Convergence and Divergence: New Data and New Results[*]

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Abstract

Recently Penn World Tables have included new data that enable calculation of Total Factor Productivity in addition to Output. We use the new data to examine convergence and divergence of output across countries. These issues have been studied previously mainly with data on output. The use of this additional data leads to two main results. First, we measure for the first time unconditional convergence of 'efficiency output per worker' to a long-run constant. Using this result we show that the findings of β-convergence should be interpreted as convergence of output per worker in each country to the productivity of that country, but not across countries. Second, we find that in 1970-2014 productivity of many countries did not follow the global frontier fully, which implies significant divergence across countries.

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Convergence and Divergence:

New Data and New Results

1. Introduction

Do income levels across countries converge or diverge over time? This question haunts empirical research on economic growth in the last three decades and it has received conflicting answers. So far the research focused on trying to find new methods to measure convergence and divergence of output across countries. This paper instead uses a new set of data in order to shed new light on this issue. These are the well-known Penn World Tables, which since version 8.0 publish data on capital and labor inputs in addition to data on output, as explained in Feenstra et al (2015). With these data we can calculate total factor productivity for a large set of countries, which has been previously available only for much fewer countries. Using these data we reach two main results. First, output per worker of each country converges to its own productivity at a rate close to 2 percent. This implies that the findings of β-convergence should not be interpreted as convergence of output across countries. Second, we find that productivities of many countries diverge away from the global frontier. Since output converges to productivity, it follows that output per worker of many countries diverges away from the frontier.

We begin our analysis by calculating total factor productivity from the new PWT 9.1 data set. We assume that productivity is labor augmenting, and so we calculate the labor augmenting total factor productivity, which we denote by LATFP. The method of calculation is very similar to that of the Solow TFP, but it is simpler to use.[1] We then examine for each country the dynamics of output per worker and of LATFP and find that the first variable tends to converge to the latter. We show it in two ways. First, by looking at the ratio between output per worker and LATFP, which is called 'efficiency output per worker,' we find that it converges to a long-run level for each country. This is done without using any explanatory variables. The second way is a cointegration test of output per worker over LATFP, where we find that the coefficient of cointegration is 1. Both tests find that the rate of convergence of output per worker to LATFP is around 2 percent, which is similar to the results of β-convergence. We therefore conclude that these results should be interpreted only as convergence of output to productivity in the same country and not as convergence across countries.

[1] Equilibrium output per worker should follow 1.5 of the Solow TFP, while it should follow LATFP precisely.

Actually, the idea that β-convergence implies convergence of output to TFP rather than convergence across countries, appears already in the literature as a theoretical possibility. One example is Durlauf, Johnson and Temple (2005), hereafter DJT, the most authoritative survey of empirical studies of economic growth. DJT present a standard model of economic growth of a country and assume that output converges over time to TFP. They then show that the tests of β-convergence can be interpreted as tests of this assumption, if there is no available data on TFP. Now, that such data has become available, we use it to provide direct empirical support to the assumption of DJT. We show that the efficiency output per worker indeed converges for a long-run level for each country.

Once we show that output per worker converges to productivity, then convergence or divergence of output across countries depends on whether productivity converges or diverges across countries. To study this issue we run cointegration tests of productivity, LATFP, in each country on the global frontier, represented by LATFP of the US, the leader in economic growth for over 140 years. We run the test for 102 countries for which we have data over the years 1970-2014 and find that many countries fail to follow the global frontier and are actually diverging away from it. More precisely, the coefficient of cointegration between a country's productivity and the global frontier, which we denote by *d*, measures this divergence. If *d* is equal to 1, the country follows the frontier fully, while if *d* is lower than 1, it follows the frontier partially and actually diverges from it and from the countries near it. This is therefore an interesting innovation of this paper, which measures divergence as a continuous parameter and not as a simple dichotomy. We find that the average *d* is lower than 1 and that it is quite low for many countries. This is the case for Central and South American countries, for South Sahara African countries, and for the MENA countries. The Eastern European countries tend to follow the frontier and only the productivity of the East Asian countries grows faster than the frontier, namely their *d* is above 1. That is probably a result of the catching up by these countries during the period.

The use of these data leads us to a few more interesting results. While the parameter *d* measures by how much a country follows the frontier in the long-run, we can also measure the rate of adjustment to this long-run path, which is around 8 percent. Hence, this rate of convergence of productivity is faster than the rate of convergence of output to productivity. In addition we use data on education attainment to split LATFP to human capital, measured by the method of 'development accounting' and the residual. This residual can be interpreted as country technology. We find that human capital of each country converges to a finite level. But we also find that levels of technology tend to diverge even more than levels of TFP. We view these results with some reservations, as we worry that years of schooling measure only potential human capital, while in many developing countries, and even in some developed countries, many graduates do not find proper jobs and their potential human capital does not fully materialize. This causes under estimation of the level of technology.

This paper is related to a few lines of literature. The main one is the empirical literature on convergence and divergence in economic growth. There are three main methods to measure divergence or convergence, which are described in detail in DJT. One method is called growth regressions, or β-convergence tests, the second examines the dynamics of the distribution of income across countries over time, while the third is called 'time series tests.'

The use of 'growth regressions' was initiated by Barro (1991), Mankiw, Romer and Weil (1992), and Barro and Sala-i-Martin (1992), though inspired by earlier work of Baumol (1986) and Kormendi and Meguire (1985). This line of research has developed over the years into a huge literature. Its main result is β-convergence, which means that the rate of growth of output per worker in a country is negatively related to its initial level of output per worker, if some additional variables are controlled for. These are called 'explanatory variables,' since they usually represent theories of economic growth, like human capital, geography, institutions, and more.[2]

Over the years this literature has been criticized on various grounds. One critique is that the economic meaning of β-convergence is not clear. Much of the critique focused on the ad-hoc choice of explanatory variables. Another critique focused on the interpretation of the use of explanatory variables as tests of growth theories, since many of the explanatory variables are actually endogenous and affected by growth. Summaries of these critiques can be found in DJT, in Durlauf (2009) and in other studies. In this paper we show how additional data on productivity can help us avoid the use of explanatory variables altogether. We also add to the critique of the interpretation of β-convergence tests, as they should be interpreted as convergence of output to productivity within each country and not as convergence across countries.

The second method to examine convergence and divergence is to study how the distribution of output per worker, or per capita, evolves over time. A common test in this literature examines the standard error of the distribution of output per capita across countries and is called σ-convergence.[3] Such studies of the distribution of output usually find divergence over time, as in Quah (1996) and

[2] An important generalization of β-convergence models are 'varying parameters models' by Liu and Stengos (1999), Durlauf *et al* (2001), Lee *et al* (1997, 1998), Di Vaio and Enflo (2011) and many others.

[3] See Barro (2015) and Jones (2015) for recent results of σ-convergence.

Pritchett (1997), who even titled his paper "Divergence, Big Time."[4] This paper focuses on the dynamics of individual countries, rather than on the dynamics of the overall distribution.

The third method of measuring convergence and divergence builds on studies of how output per worker in one country follows output per worker in another country. This method, which is called 'time series tests,' began with Bernard and Durlauf (1995, 1996) and continued with Hobijn and Franses (2000), Phillips and Sul (2007, 2009) and others. The second part of this paper follows this line of research with two main departures. First, it runs such tests on total factor productivity instead of output per worker. Second, it runs these tests for a large sample of countries, while many of the above studies focused on a small set of developed countries.

Recently, there is renewed interest in the issue of convergence and divergence. The survey by Jones (2015) on economic growth devotes much attention to it. To that we can add Barro (2015) and also recent papers by Rodrik (2011, 2013), Madsen (2014) and Madsen and Timol (2011) that look at new data, mainly on sectors and industries. This paper joins them by adding new data, this time of on TFP, to the study of convergence and divergence.

This paper is also related to the literature of 'development accounting,' as we use it to split productivity to human capital and to technical change. This method began with Klenow and Rodriguez-Clare (1997) and Hall and Jones (1999), and it is summarized in Caselli (2005) and more recently in Hsieh and Klenow (2010). This method uses data on schooling and labor studies on the effect of schooling to measure human capital. This paper shows that the use of this method in developing countries is problematic, due to large unemployment of graduates of tertiary education.

