D embodied in capital goods.

D Differences in ISTC within types

One reason why ISTC differences may not be fully explained by differences in capital goods composition is because for some reason rates of ISTC might vary within types of capital good (or for all types). We do not have a way of measuring whether ISTC rates might vary *within* capital goods types. We did in fact try to measure country-specific rates of ISTC for each good type by creating a price index using the value of imports of a given type of capital from a particular source divided by the import volume of each capital good from each source. In general, however, the units used to measure volume are not viewed as being reliable, and in addition there is the question of whether the imports from a given source into two different countries have the same quality – see Hummels and Skiba (2004). Thus the trade literature would suggest that such measures are unreliable. Indeed we were unable to relate any such measures to g_q. At the same time, the fact that the composition-based measures of g_q are highly correlated with the official numbers yet are quite different in terms of *magnitudes* suggests that country differences in ISTC by type could be important. Of course if our capital goods classification is coarser than reality then composition *within* our categories may in fact lead to the appearance of differences in ISTC by type (where type is defined according to our classification.) For example, if there are two types of lathe which experience different rates of ISTC and some producers adopt one and not the other, this will only appear as a "difference in ISTC within types" in data that is not sufficiently disaggregated as to distinguish between the two types of lathe. We leave this topic is for future work. However this observation implies that, while our measures of ISTC based on composition are useful for ruling in composition as a factor, we cannot rule *out* composition as a factor because it could just be that our composition data is insufficiently disaggregated to identify the effects of interest.

E Terms of trade

Given that many countries primarily import their capital goods, equation (17) tells us that several factors related to trade could affect g_q. For example, exogenous changes in exchange rates could affect the relative price of capital. If so, we would expect a downward trend in the value of a currency to correspond to a lower g_q. On the other hand, in the long run exchange rates are not exogenous to trade and their independent influence should thus be nihil. For example, the value of the currency of a country that imports capital may drop over time, leading the relative price of capital in that country to rise: however, the value of the currency would only drop over a prolonged period of time because of factors like long run inflation, in which case the relative prices in a consistent currency would remain much the same.

We computed average exchange rate changes for each country over the period $1950 - 2010$ using data on official exchange rates from the World Bank, where the exchange rate is the number of units of currency per dollar. We found that there was indeed a negative correlation between exchange rate growth and g_q: however this correlation was not statistically significant. Furthermore it did not attain statistical significance in any regression of our PWT-based g_q measures on exchange rate changes and on the trade-based g_q measures. We conclude that in general exchange rates do not have any exogenous influence on g_q.

F Trade costs

One reason why the cost of capital might change over time, especially among countries that import capital, is that trade costs might change over time, see equation (17). To test this hypothesis, we examine two measures of trade costs.

First, the World Bank International Trade Cost Database reports trade costs for most countries over the period $1995 - 2012$, using the method of Novy (2013). The approach in Novy (2013) is to infer trade costs based on the volume of inter-country trade relative to intra-country trade. The trade cost measures vary over time and by importer-exporter pair: thus, for example, the cost of importing goods from Australia to Burkina Faso need not equal the cost of importing goods from Burkina Faso to Australia. We proceed by computing the average trade cost between each of the 15 capital producing countries and the other countries in our database, specifically for manufacturing goods. Then we construct an average weighted import cost measure for each country based on the share of capital that they import from each of the 15.

Aside from *trends* in trade costs, there are reasons to believe that the *level* of trade costs could matter for g_q also. The reason is similar to the intuition provided in Samaniego (2006, 2010) for why firing costs and entry costs have a different impact on firms depending on the rate of ISTC experienced by the capital goods they use. In industries with high rates of ISTC, capital is optimally replaced more rapidly than in other industries and, as a result, any policy or other factor that makes the replacement of capital more costly will particularly impact firms in those industries. The level of the costs of importing capital could be such a factor. Importantly, while the growth rate of trade costs might be expected to have an independent effect on the cost of imported capital generally and therefore on g_q, the *level* of trade costs might be expected to act through changes in the composition of capital goods rather than having any general effect. Thus, we might expect trade cost levels to be related to the measure of ISTC based on composition and the quality adjusted measures of Cummins and Violante (2002), but not necessarily the official price measures.

