Investment-specific Technical Change as a factor of Economic Growth

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Abstract

The contribution of investment-specific technical change (ISTC) to economic growth varies significantly around the world. This is because, while the investment process becomes more efficient over time in some countries, in most it does not. Cross-country differences in the rate of ISTC are partly accounted for by variation in the types of capital goods used, and by variation in the pace of trade cost reductions.

Keywords: Investment-specific technical change, growth accounting, relative price of capital, trade costs.

JEL Codes: O11, O13, O33.

I Introduction

Investment specific technical change (ISTC) is thought to account for a significant portion of economic growth in the US. Greenwood, Hercowitz and Krusell (1997, henceforth GHK) and Cummins and Violante (2002, henceforth CV) find that about

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60 percent of post war growth can be accounted for by changes over time in the efficiency of investment. However, the contribution of ISTC to growth in other countries is not known.

This paper explores the impact on economic growth of changes over time in the efficiency of investment around the world. We do so using a *general equilibrium growth accounting* approach. This assigns to different sources of productivity growth a contribution that takes account of their direct effect on growth, as well as their effect through endogenous factor accumulation – see Greenwood and Jovanovic (2001). Such a framework is theoretically appealing, accounting for all channels through which a given factor of growth might endogenously affect real output.

We find that changes over time in the efficiency of investment vary significantly across countries. The mean value is close to zero, and the standard deviation is 1.0 – 1.3 percentage points. Thus, there is significant variation in rates of ISTC around the world, but at the same time ISTC is not an important contributor to growth in most countries – because the decline in the relative price of capital is not rapid in most places. Indeed, in many low income countries, the efficiency of the investment process has *declined* over time. Hsieh and Klenow (2007) find that the relative price of capital in *levels* tends to be higher in less developed economies: Figure 1 shows that these productivity gaps are in fact *exacerbated over time*. This observation has important implications for rates of economic growth.
Figure 1 – Average level and growth rate of ISTC over time, by country. The level of ISTC, labeled $q$, is the average of the inverse relative price of capital 1960-2010. The growth rate of ISTC, labeled $\log g_q$, is the average rate of decline in the relative price of capital. The correlation is 0.36 and highly statistically significant. Source – Penn World Tables 7.1.

These features of the distribution of ISTC around the world imply that, when we use our framework to quantify the contribution of ISTC to economic growth, in most places these contributions are small or even negative, although in some it is positive and significant. This is the case in our baseline specification, and is robust to several extensions of the model. We conclude that the rate at which the technology of investment improves is an important factor of differences in economic growth around the world. Indeed, if rates of ISTC worldwide were similar to what they are in the United States, global growth rates would be higher by about 2.8 percent annually!
Our findings beg the question: what is behind cross-country variation in the rate of ISTC? To answer this question, we try to decompose ISTC into some sources that our model can identify and for which the relevant data exist. First, we consider the composition of capital types. CV show that the rate of ISTC varies significantly across types of capital good, so that 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 equipment is skewed towards goods that CV identify as experiencing slower ISTC.

Furthermore, given the observation in Eaton and Kortum (2001, henceforth EK) that much of the machinery and equipment in many developing economies is imported, a possibility is that changes over time in trade costs may affect the rate at which the relative price of capital changes over time.1 To explore the trade cost channel, we adapt our model to allow for international trade in capital goods, extending the Eaton and Kortum (2001) model by allowing for different rates of technical progress across capital types. We find that trade liberalization can have a significant impact on growth by lowering the cost of imported equipment. Measured trade cost declines are positively correlated with measured ISTC, and the mean contribution of trade liberalization to economic growth rates through this channel since 1995 is 0.2 percentage points per year, ranging from −0.8 percent up to 2.2 percent. We thus contribute to the literature on quantifying the benefits of trade liberalization, by providing a benchmark quantification of its contribution to aggregate growth through changes in the price of capital goods.

The results 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) and Denison (1964). 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. The reason that in most other countries ISTC is not a significant contributor to growth is simply because the rate of ISTC is low,

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1Parro (2013) and Mutreja et al (2017) note the potential link between trade costs and the price of capital. However the focus of the first paper is on the skill premium, and that of the second is on levels in a static environment. In contrast, we quantify the link between changes in trade costs and output through the ISTC channel in a dynamic environment.
and quality adjustments much larger than what appear to be empirically relevant would be required to overturn this conclusion. Consequently, any policies that might accelerate ISTC (such as trade liberalization) may contribute significantly to growth in less-developed economies. Also, 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 of adopting policies that accelerate ISTC by changing the composition of capital could be significant too.

Section II develops the basic model economy. Section III presents the data required for growth accounting in different versions of the model. Section IV performs the general equilibrium growth accounting exercise using data on the price of capital for different countries, and Section V provides a decomposition of ISTC into different factors. Section VI suggests directions for future research.

II Economic Environment

In what follows we present the basic general equilibrium growth accounting framework, in the form of the model of GHK simplified to account only for data inputs that are available for a large number of countries. Then we provide an open economy extension which is useful for decomposing the influence of trade and composition on ISTC. Detailed derivations are in Appendix B.

A Basic model

We begin with a simple environment similar to GHK. The model economy uses capital $k_t$ and labor $n_t$ to produce output $y_t$:²

$$y_t = z_t k_t^{\alpha_k} n_t^{1-\alpha_k}$$  (1)

where $z_t = z_0 g_t^t$. Capital is accumulated according to:³

²See the Appendix for a discussion of the constancy of input shares.
³GHK distinguish between two types of capital, equipment and structures. We do not do so because we do not have measures of the composition of capital for most countries. We return to
\[ k_{t+1} = k_t (1 - \delta_k) + q_{kt} i_{kt} \]  

(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. In what remains of the paper we abstract from transitory changes in \( q_{kt} \) so as to focus on growth implications, and assume that \( q_{kt} = q_{k0} g^t_q \). Parameter \( g_q = q_{t+1}/q_t \) is the growth factor of ISTC, so \( \log g_q \) is the rate of ISTC. All parameters may vary across countries.