Of the many theories of economic growth, this paper is related mostly to theories of technology adoption. Since countries do not invent most of the technologies they use, but adopt them from the frontier, these theories try to explain why some countries adopt only part of the available technologies. Such theories appear in Krugman (1979), Parente and Prescott (1994), Zeira (1998), Eaton and Kortum (1999) and Acemoglu, Aghion and Zilibotti (2006). Recent empirical support to these theories appears in Dowrick and Rogers (2002), Comin and Hobijn (2010), Comin and Mestieri (2013) and Alesina, Battisti and Zeira (2018). This paper also presents empirical support for partial adoption. A recent paper by Gourinchas and Jeanne (2013) also assumes that productivity adjusts gradually to its long-run path, but it assumes that $d = 1$, which is refuted in this paper.

[4] See also Pesaran (2007a) and Henderson and Russell (2005).

The paper is organized as follows. Section 2 presents the data on LATFP. Section 3 presents the implications of the growth model on how output should follow LATFP. Section 4 presents empirical support to this convergence. Section 5 shows that productivities in many countries do not follow the global frontier but diverge away from it. Section 6 shows that similar divergence holds for output per worker as well. Section 7 splits productivity to human capital and to technology. It shows that human capital converges to a final level, while technology diverges across countries. Section 8 summarizes the paper while the Appendix describes how to calculate LATFP and presents a model of growth under adjustment costs to investment.

2. Labor Augmented Total Factor Productivity

2.1. Output per Worker and TFP

Our point of departure is the standard production function with labor augmenting total factor productivity, used extensively in the literature since Solow (1956). There are two main reasons to assume that productivity is labor augmenting and not multiplying the production function, as assumed in Solow (1957). One is that productivity includes also human capital, which by its definition should be labor augmenting. The second reason is that the assumption that productivity is labor augmenting implies that in the long-run output per worker should be proportional to productivity, while if productivity multiplies the production function, output per worker is proportional to productivity times 1.5. Hence, this assumption simplifies much of the following analysis, but it is not crucial to any of the results. Assume, therefore, that production in country *j* in period *t* is described by:

(1) $$Y(j,t) = G\left[K(j,t), A(j,t)L(j,t)\right].$$

In this equation $Y(j,t)$ is aggregate output, $L(j,t)$ is the input of labor during period *t*, $K(j,t)$ is the amount of capital used in the country in period *t*, and $A(j,t)$ is labor augmenting total factor productivity, hereafter LATFP, or just productivity. The function *G* is a CRS production function and we implicitly assume that it is equal across countries. ‘Output per worker’ in country *j* at time *t* is defined as:

(2) $$y(j,t) = \frac{Y(j,t)}{L(j,t)}.$$

Clearly, output per worker, also termed ‘labor productivity,’ is the main variable that informs us on the country’s potential output. But output per worker also depends strongly on LATFP, since:

(3) $$y(j,t)=\frac{Y(j,t)}{L(j,t)}=G\left[\frac{K(j,t)}{L(j,t)},A(j,t)\right].$$

Note that output per worker depends on *A* directly, but also indirectly, through its effect on the capital-labor-ratio $K(j,t)/L(j,t)$. The indirect effect of *A* operates through raising the marginal productivity of capital and thus increasing investment and capital. While previous studies of international economic growth focused on output per worker as the main variable, they did not examine productivity growth across countries, as data on productivity was not available for a large set of countries. This has changed significantly with the new PWT data sets.

2.2 Labor Augmented Total Factor Productivity

The data set PWT 9.0 includes data on output, employment, capital and the share of labor for a large panel of countries. For output levels we use the series 'rgdpna,' namely real GDP of national accounts at 2010 US dollars (millions).[5] This is the series recommended by PWT 9.0 for comparing output over time, which is the main type of tests we run in this paper. For the labor input we use the series 'emp' in millions of workers. For capital stocks we use the series 'rkna,' real capital stock of national accounts at 2010 US dollars (millions), which fits the output series. Labor share is given by the series 'labsh.' These data enable us to calculate output per worker and also LATFP.[6] There are 182 countries in the data set and its time span is 1950-2014, but not all countries have full data for the entire period. This is available for only 52 countries. In most of our estimations we focus on 85 countries, for which these data are available since 1970 and for which we can run tests for the period 1970-2014.

The new PWT 9.0 also includes calculated TFP, but we use our own calculations since we prefer labor augmented TFP to fit the model and we also prefer not to subtract from it human capital at the current stage of the analysis. The calculation of the labor augmented TFP, LATFP, is very similar to that of the standard Solow Growth Accounting, as the rate of growth of LATFP is equal to the Solow residual divided by the elasticity of output with respect to labor, η_L. More precisely, this rate of growth is given by the following formula, which is proved in Appendix 1:

[5] This series is chained, so it is also PPP adjusted.
[6] We are aware that this data set is new and might suffer from some 'childhood' problems, but these are offset by having a unified data set for both output and productivity. See also Johnson, Larson, Papagiorgiou and Subramanian (2013) and Karabarbounis and Nieman (2014).

(4)
$$\frac{A(j,t)-A(j,t-1)}{A(j,t-1)}=\frac{1}{\eta_L(j,t-1)}\left[\frac{Y(j,t)-Y(j,t-1)}{Y(j,t-1)}-\frac{K(j,t)-K(j,t-1)}{K(j,t-1)}\right]+$$
$$+\frac{K(j,t)-K(j,t-1)}{K(j,t-1)}-\frac{L(j,t)-L(j,t-1)}{L(j,t-1)}.$$

We should add three comments on our calculation of LATFP:

1. First, equation (4) holds for cases in which the changes in output, labor and capital are rather small, so the method of differentials can be applied. There are few cases in the data, mainly for Iran and Iraq, that the decline in output in a year is so large (for example in 1991, output declined by 66 percent in Iraq) that application of (4) yields absurd results. In these few cases we calculated the change in capital from levels, assuming that *G* is Cobb-Douglas.
2. Second, the elasticity of output with respect to labor, $\eta_L(j,t-1)$ is not observed in the data, but under perfect competition it should be equal to the share of labor in output, $s_L(j,t-1)$, as shown by Solow (1957). We therefore calculate LATFP in two ways. In one, we use of the actual annual labor share from PWT 9.0. In the second, we use a constant elasticity assumption, as found in many studies, of 2/3. Such an approach has been adopted by Jones (2015) as well. In the paper we report results of the empirical tests for both calculations of LATFP.
3. Finally, for some of the dynamic analysis below it is sufficient to know only the rate of growth of productivity LATFP, and not its absolute level. This rate of growth is obtained by (4) in a general way. For calculations that require the level of efficiency output per worker we also need the level of LATFP. This is done by calculating productivity in the last year of data, assuming that *G* is a Cobb-Douglas production function, $K^{\alpha}(AL)^{1-\alpha}$, where $1 - \alpha$ is the labor share of that year. From that year, LATFP is calculated by chaining to all other years by use of the annual growth rates (4).

2.3. Efficiency Output per Worker

We next follow DJT and define 'efficiency output per worker' as the ratio of output per worker to labor augmented productivity LATFP. Hence, efficiency output per worker in country *j* at time *t* is:

(5)
$$y^E(j,t)=\frac{y(j,t)}{A(j,t)}=\frac{Y(j,t)}{L(j,t)A(j,t)}.$$

Note that while DJT discuss the efficiency output per worker as an unobserved variable, since they assume that productivity *A* is not observed, PWT 9.0 enables us to calculate it and examine directly its dynamics. Figure 1 presents the graphs of the natural logarithms of efficiency output per worker, $\ln y^E$, for 5 developed countries in the years 1950-2014. The countries are the US, Germany, France, Sweden, and Japan. As figure 1 shows, efficiency output per worker has been quite stable over time for most countries, and it exhibits convergence to some long-run levels for all countries. The productivity in Figure 1 is calculated by using the constant elasticity of 2/3. The results from using the annual share of labor are similar, although the countries converge to more disperse limits.