Results are in Table 4. First, the level of trade costs as measured using the measure of Novy (2013) is negatively related to several measures of ISTC. Second, the growth rates of the trade cost measures are not related to ISTC. We conclude that there is suggestive evidence that the level of trade costs might be a factor behind cross country differences in rates of ISTC.

ISTC measure	TC	TCman	TCΔ	TCΔman
$\log g_q$	-0.29^{**}	-0.30^{**}	-0.04	-0.08
Servers	-0.34^{***}	-0.35^{***}	-0.04	-0.07
$\log g_q$, CV	-0.23^{*}	-0.24^{*}	-0.10	-0.02
$\log g_q^{8.1}$	-0.30^{**}	-0.30^{***}	-0.14	-0.09

Table 4 – Correlations between official g_q, CV-based g_q and both levels and growth rates of trade costs.

The findings in this section suggest that g_q may be susceptible to policy or to the institutional environment, with trade costs as an example. There is a precedent for this idea in the related literature: Samaniego (2006) shows in an open-economy context that policy and regulation can affect comparative advantage in industries depending on their rate of ISTC, skewing industrial structure towards industries with low values of g_q. Also, Ilyina and Samaniego (2012) show that when technology adoption costs require external finance, financial underdevelopment also skews industrial structure towards low-tech industries by slowing technical progress particularly in industries where it is rapid. In both cases, the mechanism involves changes to economic structure, begging the question as to whether any *policy or institutional indicators* might be related to our findings. Of course there is a question of reverse causality: political economy considerations imply that countries that depend on technological transfer rather than de novo innovation for growth might adopt particular kinds of institutions, see for example Boldrin and Levine (2004). Thus, in the Appendix we explore whether there is suggestive evidence of a link between the contribution of ISTC to growth and institutions, without taking a stand on the direction of causality. We find links with human capital measures, as well as financial development and property rights enforcement.

G Natural resources

Natural resources are introduced into the growth accounting model to ensure that capital shares are not overestimated. As noted, we do not need to separately identify neutral and resource-specific technical change (g_z and g_h) to identify the contribution of ISTC to economic growth. However it is of interest to think about this separation. The typical strategy for measuring ISTC would suggest that RSTC could be identified by looking at the relative price of resources for each country, which is complicated by the fact that many of these resources are not frequently traded e.g. rural land. Since this is not the focus of the paper, in lieu of a full analysis of this topic, we observe nonetheless that the median capital share α_k equals 0.4, whereas the median resource share α_h is under 0.04, indeed in our data only 8 countries have a value of $\alpha_h > 0.1$. This suggests that extremely high values of RSTC would be required for it to be an important factor of growth in more than just the few places where α_h is large.

VI Concluding remarks

Several authors have argued that improvements in the marginal rate of transformation from consumption to investment – as measured using changes in the relative price of capital – can be an important factor of economic growth. However, even though the debate about the growth impact of changes in the efficiency of the investment process goes back a long way, this is the first study that performs general equilibrium growth accounting with ISTC for a large pool of countries. This paper shows that such improvements are probably not an important factor contributing to growth in the majority of countries. Indeed, as a channel of growth, the contribution of changes in the efficiency of investment to growth is negative in about half the countries studied.

At the same time, this does not imply that changes over time in the relative price of capital are irrelevant for development questions. First, the cross-country correlation between ISTC and growth is positive and significant. Second, there is significant variation across countries in this contribution, so that if the rate of ISTC is sensitive to policy (as the literature suggests it might be) then ISTC could be an important determinant of income growth. Third, Hsieh and Klenow (2007) indicate that there exist significant differences in levels of the relative price of capital across countries. We find that these differences in the efficiency of investment are becoming exacerbated over time. Our results also suggest this is partly because these economies do not use the types of capital that experience notable productivity improvements that result from upstream R&D. Our findings suggest that trade costs might explain to some extent these differences. We leave a detailed study of these relationships for future work.