**Remark 1** Note that, as discussed below and in the appendix, many factors may contribute to \( g_q \), including technical progress in the production of capital, differences in the composition of capital, and changes over time in the cost of importing capital from abroad. We refer to all of them as ISTC, and try later to distinguish among them to the extent that we are able to do so with the available data. This use of terminology implies that variation in technology around the world has several dimensions, including productivity, the composition of inputs used (i.e. the structure of the production function) and the technology of exchange.

Output has two uses, investment and consumption, so that

\[ y_t \geq c_t + i_{kt}. \]  

(3)

Agent preferences are defined over the discounted utility from consumption:

\[ \sum_{t=0}^{\infty} \beta^t \log (c_t), \ 0 < \beta < 1. \]  

(4)

A planner maximizes preferences (4) subject to constraint (2), as well as the feasibility constraint (3). 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, along a balanced growth path, the following growth path emerges from the planner’s problem:

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this later however.
\[ g = \left(g_z g_q^a_k\right)^{\frac{1}{1-\alpha_k}}. \]  

(5)

It is then simple to see how much the growth rate would change if we were to remove ISTC from the model economy. This would be equivalent to setting \( g_q = 1 \) in equation (5). In this case, if \( \log g \) is the measured growth rate in a given economy, the counterfactual growth rate if ISTC were to be removed would be \( \frac{1}{1-\alpha_k} \log (g_z) \).

It is straightforward to prove the following result:

**Proposition 1** Define \( \Delta_0 \) to be the decline in growth rates from removing ISTC. The change implied change in growth rates is:

\[
\Delta_0 \equiv \log g - \frac{1}{1-\alpha_k} \log (g_z) = \frac{\alpha_k}{1-\alpha_k} \log g_q
\]

(6)

We refer to this as the baseline specification. Notice that to measure the change in the growth rate we only require two data inputs: the capital share \( \alpha_k \) and a measure of the growth in ISTC \( g_q \).

The model in this form does not have any implications for why \( g_q \) might vary across countries. However, it is well known since at least GHK that one can decompose \( g_q \) into different types of capital. For example, suppose there are many goods. \( I_c \) is the set of consumed goods, and \( I_k \) is the set of capital goods, where\(^4 \) \( I_c \cap I_k = \emptyset \). Let \( \xi_i \) be the share of good \( i \) in consumption or capital (so \( \sum_{i \in I_c} \xi_i = \sum_{i \in I_k} \xi_i = 1 \)). Suppose consumption has productivity growth \( g_z \) and each capital good experiences productivity growth by a factor \( g_z g_i \). Then:

**Proposition 2** Along a balanced growth path,

\[ g_q = \prod_{i \in I_k} g_i^{\xi_i}. \]

(7)

so differences in the intensity \( \xi_i \) with which different types of capital are used is a potential factor of \( g_q \) differences around the world.

\(^4\)This is without loss of generality because any industry in the intersection could be redefined as 2 identical industries but which supply different sectors.
Proof. See Appendix A. ■

This finding is interesting because, as noted in CV, rates of ISTC vary across types of capital goods, and the types of capital goods used in different industries varies too. This means that in a world where industry composition is different across countries (for example, as a result of comparative advantage), rates of ISTC will differ too, leading to persistent differences in both levels and rates of economic growth.

B Open economies

The related literature on the ISTC contribution to growth 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 certain types of capital goods, rather they import them – see EK and Caselli and Wilson (2004). We now show that the growth accounting model above can be extended in a simple way so as to apply to a version of a small open economy that imports capital goods. Essentially we extend the framework of EK to a setting where trade costs may change over time, and where there may be several types of capital that have different rates of technical progress.

Consider the case of a small open economy which does not produce certain kinds of capital. The production function is as in the baseline framework:

\[ y_t = z_t k_t^{\alpha} n_t^{1 - \alpha - \omega} \]  

The difference is that capital \( k_t \) is a composite of imported goods \( y_{mk} \) and non-imported goods \( y_{hk} \). The investment technology (2) is not available for the imported types; instead, the country must export consumption in exchange for those capital goods. Following EK, assume there is one homogeneous consumption good, and that trade must be balanced at each date, a condition that must hold along a balanced growth path.
Assume the capital goods sector uses purchase of capital goods from abroad to produce aggregate capital, using them to make aggregate capital. The production function has the Cobb-Douglas form. If \( y_{kt} \) equals new units of aggregate capital, then:

\[
y_{kt} = y_{nt}^{1-\iota_n}
\]

where \( \iota_n \) is the share of imported capital goods in investment. There are \( M \) types of capital goods, which aggregate using the following technology:

\[
y_{mt} = \prod_{\omega=1}^{M} u(\omega)^{\xi^n_\omega}, \quad \sum_{\omega=1}^{M} \xi^n_\omega = 1 \quad \forall n
\]

where \( u(\omega) \) is purchases of new capital goods of type \( \omega \) and \( \xi^n_\omega \) is the weight on capital type \( \omega \). Note that these weights \( \xi^n_\omega \) and the shares \( \iota_n \) may vary across countries.

The consumer’s budget constraint is:

\[
p_{ct}c_t + p_{mt}y_{mt} + p_{ht}y_{ht} \leq r_t k_t + w_t + s_t h_t
\]

There are \( M \) types of imported capital goods. Within each type, there is a \( [0, 1] \) continuum of varieties indexed by \( j \in [0, 1] \). In what follows, \( j \) indicates a variety of a type of capital, \( i \) indicates a country that supplies a good and \( \omega \) indicates a type of capital.