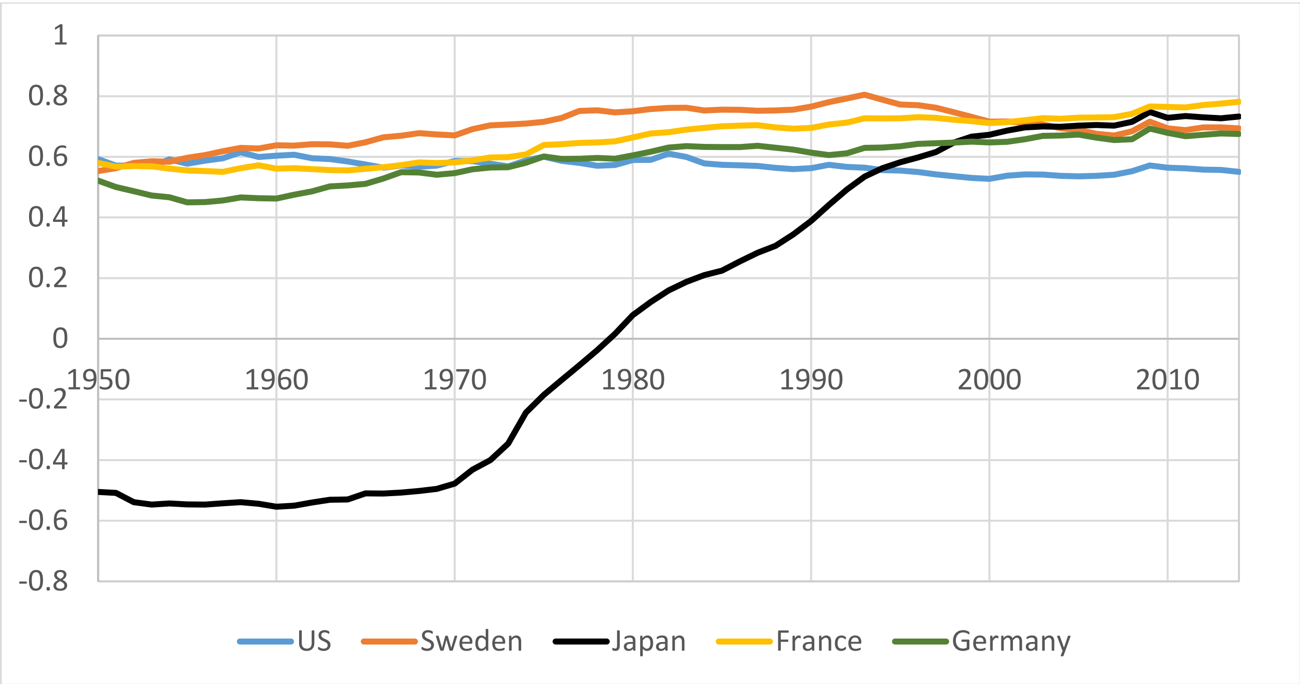

Figure 1: Efficiency Output per Worker for Five Developed Countries

Figure 2 presents the same variable, efficiency output per worker, for five less developed countries, China, India, Kenya, Colombia, and Turkey. Note that these are countries from different global regions, East Asia, South Asia, Sub-Saharan Africa, Central and South America and MENA, respectively. Although Turkey belongs to the OECD, it is one of the lower income countries in this group. The pattern in Figure 2 is similar to that of Figure 1, as efficiency output per worker in each country tends to converge to some long run level. A possible exception is China, for which the efficiency output per worker does not show leveling off yet, possibly because it is still catching up. Note also, that efficiency output for these countries fluctuates more than in the developed countries, but that could be a result of lower quality of data.

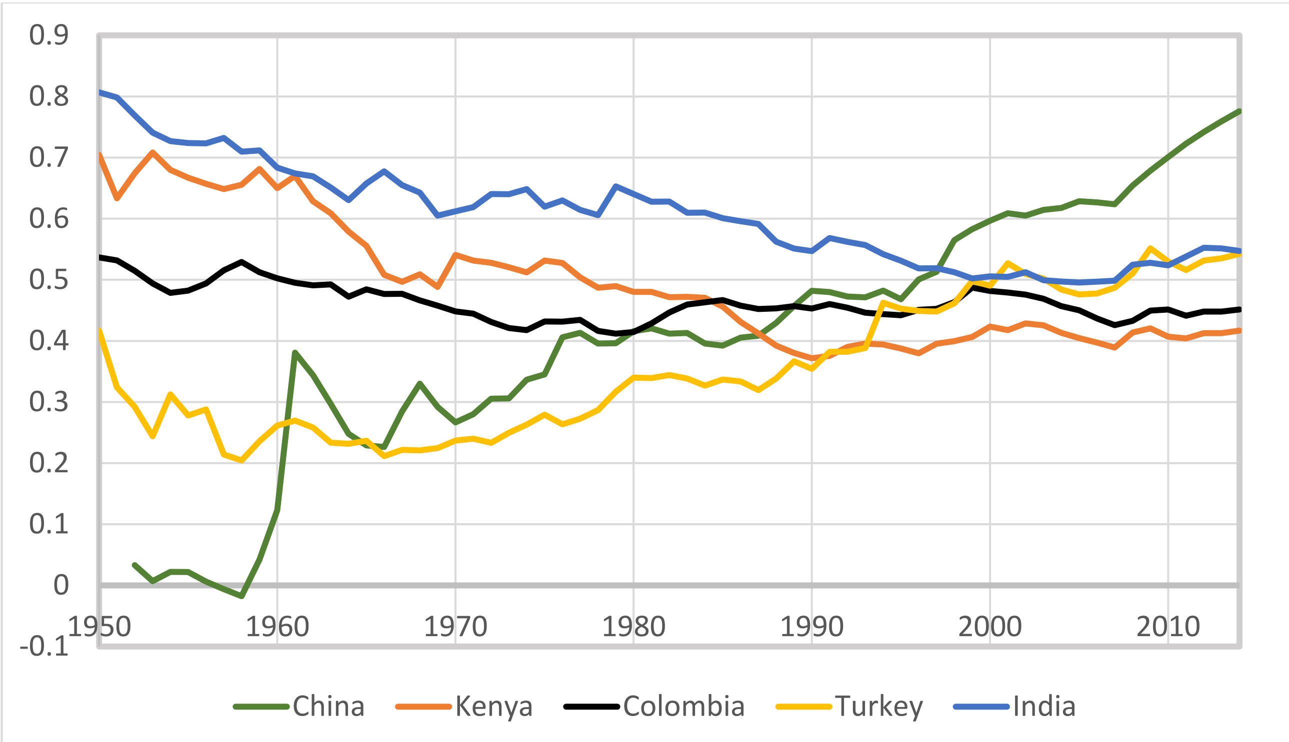

Figure 2: Efficiency Output per Worker for Five less Developed Countries

3. Convergence of Efficiency Output per Worker

As Figures 1 and 2 show, the efficiency of output per worker for each country tends to converge to a long-run level. We next explain why this convergence is theoretically justified by capital accumulation. First note that efficiency output per worker can be written as follows:

(6) $$y^E(j,t) = \frac{Y(j,t)}{L(j,t)A(j,t)} = G\left[\frac{K(j,t)}{L(j,t)A(j,t)},1\right].$$

Note that the variable K/AL is equal to the ratio between the capital-labor ratio and productivity, so we call it in a similar way the 'efficiency capital-labor ratio' and denote it by k^E. We can therefore write the efficiency output per worker as dependent on the efficiency capital-labor ratio:

(7) $$y^E(j,t) = G\left[k^E(j,t),1\right].$$

The accumulation of capital is driven, in the Neoclassical Growth Model, by discrepancy between profitability, namely the marginal productivity of capital, and the cost of capital, which is usually the sum of the interest rate and the rate of depreciation. In the long-run, the marginal productivity of capital should be equal to the long-run cost of capital, which is constant in all standard growth models. It holds in a closed economy, where the cost of capital in the long-run should equal the subjective discount rate plus the depreciation rate, ρ + *dep*. It holds in an open economy as well, where it should be equal to the global interest rate plus the depreciation rate, r^* + *dep*.[7] Note that the marginal productivity of capital is:

$$MPK(j,t) = G_K\left[K(j,t), A(j,t)L(j,t)\right] = G_K\left[\frac{K(j,t)}{A(j,t)L(j,t)},1\right] = G_K\left[k^E(j,t),1\right].$$

Hence, in the long-run, the efficiency capital-labor ratio k^E should be constant as well, at a level denoted by $k^E(j,\infty)$. If capital accumulation is gradual, the efficiency capital-labor ratio converges gradually to its long-run value:

(8) $$k^E(j,t) \xrightarrow[t\to\infty]{} k^E(j,\infty).$$

There are two possible mechanisms that can explain why capital adjustment should be gradual and not immediate. One holds in a closed economy, where capital accumulation is bounded by savings.[8] An alternative explanation is adjustment costs to investment, and this mechanism works in open economies as well, where investment can exceed savings. This mechanism is presented in Appendix 2. Actually, we think that the open economy model is better suited to compare economic growth across countries.