Finally, the open economy extensions are also important conceptually: while some papers identify ISTC with capital-embodied technical change, we find that trade conditions are a factor of ISTC in a world where capital is imported. Although the related literature argues that there are a few equipment exporting countries, the expansion of global trade linkages means that some "capital importing" countries are involved in the production of capital via outsourcing, providing either physical intermediates or assembly services for high-tech capital goods. This implies that trade patterns and trade conditions are relevant for understanding ISTC around the world, including in the so-called "capital exporting" countries.

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Technical Appendix

A Derivations in the exhaustible resource environment

Define $g_K = k_{t+1}/k_t$, $g_H = h_{t+1}/h_t$ and $g_X = X_{t+1}/X_t$. Let $g \equiv y_{t+1}/y_t$ be the growth factor of output, which along a balanced growth path (BGP) will equal the growth factors of consumption and of investment. For g_K to be constant, as along a BGP, we need $g_K = g_q g$. For g_H to be constant we need $g_H = g_h g_X$. The first order conditions are

$$\frac{1}{c_t q_{kt}} = \beta \frac{1}{c_{t+1}} \left[\alpha_k z_{t+1} h_{t+1}^{\alpha_h} k_{t+1}^{\alpha_k - 1} + \frac{1-\delta_k}{q_{k,t+1}} \right]$$

with respect to investment, and

$$\frac{\alpha_h}{c_t} z_t h_t^{\alpha_h - 1} k_t^{\alpha_k} q_{ht} = \beta \frac{1}{c_{t+1}} \left[\alpha_h z_{t+1} h_{t+1}^{\alpha_h - 1} k_{t+1}^{\alpha_k} q_{ht+1} \right]$$

with respect to resource use. These conditions can be rewritten:

$$g \times g_q = \beta \left[q_{k,t+1} \alpha_k z_{t+1} h_{t+1}^{\alpha_h} k_{t+1}^{\alpha_k - 1} + 1 - \delta_k \right] \quad (25)$$

$$g = \beta g_z g_H^{\alpha_h - 1} g_K^{\alpha_k} g_h \quad (26)$$

Equation (25) tells us that along a BGP $1 = g_q g_z g_H^{\alpha_h} g_K^{\alpha_k - 1}$ which, since $g_H = g_h g_X$ and $g_K = g_q g$, implies that

$$g = \left(g_z g_h^{\alpha_h} g_X^{\alpha_h} g_q^{\alpha_k} \right)^{\frac{1}{1-\alpha_k}} \quad (27)$$

On the other hand, equation (26) tells us that along a BGP:

$$\left(\beta g_z g_h^{\alpha_h} g_q^{a_k}\right)^{\frac{1}{1-\alpha_h}} g^{\frac{\alpha_k-1}{1-\alpha_h}} = g_X \tag{28}$$

Together, the general equilibrium growth accounting equation resulting from (27) and (28) is:

$$g = \left(g_z g_h^{\alpha_h} \beta^{\alpha_h} g_q^{a_k}\right)^{\frac{1}{1-\alpha_k}} .$$

B ISTC in a multi-good environment

In this appendix we show that the one sector model economy with ISTC can be interpreted as a two sector economy with any finite number of industries. This shows that one of the channels for variation in g_q is the composition of capital, as discussed extensively in the text.

A Preferences and Technology

Time is discrete and there is a $[0, 1]$ continuum of agents. There are 2 sectors, each of which produces an aggregate – one for consumption and one for investment. Let I_s be the set of industries that supplies sector s, where I_s contains a finite number of industries. We focus on the case in which each industry supplies only one sector, so that $I_s \cap I_{s'} = \varnothing$, $\forall s \neq s'$. Note that this is without loss of generality, as one could have two industries identical in all ways that are distinguished by the fact that they provide a given good to two different sectors.

For each sector $s \in \{c, k\}$, the production function has the Cobb-Douglas form:

$$y_{st} = \prod_{i \in I_s} u_{it}^{\xi_i}, \quad \sum_{i \in I_s} \xi_i = 1. \tag{29}$$

where u_{it} is use of good i and ξ_i is the weight on good i.