If purchases of new capital goods of variety \( j \) of type \( \omega \) are \( u_t(\omega, j) \), then \( u_t(\omega) \) is the quantity of new capital goods of type \( \omega \in \{1, ..., M\} \) equal:

\[
u_t(\omega) = \left[ \int_0^1 [u_t(\omega, j)]^{(\sigma_j-1)/\sigma_{\omega}} dj \right]^{\sigma_j/(\sigma_j-1)}
\]

Here \( \sigma_j \) is the elasticity of substitution between the services of different varieties of capital \( j \).

Country \( i \in [1, ..., N] \) provides capital of type \((\omega, j)\) with quality \( z_{it}(\omega, j) \) at production cost \( c_i(\omega) \). Buying capital good \( j \) from country \( i \), country \( n \) faces a price \( p_{nit}^K(\omega, j) = c_i(\omega) d_{nit}/z_{it}(\omega, j) \) per quality unit of capital. Here \( d_{nit} \) is the
iceberg cost to transport capital good \( j \) from country \( i \) to country \( n \) at time \( t \), where \( d_{nit} = d_{n0i}g_{nd}^t \), so trade costs faced by a buying country \( n \) grow by a factor \( g_{nd} > 0 \). The interpretation is that at any given date there is a variation of iceberg costs around the world, which grow over time at a rate which may not be the same for each country.

Note that if \( g_{nd} < 1 \) it means trade costs are declining over time for country \( n \). Thus, unlike in EK, trade costs faced by countries may change over time.\(^5\)

Goods of type \((\omega, j)\) are perfect substitutes, so the importer country \( n \) purchases good \((\omega, j)\) from the source that has the lowest price. As a result, the price of a unit of capital of type \((\omega, j)\) bought by country \( n \) is \( p_{nit}^K(\omega, j) = \min_i \{p_{nit}^K(\omega, j)\} \) where \( n \) indicates the buying country. Assume as in the related literature that the distribution of \( z_i(\omega, j) \) follows the extreme-value distribution \( \Pr [z_i(\omega, j) \leq z] \equiv \exp (-T_{it}(\omega) z^{-\theta}) \). \( T_{it}(\omega) \geq 0 \) is stock of technological knowledge for type \( \omega \) which grows in each country \( i \) at a constant rate \( g_T(\omega) > 0 \). Note that \( T_{it}(\omega) \) does not depend on \( j \), but it may depend on \( \omega \).

Therefore, the cost in country \( n \) of buying good \( j \) from country \( i \) is drawn from:

\[
\Pr [p_{nit}^K(\omega, j) \leq p] = 1 - \exp (-T_{it}(\omega) c_i(\omega)^{-\theta}d_{nit}^{-\theta}) .
\]

The capital price faced by country \( n \) is drawn from:

\[
\Pr [p_{nit}^K(\omega, j) \leq p] = 1 - \exp (-\Phi_{nit}^\omega p^{-\theta}) ,
\]

where \( \Phi_{nit}^\omega \equiv \sum_{i=1}^{N} T_{it}(\omega) c_i(\omega)^{-\theta}d_{nit}^{-\theta} \).

**Proposition 3** Define \( g_q^n \equiv q_{i+1}^n/q_i^n \) to be the rate of ISTC. Along a balanced growth path,

\[
g_q = q_{i+1}^n/q_i^n = \frac{p_{kt}}{p_{kt+1}} = \zeta_{mq} \zeta_{hq}^{1-t_n} \tag{9}
\]

where \( \zeta_{hq} \) is the ISTC growth factor affecting domestic capital and \( \zeta_{mq} \) is the ISTC growth factor for good \( q \).

\(^5\)In Eaton and Kortum (2001), the iceberg cost is constant, \( d_{nit} = d_{nai} \) for all \( t \). Also, \( M = 1 \).
growth factor affecting imported capital. In addition, $\zeta_{mq}$ can be decomposed as:

$$\zeta_{mq} = g_{nd}^{-1} \times \prod_{\omega \in \{1,M\}} g_{T}(\omega)^{\xi_{\omega}/\theta}$$

(10)

**Proof.** See Appendix B. 

This formulation introduces several factors that can contribute to ISTC:

1. domestic ISTC $\zeta_{hq}$
2. differences in the composition of imported capital $\prod_{\omega \in \{1,M\}} g_{T}(\omega)^{\xi_{\omega}/\theta}$
3. differences in the rate of trade cost declines $g_{nd}^{-1}$.

This means that, given reasonable measures of $g_{nd}$, we could use equations (9) and (10) to try to assess the extent to which overall ISTC $g_q$ is due to changes in trade costs.

One counterfactual experiment would be to set $g_{nd} = 1$.

**Proposition 4** The removal of trade cost changes ($g_{nd} = 1$) lowers $g_q$ by $\Delta_q$, where

$$\Delta_q \equiv \log g_q - \log \left[ \left( g_{nd}^{-1} \times \prod_{\omega \in \{1,M\}} g_{T}(\omega)^{\xi_{\omega}/\theta} \right)^{\xi_{mq}} \right]$$

(11)

$$= -\tau_n \log g_{nd}$$

(12)

**Proposition 5** The change in aggregate growth $\Delta_{trade}$ stemming from the removal of trade cost changes ($g_{nd} = 1$) is

$$\Delta_{trade} \equiv \frac{-\alpha_k \tau_n}{1 - \alpha_k} \log g_{nd}$$

**Proposition 6** The change in ISTC $\Delta_{tradeEqQ}$ stemming from the removal of imported capital goods is:

$$\Delta_{tradeEqQ} \equiv \tau_n \sum_{\omega \in \{1,M\}} \xi_{\omega}/\theta \log g_{T}(\omega)$$
and the change in aggregate growth stemming from ISTC in imported equipment $\Delta_{\text{tradeEq}}$ is:

$$
\Delta_{\text{tradeEq}} = \frac{\alpha_k \ln n}{1 - \alpha_k} \sum_{\omega \in [1,M]} \xi^n_\omega / \theta \log g_T(\omega)
$$

**Remark 2** Equation (10) 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 ($g_{nd} < 1$) may imply an acceleration of ISTC when a significant portion of capital is imported.