From equations (7) and (8), it follows that the efficiency output per worker should also converge to its long-run value, which is denoted by $y^E(j,\infty)$, due to continuity of *G*:

(9) $$y^E(j,t) = G[k^E(j,t),1] \xrightarrow[t\to\infty]{} G[k^E(j,\infty),1] = y^E(j,\infty).$$

The period to period dynamics of this convergence of efficiency output per worker can be described by the following log-linear approximation, as done in DJT:[9]

(10) $$\ln y^E(j,t) - \ln y^E(j,t-1) = b(j)\ln y^E(j,\infty) - b(j)\ln y^E(j,t-1).$$

The parameter $b(j)$ measures the rate of convergence of efficiency output per worker to its long-run value. Note, that with the data in PWT 9.0 we can estimate equation (10) directly, as we have data on the variable y^E, namely on efficiency output per worker. This is done in Section 4.

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[7] More precisely, in an adjustment cost model the long-run marginal productivity of capital should depend also on the rates of growth of productivity and population, as shown in Appendix 2 and as supported by our empirical analysis below. But marginal productivity of capital of a country still converges to some constant level.

[8] This was the main assumption used in growth regressions, by Mankiw, Romer and Weil (1992) Barro and Sala-i-Martin (1992) and many others who followed them.

[9] Equation (10) is the same as equation (1) in DJT, except for approximating 1 – exp(-*b*) by *b*.

Clearly, equation (10) is very similar to the basic β-convergence equation, except that instead of output per worker y, equation (10) describes the dynamics of the efficiency output per worker y^E. Note that equation (10) is more deeply related to tests of β-convergence, as they can be explained by it, as shown in DJT. If we use the definition of efficiency output per worker in equation (5), substitute it in equation (10) and calculate the average growth rate of country j over T periods, we get the following equation:[10]

$$\begin{aligned} \frac{\ln y(j,T)-\ln y(j,0)}{T} &= \frac{\ln A(j,T)-\ln A(j,0)}{T}+\frac{1-[1-b(j)]^T}{T}\ln A(j,0)+ \\ &+\frac{1-[1-b(j)]^T}{T}\ln y^E(j,\infty)-\frac{1-[1-b(j)]^T}{T}\ln y(j,0). \end{aligned} \tag{11}$$

Standard tests of β-Convergence estimate such an equation, but without observing the productivity A. Such regressions derive b from the regression coefficient of the initial output per worker, $\ln y(j,0)$, assuming that b is equal across countries.[11] Note that in these regressions initial productivity $A(j,0)$, the average rate of growth of productivity $T^{-1}\left[\ln A(j,T)-\ln A(j,0)\right]$ and $y^E(j,\infty)$ are unobserved. To overcome this problem such regressions use additional variables to control for these missing variables, which are usually called 'explanatory variables.' This is the standard structure of β-Convergence tests. Unlike these tests, we can estimate equation (10) directly by use of the new data and without any control variables. This is done in the next section.

4. Empirical Testing of Convergence of Efficiency Output per Worker

4.1 Convergence of Efficiency Output per Worker in Annual Data

We next turn to test empirically the dynamic equation (10). We estimate it over all the countries in the sample and over the years 1970-2014. Note that equation (10) has one unobserved variable, long run efficiency output per worker, $y^E(j,\infty)$, which is part of the constant. Hence, the constant might differ across countries, as can already be inferred from Figure 2. This is a country-specific variable that does not change over time. We cope with this unobserved variable in two ways. One is by adding country fixed effects to the regression and the other is by adding a variable that is supposed to negatively affect the long-run efficiency output per worker. This variable is the average rate of growth of LATFP over

[10] It is equivalent to equation (8) in DJT.
[11] A non-parametric study that differs with this assumption is Henderson (2010).

the entire period. The reason is that if productivity rises more rapidly, capital has to be adjusted at a higher rate and as a result it has a lower steady state level.[12] Table 1 presents the results of the various regressions of equation (10), where the estimated *b* is the coefficient of lagged lny^E.[13]

Dependent Variable: Difference of ln(y^E)						
Coefficient	**(1) Pooled Het. b**	**(2) Pooled Het. b**	**(3) Panel Het. b**	**(4) Panel Het. b**	**(5) Panel Same b**	**(6) Panel Same b**
Lagged ln(y^E)	-0.007** (0.003)	-0.018*** (0.002)	-0.050*** (0.006)	-0.052*** (0.005)	-0.039*** (0.004)	-0.037*** (0.003)
Constant	0.021*** (0.004)	0.017*** (0.001)	0.052*** (0.006)	0.038*** (0.003)	0.053*** (0.004)	0.027*** (0.002)
gA	-0.740*** (0.165)	-0.182*** (0.046)				
Country FE	N	N	Y	Y	Y	Y
R^2	0.044	0.037				
R^2 within					0.032	0.029
Output-Labor Elasticity	Labor Share	Constant	Labor Share	Constant	Labor Share	Constant
Observations	3564	4532	3564	4532	3564	4532
Countries	81	103	81	103	81	103

Table 1: Growth Regressions of Efficiency Output per Worker in Annual Data

Columns (1) and (2) in Table 1 present the results of pooled regressions, where the variable gA, the average rate of growth of productivity *A*, is used to control for the long-run efficiency output per worker. Regression (1) uses the annual labor share to calculate LATFP, while regression (2) uses a constant 2/3 to calculate it. The results of both regressions are similar, gA is significantly negative as expected and the coefficient *b* is highly significant. The reported coefficients are of course the average across countries. This coefficient is more significant in regression (2), where it is close to 2 percent, very close to the famous 'Iron Law' of Barro (2012). Regressions (3) and (4) present the results of a panel estimation with country fixed effects, where regression (3) uses annual labor share for the calculation of productivity and regression (4) uses the constant 2/3. The coefficients of convergence *b* are estimated for each country separately and their average in the two regressions is 0.05, which is significantly higher than 0. The results of regressions (3) and (4) are quite similar. We

[12] See Appendix 2 for a formal discussion in an adjustment costs model.
[13] In all the regressions' results in Table 1, as in all the other tables in the paper, standard errors are in the parenthesis and significance is denoted by * for 10 percent, ** for 5 percent and *** for 1 percent.

also observe in the two regressions that the *b* coefficients are quite similar across countries and across regions. For example, their average across OECD countries is 0.05, their average across Latin American countries is 0.076, their average across Sub Saharan African countries is 0.04, in East Asia it is 0.037, in MENA it is 0.049, and in East European countries it is 0.033. Due to this finding, we assume in the following regressions that *b* is uniform across countries.

Regressions (5) and (6) in Table 1 are panel regressions with country fixed effects that assume that *b* is uniform across countries. The first regression is run for productivity calculated with the annual share of labor and the second for a constant output-labor elasticity. The results of both regressions are similar, as both show that the efficiency output per worker converges to a long run value. The measured rate of convergence differs slightly between the two regressions, as it is 5 percent in when productivity is calculated by use of share of labor and 3 percent when it is calculated using a constant elasticity. Note that in the panel regressions the measured rate of convergence is higher than in the pooled one. This is not surprising and it has been noticed by many that adding country fixed effects to dynamic regressions tends to raise the measured rate of convergence. But this could also be a result of using annual non-smoothed data in Table 1, as the estimated coefficient *b* might reflect not only long-run dynamics of output, but also short-run cyclical dynamics. Hence, we turn in the next subsection to estimate the same regressions for smoothed data.