Agents consume an aggregate c_t of the output of the different consumption sectors, so $c_t = y_{ct}$.

Finally, agents have isoelastic preferences over c_t and discount the future using a factor $\beta < 1$, so that:

$$\sum_{t=0}^{\infty} \beta^t \frac{c_t^{1-\theta} - 1}{1 - \theta}. \tag{30}$$

They are endowed with one unit of labor every period which they supply inelastically, and start period zero with capital k_0.

Let q_{st} be the price of the sector aggregate s, with r_t as the interest rate and w_t as the wage. Agents choose expenditure on each good so as to maximize (30) subject to the budget constraint

$$\sum_{s \in \{c,k\}} q_{st} y_{st} \leq \sum_{s \in \{c,k\}} \sum_{i \in I_s} r_t k_{it} + \sum_{s \in \{c,k\}} \sum_{i \in I_s} w_t n_{it} + \sum_{s \in \{c,k\}} \sum_{i \in I_s} s_t h_{it} \tag{31}$$

and the capital accumulation equation

$$k_{t+1} = y_{kt} + (1 - \delta) k_t. \tag{32}$$

Notice that for now new capital y_{kt} is defined in units of capital, not in units of foregone consumption (investment). We will redefine the model in those terms later.

On the supply side, each industry features a Cobb-Douglas production function:

$$y_{it} = z_{it} h_{it}^{\alpha_h} k_{it}^{\alpha_k} n_{it}^{1-\alpha_h-\alpha_k}, \; z_{it} = z_{i0} g_i^t \tag{33}$$

where $g_i = z_{i,t+1}/z_{it}$ is the TFP growth factor of industry i and z_{i0} is given. Producers maximize profits

$$\max_{n_{it}, K_{it}} \{p_{it} y_{it} - w_t n_{it} - r_t k_{it} - s_t h_{it}\} \tag{34}$$

subject to (33), where p_{it} is the output price of industry i at time t. The return to labor, capital and the resource are w, r and s respectively. Capital, the resource h and labor are freely mobile across sectors.

B Equilibrium

The producers' first order conditions imply that the capital labor ratio is constant across industries, which implies that $z_{it} p_{it} = z_{jt} p_{jt}$. Thus, as in related models, goods that experience rapid productivity growth display a decline in their relative price. This result, combined with the consumer's first order conditions implies that the ratio of value added $p_{it} y_{it}$ in any two industries in the same sector s depends on parameters:

$$\frac{p_{it} y_{it}}{p_{jt} y_{jt}} = \frac{\xi_i}{\xi_j} = \frac{n_{it}}{n_{jt}} \qquad \forall i, j \in I_s. \tag{35}$$

Notice that the same relationship holds for the ratio of employment, except that it only holds comparing industries that are in the same sector.

C Sectorial and Aggregate Growth: Closed economy

In equilibrium we can aggregate the industries in a given sector into a sectorial production function. To see this, define q_{st} as the price index for final goods in sector s, so that

$$q_{st}y_{st} = \sum_{i \in I_S} p_{it} z_{it} \tilde{h}_t^{\alpha_h} \tilde{k}_t^{\alpha_k} n_{it}$$

where $\tilde{k}_t$ is the equilibrium capital-labor ratio and $\tilde{h}_t$ is the equilibrium resource-labor ratio, which are common across industries. Define input use in sector s as $k_{st} = \sum_{i \in I_s} k_{it}$ and $n_{st} = \sum_{i \in I_s} n_{it}$. Then, define a sectorial production function:

$$y_{st} = z_{st} h_{st}^{\alpha_h} k_{st}^{\alpha_k} n_{st}^{1-\alpha_h-\alpha_k}, \;\; z_{st} = z_{s0} \bar{g}_s^t \tag{36}$$

where $\bar{g}_{st} = z_{s,t+1}/z_{st}$.