**Remark 3** Equation (10) also suggests that there are two distinct channels through which trade affects ISTC: declining trade costs ($g_{nd} < 1$) and differences in composition across types of capital with different rates of ISTC ($\prod_{\omega \in [1,M]} g_T(\omega)^{\xi^n_\omega}$). Later we will present measures of both of these factors, so that we are able to see whether they do indeed statistically explain measured country differences in ISTC – in Table 3 below.

### III Data

The following are central data inputs for our growth accounting exercises. We start with a comprehensive data description, as opposed to introducing new data sources each time we present a variation on the basic framework. We use several approaches to measuring ISTC. Some of them are inputs into the main growth accounting exercise, whereas others are best suited 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). Notice that this is a relatively early version of the PWT: 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. The data sample is 1950 – 2010, or the subset thereof available for each country. Our measurement strategy is similar to GHK and also to Hsieh and Klenow (2007), who use relative price of capital data in the PWT to look at cross-country differences in levels of the efficiency of investment: our focus is instead on changes.

We also require a measure of the capital share, which we term $\alpha_k$. We measure $\alpha_k$ as one minus the labor share of GDP. Data on labor shares are the variable labsh in the PWT 9.0.$^6$

For the purposes of this paper, it is important to underline that the data in the latest Penn World Tables version 9.0 (Feenstra et al (2015)) are not suitable 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.$^7$ 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

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$^6$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).

$^7$See the ICP 2003-2006 Handbook from the World Bank for a detailed discussion.
indices in versions 8.0 and above are unsuitable for our purposes of measuring $g_q$.

B Quality adjustments

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. 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. National accounting standards call for prices to be adjusted for quality, so that official price measures should be adequate for our purposes – for example, in their influential study of the impact of levels of capital goods prices on development, Hsieh and Klenow (2007) do not apply a quality adjustment. 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 $g_q$. We will use official price data as a benchmark. 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, to consider the possibility of further unmeasured quality improvements in capital. Given the attention given to the topic in the literature, we verify that our findings are robust to allowing for unmeasured quality differences of reasonable magnitude in

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9 Gordon (1990), Greenwood et al (1997) and Cummins and Violante (2002) argue that capital goods prices should be adjusted for quality. In contrast, Whelan (2003) argues against the use of such measures, as there may be unmeasured quality improvements in consumption and services too: thus, a measure of the relative price of capital that adjusts for quality in the numerator but not the denominator may be less accurate than one that does not. Again, to the extent that countries follow UN mandated national accounting standards, quality adjustments should be applied to the numerator and the denominator so official prices should be suited to the task.
the measurement of capital prices.

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 a quality-adjusted measure that builds on the official data and on IT penetration. Second, we use the composition of capital in each country and the capital good-specific estimates in CV to obtain a measure that isolates the impact of capital composition on ISTC.

B.1 Adjustment using Information Technology

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

How could we measure \( \Theta(c) \)? It is well known that a key source of quality improvements in capital goods is information technology (IT), see GHK and CV among others. Indeed, 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 are available, to get industry rates of ISTC over the period 1947 – 2004 (see CV for details of the procedure). We found that the correlation between industry rates of equipment ISTC and the average share of equipment investment in Computers and Peripheral Equipment over the period was 0.70*** (and the standard error was just 0.091). Thus, we 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.\(^\text{10}\) A secure server is defined as a computer that contains websites that may

\(^{10}\) 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
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 confidential 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 to 2.2 in Iceland.\footnote{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.} The measure Θ exceeds unity only in Switzerland, Denmark, Finland, Iceland, South Korea, Luxembourg, Malta, Netherlands, Norway and Sweden. The measure Θ is also strongly positively correlated with average log GDP per head over the period (0.77***), 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 0.27, significant at the 1 percent level.

In US official data, $g_q = 1.0058$. On the other hand, according to GHK, using quality adjusted data $g_q = 1.018$.\footnote{The model of GHK distinguishes between equipment and structures, with different values of $g_q$ for each type of capital. We follow the literature in setting $g_q = 1.018$ which is the geometric average across equipment and structures using the weights in GHK.} This implies that $g_{quality} = (1.018/1.0058)$.

\section*{B.2 Adjustment based on Composition}

Gordon (1990) and CV show that the rate of ISTC differs significantly across types of capital good. Thus, countries that use a different mix of capital goods might experience different rates of ISTC as a result. The same may be true of countries that import a different mix of capital goods.

To isolate the possible influence of capital goods composition on ISTC, we use the CV 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 capital goods price data relative to the consumption and services price index, extended using forecasting methods as detailed in CV.\textsuperscript{13} These prices are available only for equipment and machinery, not for structures, so we will be able to use them to identify mainly ISTC directed towards equipment and machinery. GHK and CV argue that there is little of any ISTC embodied in structures, however, so this measure should capture most of the cross country variation in ISTC due to compositional differences.\textsuperscript{14}

To compute detailed shares of capital good types by country, we build on the observation of EK and Caselli and Wilson (2004) that for much of the post war period all but 15 countries import a significant portion of the equipment and machinery they use, 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, so that import shares are in fact a reasonable proxy for capital composition in most countries.\textsuperscript{15} Shares are computed using the data on trade composition 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.