4.2 Convergence of Efficiency Output per Worker in Smoothed Data

In Table 2 we repeat the regressions of Table 1, but instead of using annual data of efficiency output per worker, we use five years averages of the natural logarithms of efficiency output per worker. The regressions in Table 2 yield similar results to those in Table 1, except that the values of *b* are lower for panel regressions and they are close to 0.02. Hence, the estimated rate of convergence of efficiency output per worker is very close to the estimated rate of β-convergence in many studies. Note, that the data for Table 2 is smoothed but we use it in annual frequency and the coefficient *b* is for the one period lag of the smoothed variable. We have also estimated the regression for lower frequency, of five years, which avoids overlap, the coefficient is estimated from a five year lag and the results are similar.

Dependent Variable: Difference of ln(y^E)						
Coefficient	**(1) Pooled**	**(2) Pooled**	**(3) Panel**	**(4) Panel**	**(5) Panel**	**(6) Panel**

	Het. b	**Het. b**	**Het. b**	**Het. b**	**Same b**	**Same b**
Lagged ln(y^E)	-0.0003 (0.006)	-0.013*** (0.001)	-0.018*** (0.004)	-0.024*** (0.004)	-0.036*** (0.003)	-0.016*** (0.002)
Constant	0.017** (0.008)	0.014*** (0.001)	0.021*** (0.003)	0.020*** (0.003)	0.053*** (0.004)	0.014*** (0.001)
gA	-0.644*** (0.213)	-0.162*** (0.021)				
Country FE	N	N	Y	Y	Y	Y
R^2	0.047	0.074				
R^2 within					0.042	0.020
Output-Labor Elasticity	Labor Share	Constant	Labor Share	Constant	Labor Share	Constant
Observations	3652	4532	3564	4532	3564	4532
Countries	81	103	81	103	81	103

Table 2: Growth Regressions of Efficiency Output per Worker in Smoothed Data

4.3 Convergence of Output per Worker to Productivity

Equation (10) describes the dynamics of the efficiency output per worker. Substituting equation (5) that defines efficiency output per worker as the ratio between output per worker and productivity, we derive the following dynamic equation, which describes how output per worker follows productivity:

$$\begin{aligned} &\ln y(j,t) - \ln A(j,t) - \ln y^E(j,\infty) = \\ &= [1-b(j)]\left[\ln y(j,t-1) - \ln A(j,t-1) - \ln y^E(j,\infty)\right]. \end{aligned} \tag{12}$$

Equation (12) means that output per worker, in logarithm, converges to the dynamic path of productivity, more precisely to: $\ln A(j,t) + \ln y^E(j,\infty)$. Empirically, equation (12) states that the logarithm of output per worker in each country should be cointegrated with $\ln A(j,t)$, where the coefficient of cointegration should be equal to 1, the error correction coefficient should be equal to $b(j)$ and the long-run distance between logarithms of output per worker and productivity should be $\ln y^E(j,\infty)$. Therefore, our next step is to run a cointegration test of $\ln y(j,t)$ over $\ln A(j,t)$ and measure the coefficient of cointegration and the coefficient $b(j)$. Note that this regression does not require any information or assumption on the long-run efficiency output per worker. Actually, it can be measured from the cointegration test, though we do not report it here.

We estimate the dynamic equation (12) by running a panel cointegration test of output per worker on LATFP. We estimate cointegration and error correction equations by use of the Pesaran and Smith (1995, 1996) procedures. More specifically, we use MG, the mean group estimator, which allows for heterogeneous coefficients for every country. The results of the cointegration estimation are presented in Table 3. Some regressions estimate it for the larger set of countries, over the period 1970-2014, and some for a smaller set of countries, over a longer period 1950-2014. The numbers of countries in each group differ when we calculate productivity by labor share or by a constant, due to missing data in some countries. In the estimation for Table 3 we use smoothed data, as in Table 2. In the cointegration test of the larger set of countries, for the period 1970-2014, we eliminated 3 outliers (Ecuador, Italy and Japan) for productivity calculated by labor share, and 2 outliers (Japan and Uganda) for productivity calculated by a constant elasticity. Outliers were countries with cointegration coefficient above 10 or below -10.

Coefficient	**(1)**	**(2)**	**(3)**	**(4)**
Co-integration Coefficient	0.809*** (0.168)	0.829*** (0.228)	0.915*** (0.060)	1.036*** (0.061)
Probability of Failure to Reject Coeff. = 1	0.25	0.45	0.16	0.56
b	0.024*** (0.003)	0.016*** (0.002)	0.027*** (0.006)	0.017*** (0.002)
Output-Labor Elasticity	Labor Share	Labor Share	Constant	Constant
Period	1970-2014	1950-2014	1970-2014	1950-2014
No. of Countries	80	46	101	50

Table 3: Cointegration Estimation of the Convergence of Output to LATFP

The results of Table 3 fit the results of Table 2 and add empirical support to the assumption that efficiency output per worker converges to a long-run value. Table 3 shows that output per worker follows the long-run path of productivity for each country. First, in all four regressions, the co-integration coefficient is 1 or close to 1 as expected by equation (12). The probability of failure to reject the null hypothesis that the coefficient is equal to 1 is higher than 0.05 in all four regressions. The coefficient *b*, which is the error correction coefficient, is close to 0.02 in all four regressions and that fits the results of Table 2 as well.

Importantly, the rates of convergence of output *b* and of the cointegration coefficients are estimated separately for each country, but their values are quite close. The following figures give an idea on the concentration of the results across countries. For instance, the value of the coefficient of cointegration is between 0.5 and 1.5 for 80 countries out of 103 for productivity calculated with constant elasticity over 1970-2014.[14] In the estimation of the smaller sample over 1950-2014 with the

[14] Since the MG estimator is unconstrained, even 1 or 2 outliers may strongly affect the average coefficient and the standard errors, as noted by Eberhardt and Teal (2013). We have only 3 extreme values in the 1970-2014 sample and report the

same elasticity, the coefficient of cointegration is between 0.5 and 1.5 for 42 countries out of 50. The results with respect to *b* are also concentrated. In the estimation of the larger sample, *b* is between 1 and 4 percent for 52 countries out of 103. Concentration of *b* is even higher in the estimation over the smaller sample, where *b* is between 1 and 4 percent for 30 countries out of 50. We obtain very similar results when using productivity calculated by variable labor share. These results therefore support the assumption made in many empirical studies, that *b* is similar for all countries.

4.4. Implications for Tests of β-Convergence

This section supplies strong empirical direct support to the assumption of DJT that efficiency output per worker converges to a long run level. We do not need to run standard growth regressions and use various explanatory variable, as we use data on total factor productivity instead. This direct empirical support for the assumption of convergence of efficiency output per worker has a very important implication. It shows that this convergence should not be interpreted as evidence of convergence of one country to another. It only implies that output converges to its own productivity path, while these country productivity paths can either converge or diverge across countries, and we show in the next section that they diverge for many countries. Since the rate of convergence of output to productivity is around 2 percent, which is similar to the rate found in many β-convergence studies, and since the two rates are related, as DJT derive equation (11) from equation (10), it further strengthens the conclusiotn that these β-convergence studies cannot actually infer any convergence of output across countries.

5. Divergence of Productivity from the Global Frontier

If output per capita in each country follows productivity, then the question of convergence or divergence between countries boils down to whether the levels of productivity tend to converge or diverge from one another. We try to examine it by measuring by how much productivity in each country follows the global frontier. For that we need to identify the global frontier. While at the early stages of the industrial revolution, England led economic growth, in the second half of the 19th century the US took over and has remained the leader of global economic growth ever since. Hence, we measure by how much productivity of each country is following the productivity of the US. For that

results without them, and no extreme values in the 1950-2014 sample. We tried two robustness checks. First, we applied the pooled mean group estimator assuming that the coefficient of cointegration is uniform across countries, for the case of 1970-2014 with constant elasticity and it came out 0.94. Second, we computed the median of MG estimation coefficients and it is equal to 0.90.

we run cointegration tests of LATFP of each country versus the LATFP of the US. Such tests of are called by DJT and others 'time series tests' and were applied so far only to output per worker or per capita. We apply them here to time series of total factor productivity and for a large set of countries.