The problem of the sector s firms and the industry $i \in I_s$ firms can be combined as

$$\max_{n_{it}} \left\{ q_{st} \prod_{i \in I_s} \left(z_{st} \tilde{h}_t^{\alpha_h} \tilde{k}_t^{\alpha_k} n_{it} \right)^{\xi_i} - r_t \sum_{i \in I_S} k_{it} - w_t \sum_{i \in I_S} n_{it} - s_t \sum_{i \in I_S} h_{it} \right\} \tag{37}$$

The first order conditions imply that:

$$\frac{n_{jt}}{n_{it}} = \frac{\xi_j}{\xi_i} \tag{38}$$

and we also have that $\sum_i n_i = n_s$ by definition, so $n_i = \xi_i n_s$. Then we can use (38) write n_i in terms of n_s. Substituting this back into problem (37), we have that a sector s firm solves the problem

$$\max_{n_{it}} \left\{ q_{st} z_{st} \tilde{h}_t^{\alpha_h} \tilde{k}_t^{\alpha_k} n_{st} - r_t \tilde{k}_t n_{st} - w_t n_{st} - s_t \tilde{h}_t n_{st} \right\}$$

where

$$z_{st} = \left[\prod_{i \in I_s} (\xi_i z_{st})^{\xi_i} \right]. \tag{39}$$

Recalling that $\bar{g}_{st} = z_{s,t+1}/z_{st}$, we have that

$$\bar{g}_{st} = \prod_{i \in I_s} g_i^{\xi_i} \tag{40}$$

which is constant over time. As a result, the aggregate behavior of the model economy with many industries is the same as that of a 2-sector economy that produces c_t using technology $z_{ct} h_{ct}^{\alpha_h} k_{ct}^{\alpha_k} n_{ct}^{1-\alpha_h-\alpha_k}$ and produces capital goods using technology $z_{kt} h_{kt}^{\alpha_h} k_{kt}^{\alpha_k} n_{kt}^{1-\alpha_h-\alpha_k}$. In the consumption goods sector, firms maximize

$$\max_{k_{ct}, n_{ct}, h_{ct}} \left\{ p_{ct} z_{ct} h_{ct}^{\alpha_h} k_{ct}^{\alpha_k} n_{ct}^{1-\alpha_h-\alpha_k} - r_t k_{ct} - w_t n_{ct} - s_t h_{ct} \right\} \tag{41}$$

whereas in the capital goods sector:

$$\max_{k_{ct}, n_{ct}, h_{ct}} \left\{ p_{kt} z_{kt} h_{kt}^{\alpha_h} k_{kt}^{\alpha_k} n_{kt}^{1-\alpha_h-\alpha_k} - r_t k_{kt} - w_t n_{kt} - s_t h_{kt} \right\} \tag{42}$$

Consumers choose consumption c_t and new capital y_{kt} to solve:

$$\max_{c_t, h_t} \left\{ \sum_{t=0}^{\infty} \beta^t \frac{c_t^{1-\theta} - 1}{1-\theta} \right\} \tag{43}$$

$$s.t. \quad p_{ct} c_t + p_{kt} y_{kt} \leq r_t k_t + w_t + s_t h_t \tag{44}$$

$$k_{t+1} = k_t (1-\delta) + y_{kt} \tag{45}$$

$$k_0 \text{ given.} \tag{46}$$

In equilibrium, capital, resource and labor markets must clear at all dates.

It will be convenient to set $p_{ct} = 1 \forall t$, so that capital goods prices p_{c_t} are expressed relative price to the price of capital goods. In this case, the constraints in the above problem become

$$\begin{aligned} c_t + p_{kt} y_{kt} &\leq r_t k_t + w_t + s_t h_t && (47) \\ k_{t+1} &= k_t (1 - \delta) + y_{kt}. && (48) \end{aligned}$$

Now define $i_t = p_{kt} y_{kt}$, i.e. forgone capital goods, and define $q_{kt} = \frac{1}{p_{kt}}$. Then we have as before that

$$\begin{aligned} c_t + i_t &\leq r_t k_t + w_t + s_t h_t && (49) \\ k_{t+1} &= k_t (1 - \delta) + i_t q_{kt}. && (50) \end{aligned}$$

As in the 2-sector version of GHK it is straightforward to show the allocation of resources across sectors allows the imposition of a single production function for both sectors, and that q_{kt} is proportional to z_{kt}/z_{ct}.