CV also provide measures that are \textit{not} quality adjusted, i.e. they are constructed

\begin{itemize}
\item \textsuperscript{13}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.
\item \textsuperscript{14}Of course the share of structures vs. equipment in investment would itself be a measure of compositional differences. The ICP contains information on the share of expenditure on equipment as opposed to structures in benchmark years. If we look at the share of equipment reported in the ICP data for 2005, which maximizes coverage, we find that our benchmark measure has a correlation of 0.22* with this share, which is positive as expected. Revisions to the procedure for measuring structures prices means that prior rounds of ICP data may not be comparable.
\item \textsuperscript{15}The only country with a correlation below 0.35 in our data is Malta, see Figure 1 in Caselli and Wilson (2004).
\end{itemize}
without applying hedonic adjustments to capital goods prices. We construct another measure in the same way using these prices, as this would be a better data counterpart to the official measures of $g_q$ (which do not have a quality adjustment either).

One caveat: by construction, the CV-based measures of $g_q$ never decline. For all types of equipment in the CV data, the change in the relative price of capital indicates a positive rate of ISTC. Thus, these measures of ISTC are indicators of ISTC if it were solely based on *compositional differences*.\footnote{This measure captures compositional differences assuming rates of ISTC for each type of capital good are similar in different places. Certainly for 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 could be factors that affect ISTC which are unrelated to composition i.e. which affect the price of all capital goods. Thus we will use this ISTC measure for interpretation regarding the relevance of compositional effects, rather than as an input into the growth accounting exercises.

Another caveat is that the CV-based measure of $g_q$ is only for equipment: it does not measure $g_q$ among structures. We cannot impute $g_q$ among structures because these data are not available in PWT 7.1. As mentioned, the price data in PWT 9.0 are not adequate for measuring $g_q$ because of the re-benchmarking procedure.\footnote{In fact we did try to construct measures of $g_q$ for structures by measuring the relative price of structures over time, obtaining sometimes absurdly large or small numbers.}

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 focuses on compositional differences in equipment, using quality-adjusted CV data. Fourth, we have a measure of $g_q$ which is similar to the third, using the CV data that are not quality-adjusted.

C Other data

Data on GDP are drawn from the Penn World Tables 9.0, see Feenstra et al (2015), 1950 – 2014. We define $g$ as the geometric average growth factor of GDP per capita. Version 9.0 also contains the share of investment in different types of capital – struc-
tures, machinery, transportation equipment and other – which we also use.

We also make use of trade cost data for the open economy framework. We use the measure of trade costs reported by the World Bank International Trade Cost Database. This 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 (as suggested by gravity equations). 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\(^\text{18}\) 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.\(^\text{19}\)

Finally we require measures of the share of new capital goods that are imported \(\tau_n\). We construct it using the share of imports of capital goods from the Feenstra et al (2015) data. We add up the values of capital goods imports, divide by GDP, and then use the investment share of GDP to derive the share of investment that is imported. This is available for 120 countries. On the other hand, since this measure was constructed indirectly, we check an alternative measurement strategy for validation. A more direct measure is to use the World Input-Output tables. The WIO tables report the purchases of different kinds of goods by industries in the using countries. We use the tables from year 2000 as it is the year with the most coverage – 40 countries. For the countries for which there is an overlap we find that the correlation is 0.46, significant at the 1 percent level, and that the regression coefficient when the trade-based measure is regressed on the WIO-based measure is 1.02 (not significantly

\(^{18}\)The 15 countries are Australia, Canada, Denmark, Finland, France, (unified) Germany, Ireland, Italy, Japan, Netherlands, Norway, Spain, Sweden, Great Britain, and USA. See Caselli and Wilson (2004).

\(^{19}\)We add the growth in the cost of outbound trade with the cost of inbound trade. This is because the costs are incurred both when the capital goods are imported and when the goods from the capital-importing country are exported to buy the capital goods, thus both inward and outward trade costs affect the marginal rate of transformation of domestic goods into foreign capital goods.
different from one). We view this as validation of the trade-based measure, which we use as a benchmark given the broader coverage.

To assess the impact of trade composition (as opposed to trade costs) on growth to ISTC we require a value of $\theta$, the EK productivity dispersion parameter. EK find a value of 9.2 using data on capital goods, whereas Eaton and Kortum (2002) find a value of 8.3. We use the mean which is 8.75. As an alternative, Simonovska and Waugh (2014) estimate values around 4, we examine them too. As we see below the specific value is not very important: estimates of $\theta$ an order of magnitude smaller would be required to change results that depend on this parameter.

D Basic observations

<table>
<thead>
<tr>
<th>Correlation</th>
<th>log $g_q$</th>
<th>Servers</th>
<th>$g_q^{CVadj}$</th>
<th>$g_q^{CVnoadj}$</th>
<th>logGDPpercap</th>
</tr>
</thead>
<tbody>
<tr>
<td>Official</td>
<td>.82***</td>
<td>.30***</td>
<td>.31***</td>
<td></td>
<td>.19</td>
</tr>
<tr>
<td>Servers</td>
<td></td>
<td>.43***</td>
<td>.45***</td>
<td></td>
<td>.45***</td>
</tr>
<tr>
<td>$g_q^{CVadj}$</td>
<td></td>
<td></td>
<td>.72***</td>
<td></td>
<td>.41***</td>
</tr>
<tr>
<td>$g_q^{CVnoadj}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>.32***</td>
</tr>
</tbody>
</table>

Table 1 – Spearman 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 five ISTC measures are related among themselves. There are several findings. Most importantly, all the measures are significantly positively correlated. This is important because it indicates that official price measures do appear to be capturing the same variation as the quality adjusted measures in CV. In addition, the quality-adjusted measures are significantly related to the average level of GDP per capita, although the baseline measure is not. Thus, according to the quality-adjusted measures, 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. Indeed, the correlation between log $g_q$ and the average level of log $q$ in official data is $0.36^{***}$, see Figure 1. None of them is statistically significantly correlated with GDP growth rates (although the correlations are all positive): however, this does not mean that the growth accounting exercises will not reveal an economically significant contribution of ISTC to growth.