Such a cointegration regression tests the following relationship between the productivity of country *j* and the global frontier:

(13) $$\ln A(j,t) - d(j)\ln A(US,t) - a(j) = [1 - c(j)][\ln A(j,t-1) - d(j)\ln A(US,t-1) - a(j)].$$

The coefficient *d*(*j*) is the cointegration coefficient between country *j* and the US. It means that over time the country follows only *d* of the annual growth of the US. Hence, if the cointegration coefficient is equal to 1, the country follows the frontier fully, though it might follow it with a lag. Such a lag is captured by the constant *a*(*j*), which describes only a level difference from the frontier, but not a difference in the rates of growth. If the cointegration coefficient is lower than 1, it means that country *j* lags progressively behind the frontier and is actually diverging away from it. In this case its rate of growth is on average lower than that of the US and is actually *d* times its rate of growth. Hence, the cointegration coefficient can actually tell us whether a country follows the frontier or diverges away from it. In our estimations we find that for a few countries the coefficient of cointegration is higher than 1, which occurs when a country is catching up with the frontier during the period of the estimation. This is a problem discussed already in DJT. We deal with these cases below.

The coefficient *c* is the error correction coefficient. If the long-run growth path of productivity in country *j* is $a(j) + d(j)\ln A(US,t)$, then *c* measures how fast productivity is converging to this long-run path, if the country is below or above the path. This is therefore a coefficient similar to *b*, but it measures the country's rate of adjustment of its productivity, namely of its technology or of its human capital, and not of its adjustment of capital, which is measured by *b*. This coefficient does not indicate how the country is doing relative to other countries or relative to the frontier. The state of a country relative to the frontier is described only by the coefficient *d* with respect to the growth rate, and by the coefficient *a*, with respect to the level of productivity.

5.1. Results for Productivity Calculated by Constant Elasticity

Table 4 describes the results of the cointegration tests for the countries in the sample of 1970-2014 when LATFP is calculated by assuming that the elasticity η_L is constant and equal to 2/3. Since this sample includes 103 countries and the US is one of them, the number of countries in the cointegration test is 102. Regression (1) presents the average results for the whole panel. It covers 99 countries, as we exclude from Table 4 three outliers, Egypt, Kuwait and Qatar. We also examine the average results for sub-samples of various regions. Regression (2) presents the results for the OECD countries, where we moved three countries, Mexico, Turkey and South Korea, to their respective geographic regions. Regression (3) presents the results for East Asia, while regression (4) describes Central and South American countries. Regression (5) presents average results for Sub-Saharan African countries and regression (6) for Middle Eastern and North African countries. Regression (7) presents the results of the cointegration test for Eastern European countries.

Coefficient	**1970-2014 (1)**	**OECD (2)**	**EA (3)**	**CSA (4)**	**SSA (5)**	**MENA (6)**	**EE (7)**
d	0.313* (0.174)	0.423** (0.202)	1.483*** (0.224)	-0.121 (0.158)	0.303 (0.537)	0.761 (1.646)	0.917*** (0.189)
c	0.070*** (0.005)	0.081*** (0.024)	0.066*** (0.010)	0.080*** (0.007)	0.042*** (0.009)	0.077*** (0.012)	0.068*** (0.017)
Test *d* = 1	(0.000)	(0.000)	(0.000)	(0.000)	(0.195)	(0.88)	(0.662)
Countries	99	23	16	20	21	15	5

Table 4: Cointegration of Productivity over US Productivity Calculated with Constant Elasticity

The results of Table 4 show significant divergence of countries from the global frontier, namely from the US, as *d* is significantly lower than 1. Table 4 also shows that there is a regional pattern for following the frontier. For all regions except East Asia and Eastern Europe the coefficient *d* is below 1. Furthermore, for the Latin American countries, Sub Saharan African countries and MENA, this coefficient is not significantly different from 0, namely they do not follow most of the progress of the global frontier. Interestingly, the error correction coefficient, which measures catching up with long-run productivity growth, is around 8 percent, namely higher than *b*. Hence, the speed of catching up with technology and with human capital is faster than the speed of catching up with physical capital. Interestingly, this coefficient is quite similar across the global regions, despite differences in *d*.

Table 4 also shows that the value of *d* for East Asia is above 1. This is caused by the famous Asian Tigers: Hong Kong, South Korea, Singapore, Taiwan and recently China. These countries went through rapid ‘catch up’ processes over much of the period. Since this process might involve a gradual rise of the coefficient *a* from equation (13) in such countries, it might bias the estimation of *d* upwards. We therefore treat the high values of *d* in this region with some caution. This problem of a biased coefficient in time series tests, due to convergence to the long-run path, is already discussed in DJT. Note that our estimations do not constrain the coefficient *d* to be between 0 and 1 as implied by economic intuition. The main reason is to avoid possible misspecification in the estimation of (13). We therefore follow Eberhardt and Teal (2013), who claim that unconstrained heterogeneous estimation is preferred, since it reduces bias of average estimates, where the noise created by misspecification at the country-level is filtered out.

5.2. Results for Productivity Calculated by Share of Labor

While in Table 4 productivity is calculated by assuming a constant elasticity of output to labor, Table 5 presents the results of the same regressions for productivity calculated by use of labor share. The sample has less countries due to missing data on labor share and we also omit from the average four outliers. The results of Table 5 are quite similar to those of Table 4, especially the coefficient of catching up with long-run productivity growth path, which is around 8 percent as in Table 4. Both tables show that many countries diverge from the global frontier, especially in Sub-Sahara, in Central and South America and in MENA.

Coefficient	**1970-2014 (1)**	**OECD (2)**	**EA (3)**	**CSA (4)**	**SSA (5)**	**MENA (6)**	**EE (7)**
d	0.201 (0.159)	0.582*** (0.116)	1.587*** (0.219)	-0.092 (0.118)	-0.184 (0.426)	-0.970 (0.739)	0.435 (0.448)
c	0.081*** (0.006)	0.087*** (0.011)	0.082*** (0.014)	0.088*** (0.009)	0.057*** (0.013)	0.083*** (0.020)	0.066*** (0.016)
Test d = 1	(0.000)	(0.000)	(0.007)	(0.000)	(0.005)	(0.460)	(0.207)
Countries	78	23	10	18	11	12	4

Table 5: Cointegration of Productivity over US Productivity Calculated with Labor Share

5.3. Estimation of Productivity without the Crisis Years

Both Table 4 and Table 5 present the results for the period 1970-2014. Since 2008 the world experiences significant economic downturn, which is called the Great Recession. This economic downturn has a significant effect on the dynamics of output and productivity, which might bias the estimation of long-run growth parameters. Furthermore, the recession hit many countries outside the US worse than the US, especially European countries. Hence, a cointegration test of such countries on the US might be further biased by the recession. One way to avoid this short-run effect is to remove the recession years from the estimation. This is what is done below.

Table 6 presents the results of the cointegration tests of LATFP of 98 countries on LATFP of the US. The productivity LATFP is calculated by assuming that the elasticity of output with respect to labor is constant and equal to 2/3. The results are in general similar to the results of Table 4, but the estimated coefficients happen to be more significant. Also, the test that *d* is 1 is rejected more significantly for the Mena countries. The average coefficient *d* across the whole sample is higher in Table 7, 0.37 compared with 0.31 in Table 4, but both are significantly lower than 1. The values of *d* in the various regions are similar in the two regressions, but higher for the OECD countries. We assume that it reflects the slow recovery of the European countries and Japan from the Great Recession. The average value of the coefficient *c* is 8 percent in Table 6, while it is only 0.7 in Table 4. We consider the results of Table 6 to be more representative of the long-run divergence than the results of Table 4.