Total spending on consumption is $S_c = p_c c$. Also recall that $\frac{p_{it} y_{it}}{p_{jt} y_{jt}} = \frac{\xi_i}{\xi_j}$. Thus $p_{it} y_{it} = \xi_i / S_c$.

Since

$$y_{st} = \prod_{i \in I_s} u_{it}^{\xi_i}, \;\; \sum_{i \in I_s} \xi_i = 1 \tag{51}$$

we have

$$y_{st} = \prod_{i \in I_s} \left(\frac{\xi_i}{S_c p_{it}} \right)^{\xi_i} = \frac{1}{S_c} \prod_{i \in I_s} \left(\frac{\xi_i}{p_{it}} \right)^{\xi_i} \tag{52}$$

so

$$p_c = \frac{S_c}{c} = \prod_{i \in I_s} \left(\frac{p_{it}}{\xi_i} \right)^{\xi_i}$$

This is the same for consumption and for investment. Letting $p_c = 1$, we have that

$$q_{kt} = \frac{p_{ct}}{p_{kt}} = \frac{\prod_{i \in I_c} \left(\frac{p_{it}}{\xi_i} \right)^{\xi_i}}{\prod_{i \in I_k} \left(\frac{p_{it}}{\xi_i} \right)^{\xi_i}}$$

So

$$g_q = \left(\frac{\prod_{i \in I_c} \left(\frac{p_{i,t+1}}{p_{it}} \right)^{\xi_i}}{\prod_{i \in I_k} \left(\frac{p_{i,t+1}}{p_{it}} \right)^{\xi_i}} \right)$$

Thus, g_q is the geometric average price growth factor in the consumption sector, divided by the geometric average price growth factor in the investment sector. Finally, since $z_{it}p_{it} = z_{jt}p_{jt}$, we have that

$$g_q = \left(\frac{\prod_{i \in I_c} g_i^{\xi_i}}{\prod_{i \in I_k} g_i^{\xi_i}} \right)^{-1}$$

so g_q is the (inverse) geometric average TFP growth factor in the consumption sector, divided by the geometric average TFP growth factor in the investment sector. Thus, there are three reasons why g_q might differ across countries. One is that g_i (or $\frac{p_{i,t+1}}{p_{it}}$) might differ across countries for some industries. Another is that the composition of capital goods might vary across countries – in other words, ξ_i for $i \in I_k$ varies across countries. A third is that the composition of consumption goods might vary across countries – in other words, ξ_i for $i \in I_c$ varies across countries. Under the assumption in the related literature (see GHK) that variation in g_i varies little among non-capital producing industries, we have two leading hypotheses underlying cross country variation in g_q: variation in ξ_i for $i \in I_k$ and variation in g_i for $i \in I_k$.

D Institutions

The findings in this section suggest that g_q may be susceptible to policy or to the institutional environment. As mentioned of course the institutional environment could in turn be affected by the technology in use. Thus we explore correlations between g_q and institutions without taking a stand on the direction of causality.

Following Samaniego (2006) we look at firing costs (drawn from the World Bank, firing costs paid by workers with at least one year's tenure, FC). We also look at other forms of regulation that have been found to be important for aggregate outcomes, namely product market regulation (measured using entry costs paid as a share of GDP, EC, as reported by the World Bank). See Moscoso-Boedo and Mukoyama (2012). Another possibility suggested by Ilyina and Samaniego (2012) is financial development, measured using FD, the credit-to-GDP ratio, as in King and Levine (1993) – data are from the World Bank $1960 - 2010$.

In addition, Acemoglu and Johnson (2005) and others argue that financial development is ultimately derived from the state of contracting institutions and property rights institutions. We measure the strength of contracting institutions using the World Bank measure of contracting costs, $CONT$. We measure property rights enforcement using the index developed by the Property Rights Alliance (2008), $PROP$, averaged over the available period $2007 - 2013$.