<table>
<thead>
<tr>
<th>Measure of log $g_q$</th>
<th>Statistic</th>
<th>Official</th>
<th>Servers</th>
<th>CV adj</th>
<th>CV no adj</th>
</tr>
</thead>
<tbody>
<tr>
<td>Median</td>
<td>$-0.005%$</td>
<td>$0.124%$</td>
<td>$3.706%$</td>
<td>$0.789%$</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>$-0.001%$</td>
<td>$0.356%$</td>
<td>$3.952%$</td>
<td>$0.852%$</td>
<td></td>
</tr>
<tr>
<td>s.d.</td>
<td>$1.259%$</td>
<td>$1.026%$</td>
<td>$0.828%$</td>
<td>$0.264%$</td>
<td></td>
</tr>
<tr>
<td>Share below zero</td>
<td>$54.7%$</td>
<td>$43.3%$</td>
<td>$-%$</td>
<td>$-%$</td>
<td></td>
</tr>
</tbody>
</table>

Table 2 – Summary information for each measure of log $g_q$.

The measures based on Cummins and Violante (2002) are all positive by construction.

It is worth noting that the mean official value of log $g_q$ is about zero, i.e. there are several countries where the relative price of capital rises. This occurs in 104 out of 190 countries – see Figure 2 and Table 2. Also observe that the ranking of countries by different measures of $g_q$ are similar to the rankings using the official measure (Table 1). Since these other measures are based on measuring or imputing compositional differences, we conclude that cross-country differences in composition are likely an important factor of country differences in ISTC.
IV  Quantitative Experiments

A  Baseline results

Figure 3 reports the reported decline in growth rates if ISTC were to be removed, using the growth accounting equation 6. It should be clear that in most countries the removal of ISTC actually would have increased growth. In addition in almost all countries where ISTC does contribute to growth, the contribution is very small.\(^{20}\)

\(^{20}\)Ngai and Samaniego (2009) show that the contribution of ISTC to growth may be boosted by the fact that some of the output of the capital goods sector is used as an intermediate good.
Figure 3 – Decrease in growth rates if ISTC is removed (i.e. $g_q = 1$), baseline specification $\Delta_0$. A positive value indicates that ISTC was contributing to growth.

We now repeat the above exercises using the measure of $g_q$ adjusted for quality using a proxy for IT penetration, as discussed in Section III. This will raise the importance of ISTC for growth. See Figure 4. We observe that the distribution appears more skewed towards higher values than before, consistent with the literature on the contribution of IT to quality improvements in capital goods. At the same time, it remains the case that about half of the countries report values of $g_q$ below one, in other sectors. In results available upon request we modified our growth accounting equations to allow for this. Results are very similar for two reasons: the share of capital goods used as an intermediate is small, and while this consideration increases the contribution of ISTC to growth where this contribution is positive, it also decreases the contribution of ISTC to growth where this contribution is negative.
and most of the positive values are also very close to unity.

![Decrease in growth if $g_q=1$: IT-adjusted](image)

Figure 4 – Decrease in growth rates if ISTC is removed (i.e. $g_q = 1$), baseline specification $\Delta_0$. A positive value indicates that ISTC was contributing to growth. This Figure assumes a quality adjustment the magnitude of which is set by $\Theta$, the density of secure servers relative to the US.

To assess the economic significance we ask two questions. First, what is the contribution of ISTC to growth globally? Second, what would happen to global growth if there were some way to raise $g_q$ across the board?

First, we measure the global contribution of ISTC to growth by computing $\Delta_0$ for the entire world. We do so by computing the average weighted by the average GDP level of each country over the period. When we do not apply a quality adjustment we get that $\Delta_0$ worldwide is about 0.05 percent – essentially zero. When we do apply
a quality adjustment, however, we find that $\Delta_0$ is 1.3 percent, far more substantial. This reinforces the controversy in the literature regarding the contribution of ISTC to growth in the US among, for example, Greenwood et al (1997) and Whelan (2003): the presence or not of quality adjustments to capital goods prices changes the conclusions significantly.

On the other hand, suppose we perform a different experiment: to raise the rate of ISTC everywhere to the level of the US. If this were somehow possible, it would raise the world growth rate by fully 2.8 percent using the official measure of $g_q$, or by 3.8 percent using the quality adjusted measure. Again, this essentially reflects the fact that for most countries in the world $g_q < 1$, so that raising $g_q$ to values that are reasonable elsewhere could have substantial growth implications.

Another way to look at this is to consider a hypothetical country with median values of all the parameters, so that $g_q = 1$, $\alpha_k = 0.45$ and $g = 1.019$. 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 1.0238, a difference that would generate a 10% gap in GDP per capita in 20.5 years. If $g_q$ were to rise to 1.018 (the quality-adjusted US value) then $g$ would rise to 1.034, enough to generate a 10% gap in 6.5 years.

These experiments show that identifying the reasons why $g_q$ is small in some developing economies could be highly economically significant for understanding the mechanisms of economic development, and whether $g_q$ is sensitive to policy could be important for accelerating economic growth.

V Decomposing ISTC

We now decompose the contribution of ISTC into two possible sources: trade cost declines and composition.