Coefficient	**1970-2008 (1)**	**OECD (2)**	**EA (3)**	**CSA (4)**	**SSA (5)**	**MENA (6)**	**EE (7)**
d	0.367*** (0.137)	0.570*** (0.138)	1.534*** (0.155)	-0.163 (0.158)	0.199 (0.462)	-0.431 (0.442)	0.973 *** (0.188)
c	0.078*** (0.006)	0.086*** (0.013)	0.092*** (0.018)	0.086*** (0.007)	0.052*** (0.014)	0.075*** (0.012)	0.068*** (0.020)
Test *d*=1	21.30 (0.000)	9.68 (0.002)	11.94 (0.001)	53.87 (0.000)	3.00 (0.083)	10.48 (0.001)	0.02 (0.885)
Countries	98	23	16	20	18	16	5

Table 6: Cointegration of Productivity on US Productivity over the period 1970-2008

The results on the coefficient of divergence *d*, that happens to be significantly lower than 1 for many countries, are an important result of the paper. They show that there is significant divergence of output across countries. Figure 3 provides additional support to our claim that the coefficient *d* is indeed indicative of divergence. This figure plots a scatter of countries with *d* on the horizontal axis and the average rate of growth of productivity, *gA*, over the period 1970-2008 on the vertical axis. As Figure 3 shows, the two variables are positively correlated. This means that countries with high *d* tend to grow faster than countries with low *d*. This supplies an additional motivation to our focusing on this parameter and its importance for understanding the growth dynamics of countries over time.

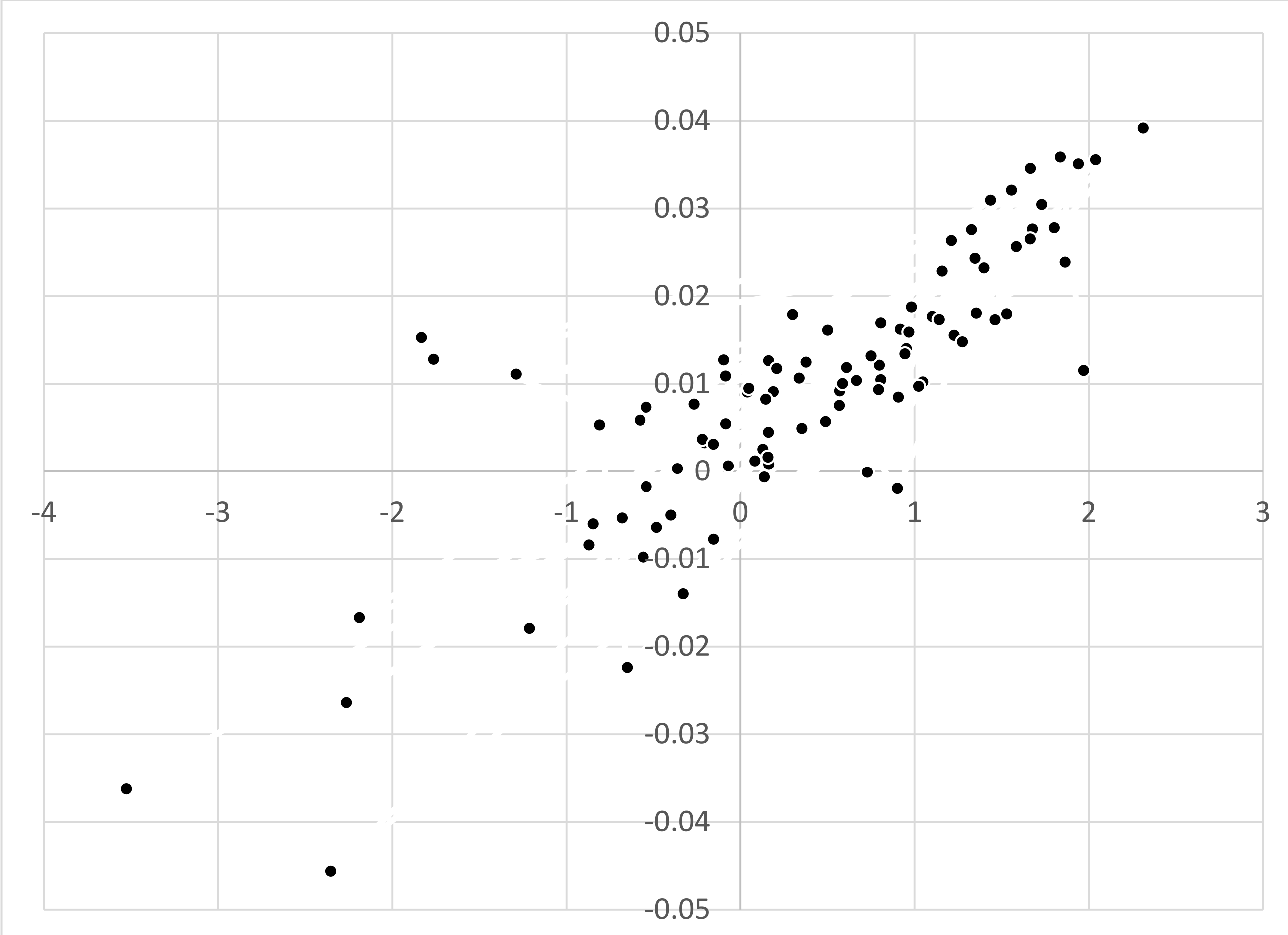

Figure 3: A Scatter Diagram of *d* vs. *gA*

6. Divergence of Output per Worker from the Global Frontier

If output per worker converges to productivity and if productivity in a country diverges away from the global frontier, then output per worker in that country should diverge from the global frontier as well. Formally, we derive from equations (10) and (13) the following dynamic relationship:

(14) $$\ln y(j,t) - d(j)\ln y(US,t) - a(j) - \ln y^E(j,\infty) + d(j)\ln y^E(US,\infty) \xrightarrow[t\to\infty]{} 0.$$

Equation (14) implies that output per worker $\ln y(j,t)$ and output per worker of the US should be cointegrated. The coefficient of cointegration should be $d(j)$, the same rate of divergence between productivity and the US productivity. Hence, a cointegration test of output per worker over the global frontier, can be an additional test to the coefficient *d*. Note that estimating (14) does not enable us to identify the rates of convergence *b* and *c*, since the error correction coefficient of (14) should be some average of these two. Table 7 presents the results of such tests.

Coefficient	**1970-2014 (1)**	**OECD (2)**	**EA (3)**	**CSA (4)**	**SSA (5)**	**MENA (6)**	**EE (7)**
d	0.667*** (0.111)	0.668*** (0.087)	2.082*** (0.261)	0.281** (0.115)	0.164 (0.258)	-0.006 (0.282)	1.728*** (0.158)
EC	0.068*** (0.004)	0.066*** (0.012)	0.050*** (0.007)	0.081*** (0.006)	0.062*** (0.011)	0.076*** (0.012)	0.067*** (0.012)
Test *d* = 1	(0.003)	(0.000)	(0.000)	(0.000)	(0.001)	(0.000)	(0.000)
Countries	98	22	16	21	18	16	6

Table 7: Cointegration Test of Output per Worker over the US Output per Worker

The results of Table 7 are reinforcing our conclusion above, that there is divergence between many countries and the US. The average *d* is significantly lower than 1 for most countries, except for the East Asian and the East European countries. These countries are in a period of catching up with the global frontier and hence their *d* reflects this rapid catching up rather than a steady state behavior. Note, that the coefficient *d* in this Table is higher than in Tables 4 and 5, but it is still much lower than 1. Note also that the error correction coefficient is close to 6%, which is somewhere between the previously measured sizes of *b* and *c*, namely between 2% and 8%.

Table 8 presents the results of the cointegration of output per worker on the US output per worker for the period 1970-2008, without the period of the Great Recession. The results of Table 8 are very similar to the results of Table 7. Unlike the comparison between Table 4 and 6, the coefficient *d* in Table 8 is slightly lower than the same coefficient over the longer period, which includes the years of the Great Recession.