	Institutional indicator					Other
Variable	FD	$CONT$	EC	FC	$PROP$	HC
g_q	$.33^{***}$	$-.16$	$-.23^{**}$	$-.17$	$.34^{***}$	$.48^{***}$
Server	$.51^{***}$	$-.29^{**}$	$-.34^{***}$	$-.37^{***}$	$.66^{***}$	$.60^{***}$
g_{CV}	$.18$	$-.15$	$-.15$	$-.12$	$.07$	$.20$
$g_q^{8.1}$	$.15$	$-.24^{**}$	$-.46^{***}$	$-.05$	$.21^{*}$	$.40^{***}$

Table 5 – Correlations between different measures of g_q and institutional measures.

We find that the official measure of g_q is positively correlated with financial development, as well as the measure of property rights enforcement and entry costs. See Table 5. Interestingly, although this evidence is suggestive, it indicates that one channel through which financial development might contribute to growth is by encouraging ISTC. Also this relationship does not hold for the CV measure of g_q, again indicating that there are channels other than the composition of capital that link ISTC to growth.

We find a significant positive correlation between ISTC and the Barro and Lee (2010) human capital measure averaged between 1970 and 2010. It is not an institutional variable and the direction of causality is unclear since human capital and high-tech physical capital are known to be complementary, see Krusell et al (2000). At the same time it suggests the possibility that either factors limiting the stock of human capital have an impact on the kind of capital used and hence on the rate of

ISTC, or that factors that affect the rate of ISTC have a spillover effect on the incentives to accumulate human capital. The former possibility seems more likely since it takes generations to significantly affect the stock of human capital as measured by schooling.

	Property rights indicator					
Variable	$ACEM$	LP	PPR	IPR	$COPY$	PAT
g_q	$.44^{***}$	$.34^{***}$	$.16$	$.40^{***}$	0.42^{***}	$.41^{***}$
Servers	$.58^{***}$	$.68^{***}$	$.46^{***}$	$.67^{***}$	0.69^{***}	$.57^{***}$
g_{CV}	$.17$	$.00$	$.13$	$.10$	0.12	$.16$
$g_q^{8.1}$	-0.35^{***}	$.22^{*}$	$.24^{**}$	$.17$	0.11	$.25^{**}$

Table 6 – Correlations between different measures of g_q and measures of property rights.

To go deeper, since property rights are thought to underpin financial development and since they appear to have an independent effect, we examine the impact of different *dimensions* of property rights. We examine:

- $ACEM$: Acemoglu and Johnson (2005) measure property rights using *constraints on the executive.* This measures the strength of property rights as enforced against government expropriation.

- LP: The Property Rights Alliance (2008) reports a measure of protections afforded by the legal and political environment, including judicial independence, rule of law, political stability and control of corruption.

- PPR: The Property Rights Alliance (2008) reports a measure of physical property rights, based on experts' views of the enforcement of physical property rights and the complexity of procedures for registering property.

- IPR: The Property Rights Alliance (2008) reports a measure of intellectual property rights, based on experts' views of the enforcement of intellectual property rights, measures of copyright protection and measures of patent protection (see below).

- $COPY$: The BSA (Software Alliance) publishes the rate at which unlicensed software is used in different countries. Following the Property Rights Alliance (2008), we take this as a measure of copyright (non) enforcement.

- PAT: We use the patent enforcement method developed in Ginarte and Park (1997), as reported by the World Bank, averaging over the available sample.

We find that there is a link mainly between g_q and intellectual property rights – and that this is primarily for the measure that does not focus on compositional differences. See Table 6. This suggests that one reason behind cross country differences in rates of ISTC could be that producers of high-tech capital goods may not want to provide them to places where the goods may be freely reverse-engineered and copied, so their intellectual property is not protected. A full exploration of this possibility is left for future research, but it is interesting to note that Ilyina and Samaniego (2012) show that financial development can encourage growth by stimulating R&D: our findings suggest that it may also stimulate the adoption of goods that embody R&D performed elsewhere in the world.