A Trade liberalization

First we revisit the environment with international trade. Figure 6 shows that ISTC would decrease in most countries with available data if trade cost changes were set
to equal one – as computed using growth accounting equation 11. In most countries trade costs declined since 1995, and the model implies that if trade costs had been constant then ISTC would have slowed in many places. The mean value is 0.4%, and it is greater than zero in 58 of 69 countries. Notably, the correlation between $\Delta_q$ (which uses only $t_n$ and trade costs as inputs) and the baseline measure of ISTC $\log g_q$ is positive (0.24) and statistically significant at the 5 percent level.

Figure 6 – Decrease in $g_q$ if trade costs were constant over time, $\Delta_q$.

We find that the contribution to economic growth of trade liberalization through the ISTC channel can be quite large. Figure 7 displays the decrease in growth from making trade costs constant, against the baseline decrease in growth from setting ISTC to zero. This is equivalent to seeing how the impact of trade costs on $g_q$ in Figure 6 translates into changes in rates of economic growth, using Proposition 5.
Given that the relative price of capital rises in many countries, whereas trade costs rose in very few, the contribution of trade cost declines to growth is positive in most cases. The mean value is 0.18 percent, and in some cases it is much higher.

Figure 7 – Decrease in growth rates from setting \( g_q \) to one in the baseline scenario (\( \Delta_0 \)) and from setting trade costs to be constant (\( \Delta_{\text{trade}} \)). Figure includes only countries for which both \( \Delta_0 \) and \( \Delta_{\text{trade}} \) could be computed.

**B Capital goods composition**

**B.1 Trade composition**

The model also allows us to measure the impact of trade composition on economic growth. Note that this is intermediated by the share of imported capital \( t_n \) and also
by the parameter \( \theta \) which captures the cross-country dispersion of productivity in the EK framework – see Proposition 6. Assuming that \( \theta = 8.75 \), we find that the average change in growth due to imported capital (\( \Delta_{\text{trade},E_q} \)) is negligible. The mean is 0.06 percent with a standard deviation of 0.05 for the benchmark measure of \( g_q \) or 0.02 percent with a s.d. of 0.02 in the quality adjusted case. If instead we use the WIO-derived measure of \( \lambda_n \), we find means of 0.03 percent (std 0.02 percent) for the baseline measure or 0.01 percent (std 0.08 percent) for the quality adjusted measure. This is no surprise because the values of \( \log g_q \) are generally the order of magnitude of the values of \( \log g \), whereas the impact of imported ISTC on growth is intermediated by the parameter \( \theta \) which in turn reduces the impact of trade composition on growth by an order of magnitude. If we use a smaller value found in the literature (\( \theta = 4 \)), this will roughly double all of these values, but they remain very small. We conclude that a typical EK–style framework suggests that the composition of imported capital has little impact on growth – although the composition of capital in general could still matter, through equation 7.

B.2 Broad 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 measures 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 differences in the composition of equipment – recall Table 1. Since these measures are based on trade data they are particularly informative regarding imported equipment, but as observed in Caselli and Wilson (2004) there is a strong relationship between the composition of imported equipment and the composition of equipment more broadly.

To see that the data support a role for the composition of capital beyond simply the composition of trade, we regress \( \log g_q \) on the CV (i.e. purely composition-based) measures of ISTC and (to avoid omitted variables) on the trade cost-implied change
in ISTC ($-\log g_{nd}$):

$$\log g_{qc} = \alpha + \beta CV measure_c + \gamma Tradecostmeasure_c + \varepsilon_c$$

where $\log g_{qc}$ is a measure of the rate of ISTC in country $c$, $CV measure_c$ is a composition-based measure of ISTC from CV for country $c$ (either adjusted or not adjusted for quality) and $Tradecostmeasure_c$ is the rate of decline of trade costs for country $c$. We find that in general both $CV measure_c$ and $Tradecostmeasure_c$ are significant: see Table 3. However, equation (11) suggests that the coefficient on the compositional measure should equal $t_n/\theta$. The mean value of $t_n$ is around 0.36, and if we assume $\theta = 8.75$ then the mean of $t_n/\theta$ is 0.04, or closer to 0.1 if $\theta = 0.4$. This would suggest that we would expect coefficients on compositional ISTC of around 0.04 – 0.1 if they were capturing only the composition of trade. On the other hand, if they capture the composition of equipment overall then we would expect much larger coefficients. In fact, we find coefficients that are larger by an order of magnitude. The reason the coefficient on ISTC might be higher than expected is that, as discussed, the composition of imported capital goods is highly correlated with the composition of capital overall (whether imported or domestically produced), so this simple regression likely captures the impact of composition in general, not just
through trade (recall equation 7).

<table>
<thead>
<tr>
<th>Measure of log $g_q$</th>
<th>$\log g_1^{CV_{adj}}$</th>
<th>Trade cost measure</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Official</td>
<td>0.520*** (0.131)</td>
<td>0.085*** (0.023)</td>
<td>0.140</td>
</tr>
<tr>
<td>Servers</td>
<td>0.872*** (0.184)</td>
<td>0.109*** (0.027)</td>
<td>0.170</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Measure of log $g_q$</th>
<th>$\log g_1^{CV_{noadj}}$</th>
<th>Trade cost measure</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Official</td>
<td>1.065** (.476)</td>
<td>0.060** (.030)</td>
<td>0.116</td>
</tr>
<tr>
<td>Servers</td>
<td>1.774*** (.659)</td>
<td>0.067*** (.033)</td>
<td>0.135</td>
</tr>
</tbody>
</table>

Table 3 – Results from the regression: $\log g_{qc} = \alpha + \beta CV_{measure_c} + \gamma Tradecostmeasure_c + \varepsilon_c$. The CV measure are the measures of ISTC constructed using the measures of ISTC by capital good type – quality and not quality adjusted – weighted by the import share of each type of capital. The trade cost measure is $-\ell_n \log g_{nd}$ – the log (negative) rate of increase in trade costs times the share of capital imports in capital. Sample size is 69.

Of course the composition of equipment is not the only relevant statistic for understanding the impact of composition on ISTC. Another is the share of equipment (as opposed to structures) in the capital stock. Equation (7) shows that if ISTC rates vary across capital good types then variation in these shares will lead to variation in overall ISTC. GHK and CV argue that structures experience slower ISTC than equipment. If so, we would expect countries with larger investment shares in structures to have lower ISTC. We find that these shares as measured in PWT 9.0 are weakly negatively correlated with the benchmark ISTC measure ($-0.10$), as expected, but this is not statistically significant at conventional levels. We conclude that variation in structures’ share of investment likely does not significantly contribute to observed
differences in ISTC around the world: the composition of equipment is much more important.

C Interpreting compositional differences

Focusing on equipment/machinery, Wilson (2002) and Caselli and Wilson (2004) argue that upstream R&D may be responsible for differences in ISTC across types of capital good (as suggested by the theoretical model of Krusell (1998)). This begs the question of whether 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 EK. 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 or flow and the import-based $g_q$ values using the CV quality adjustment for equipment is over 80 percent. The correlation between $g_q$ measured using official data and R&D stock is 0.21, and the correlation between official $g_q$ and R&D flow is 0.23, both
positive and significant. See Table 4.

<table>
<thead>
<tr>
<th>log ( g_q ) measure</th>
<th>Correlation</th>
<th>Official</th>
<th>Server</th>
<th>( g_q^{CV_{adj}} )</th>
<th>( g_q^{CV_{noadj}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>R&amp;D stock</td>
<td>0.21**</td>
<td>0.38***</td>
<td>0.86***</td>
<td>.63***</td>
<td></td>
</tr>
<tr>
<td>R&amp;D flow</td>
<td>0.23**</td>
<td>0.40***</td>
<td>0.87***</td>
<td>.66***</td>
<td></td>
</tr>
</tbody>
</table>

Table 4 – Correlations between \( \log g_q \) and upstream R&D.

Thus, cross country differences in \( g_q \) can be interpreted at least partly as differences in the quantity of R&D embodied in the imported equipment in use. This is interesting for at least 2 reasons. First, it suggests that among capital-importing countries 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.

D Exploring institutional differences

Could differences in rates of ISTC be due to institutional differences? There is a precedent in the literature for the idea that policy or institutional factors may affect rates of ISTC: Samaniego (2006) shows in an open-economy context that labor market regulation can affect comparative advantage in industries depending on their rate of ISTC, skewing industrial structure towards industries with low values of \( g_q \) (an effect termed "high-tech aversion"). Also, Ilyina and Samaniego (2012) show that when technology adoption requires external finance, financial underdevelopment also skews industrial structure towards low-tech industries by slowing technical progress particularly in industries where it is rapid. This begs the question as to whether any policy or institutional indicators might be statistically 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). As a result, we briefly 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.

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, which we measure 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. Finally, we also look at intellectual property rights, which have been related to the generation and diffusion of technology, see Samaniego (2013) for a survey. We measure intellectual property rights $IPR$ using the patent enforcement method developed in Ginarte and Park (1997), as reported by the World Bank, averaging over the available sample. Ilyina and Samaniego (2011) find that copyright enforcement specifically is a form of IPR enforcement that bears the strongest relationship to financial development – interpreted as a deep institutional determinant of financial development. See also Samaniego (2013). 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 measure (times minus one) as an indicator of copyright enforcement. Finally we also look at human capital $HC$, using the standard Barro and Lee (2010) schooling-based measure averaged over the period. While this is not an institutional measure as such it is an important country characteristic which could be related to the need/ability to produce/import high-tech capital goods.
We find that the official measure of $g_q$ is positively correlated with financial development. 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. We also find that there is a link between $g_q$ and intellectual property rights. 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 – alternatively, countries that don’t use high-tech capital goods do not adopt strong IPR regulations in order to facilitate technology transfer. A full exploration of this possibility is left for future research, but it is interesting to note that Ilyina and Samaniego (2011, 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. The server-based measure is linked with firing costs – as in Samaniego (2006). The server-adjusted and CV measures are related to many institutional indicators (including those mentioned above), however, so it is possible that our exercise simply captures broad institutional quality.

Finally, 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 again 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.

VI Concluding remarks

This is the first study that performs general equilibrium growth accounting with ISTC for a large pool of countries. We show that such improvements vary significantly across countries and are an important factor contributing to differences in growth rates across countries. We find that this can be partly attributed to differences across countries in the types of capital good used, and that this is interpretable in terms of differences in the upstream R&D devoted to capital goods. The results imply that significant acceleration in rates of economic growth is possible if ISTC rates are susceptible to policy. In particular, we find that declines over time in trade costs also account for a portion of differences in ISTC and in economic growth, indicating that the process of trade liberalization can contribute to economic growth through the encouragement of ISTC.\footnote{We also find variation in structures ISTC across countries. Considering that a significant share of construction workers in many developed economies are migrants, and that Ngai and Samaniego (2009) find that declines in the prices of inputs used in the capital goods sector may lower the price of capital goods, this raises the intriguing possibility that migration could be a factor of ISTC.} More broadly, our findings underscore the importance of ISTC as a factor of economic development, and thus of future work on the institutional or other determinants of differences in rates of ISTC around the world. On or diffusion might give countries a comparative advantage or disadvantage in the production of goods with high rates of ISTC.
VII References


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