Coefficient	**1970-2008 (1)**	**OECD (2)**	**EA (3)**	**CSA (4)**	**SSA (5)**	**MENA (6)**	**EE (7)**
d	0.566^{***} (0.147)	0.587^{***} (0.153)	2.090^{***} (0.256)	0.235^{*} (0.126)	-0.196 (0.453)	-0.066 (0.415)	1.829^{***} (0.148)
EC	0.071^{***} (0.005)	0.060^{***} (0.012)	0.074^{***} (0.016)	0.086^{***} (0.007)	0.067^{***} (0.014)	0.072^{***} (0.011)	0.066^{***} (0.020)
TEST *d*=1	8.70 (0.003)	7.29 (0.007)	18.19 (0.000)	36.97 (0.000)	6.97 (0.008)	6.61 (0.010)	31.35 (0.000)
Countries	99	23	16	20	19	16	5

Table 8: Cointegration of Output per Worker on US Output per Worker over the period 1970-2008

7. Divergence of Technology and Convergence of Human Capital

This paper introduces data on productivity, made available by new versions of PWT, in order to examine convergence and divergence across countries. Productivity changes over time and these changes are results of two changes. One is accumulation of human capital, as education systems develop and absorb larger shares of the population. The second is adoption of technologies from the global frontier, or technologies that were invented in the past and reach the country only at the present. The new method of 'development accounting' enables us to split total factor productivity into these two components, accumulation of human capital and technical change. Using data on education attainment from Barro and Lee (2010), and the studies on the effect of education on wages, as described in Caselli (2005), we can derive a time series of human capital for many countries. Since data on education attainment at 5 years frequency in Barro and Lee (2010), we complete it to annual data by interpolation. Denote the average human capital in country j in period t by $h(j,t)$. Assume that productivity LATFP is a multiple of technology and human capital:

$$A(j,t) = T(j,t) \cdot h(j,t).$$

Hence, we can also calculate the level of technology in a country as the following residual:

$$\ln T(j,t) = \ln A(j,t) - \ln h(j,t). \tag{15}$$

We next turn to examine the dynamics of the two variables. Assume first that human capital accumulation is gradual in each country, due to the need to build and expand systems of education. Since human capital in the long run should be bounded, by some maximum years of schooling, the adjustment of human capital is assumed to follow the standard convergence to a constant:

$$\ln h(j,t) - \ln h(j) = \left[1 - e(j)\right]\left[\ln h(j,t-1) - \ln h(j)\right]. \tag{16}$$

Here, $h(j)$ is the long run level of human capital and $e(j)$ is the rate of convergence of human capital. As the long-run level of human capital is unknown, we estimate a difference version of equation (16):

$$\ln h(j,t) - \ln h(j,t-1) = \left[1 - e(j)\right]\left[\ln h(j,t-1) - \ln h(j,t-2)\right]. \tag{17}$$

Table 9 presents the results of the estimation of human capital over the years 1970-2010. The data is taken from Barro and Lee (2010), where we use the average years of schooling for the age group 15-64 as our measure and apply the method of Caselli (2005) to calculate the level of human capital from such data. We use four different estimations, Fixed Effects, Arellano-Bond, Kiviet, and Pesaran-Smith. We use the fixed effects estimation to account for differences in the constants across countries, although the constant should be zero according to (17). We then apply Pesaran-Smith estimation to account for the possibility that the coefficient $1 - e$ is not uniform across countries. The results show that it is quite equal across countries. We use this estimation to calculate the regional averages as well. In this case of human capital we also add the Arellano-Bond and the Kiviet corrected estimation as two alternative solutions for the Nickell (1981) bias problem.

Coefficient	**Full Sample**				**OECD**	**EA**	**CSA**	**SSA**	**MENA & EE**
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**	**(9)**
$1 - e$	$.872^{***}$ (.008)	$.850^{***}$ (.012)	$.921^{***}$ (.011)	$.820^{***}$ (.028)	$.868^{***}$ (.014)	$.771^{***}$ (.081)	$.880^{***}$ (.018)	$.621^{***}$ (.132)	$.899^{***}$ (.018)
Test: e=0	(.000)	(.000)	(.000)	(.000)	(.000)	(.005)	(.000)	(.004)	(.000)
Countries	96	96	96	96	24	16	19	16	21
Method	F.E.	A-B	Kiviet	P-S	P-S	P-S	P-S	P-S	P-S

1. Standard errors in parenthesis.
2. Estimations are: F.E. – fixed effects, A.B. – Arellano-Bond, Kiviet corrected, and P-S – Pesaran-Smith.

Table 9: Convergence of Human Capital to a Long-Run Target

The results of all four estimators are quite similar. All tests show that human capital converges to some long-run target and the rate of convergence of human capital is quite high, around 15 percent. It is much higher than the rate of convergence of physical capital and is even higher than the rate of convergence of productivity. The rate of convergence of human capital is similar across regions, except that it is higher in South Saharan Africa and in Eastern Asia. This might reflect the rapid growth of public education in these countries in recent decades.

If the human capital is converging to a constant, and productivity A is following the global frontier at a long-run rate d, as shown above, then we can deduce that technology follows the global frontier at a rate d as well. We therefore examine this by estimating a cointegration regression of the level of technology of each country on the level of technology of the US. These regressions are presented in Tables 10 and 11. While Table 10 is based on calculation of productivity by assuming a constant output labor elasticity, Table 11 is based on assuming that the elasticity is the labor share. The cointegration regressions in Table 10 supports the main results of Tables 4 to 8. According to Table 10 many countries do not converge to the global technology frontier. Actually, Table 10 presents an even grimmer picture than the tests on productivity or on output per worker. The average *d* over all the sample is close to 0 and insignificant. Furthermore, it is significantly negative for Central and South America and for the MENA countries. It is insignificant for all the other regions, namely OECD, East Asia, Eastern Europe and Sub Saharan Africa.

Coefficient	**1970-2010 (1)**	**OECD (2)**	**EA (3)**	**CSA (4)**	**SSA (5)**	**MENA (6)**	**EE (7)**
d	-0.079 (0.170)	0.216 (0.137)	1.072 (0.344)	-0.721*** (0.207)	0.120 (0.489)	-1.442** (0.595)	0.786 (0.478)
EC	0.079*** (0.006)	0.092*** (0.014)	0.074*** (0.012)	0.092*** (0.011)	0.052*** (0.012)	0.083*** (0.016)	0.067*** (0.017)
Test $d = 1$	0.000	0.000	0.835	0.000	0.070	0.000	0.654
Countries	94	23	16	19	16	15	5

Table 10: Cointegration Test of Technology over Global Technology with Constant Elasticity

These results seem to be quite exaggerated and the reason for that is that our measure of technology, *T*, might be biased downward for many developing countries. The reason for that is that our measure of human capital is based on years of schooling, adjusted to human capital by use of returns to education, as done in all ‘development accounting’ studies and as summarized in Caselli (2005). But such a calculation assumes that all those who acquired education find jobs that fit their skills, while this is not the case in many countries. There has been rapid spread of education in recent decades in many countries and many of those who graduated do not necessarily find jobs and are either unemployed or have to compromise on jobs of much lower quality. This has not been the case at the US, where accumulation of education attainment has slowed down in recent decades and the newly educated found jobs that fit their human capital. Hence, our measure of human capital is probably higher than the real one in developing countries, while it is not so in the US. As a result, our measure of technology is lower than the real one in developing countries. That explains why the estimated values of *d* in Table 10 are much lower than in Tables 4 to 8. Table 11 reaches similar results when the calculation of productivity and technology uses labor shares instead of a constant output-labor elasticity. Interestingly in both Tables 10 and 11 the error correction coefficient is between 8 and 9 percent, which is similar to the other estimations. Hence, the rate of convergence of technology to its long-run path is quite robust and is not affected by the faster convergence of human capital.

Coefficient	1970-2010 (1)	OECD (2)	EA (3)	CSA (4)	SSA (5)	MENA (6)	EE (7)
d	-0.264 (0.213)	0.248* (0.136)	1.123*** (0.333)	-0.786*** (0.178)	0.048 (0.348)	-1.931* (1.090)	-0.105 (0.586)
EC	0.095*** (0.006)	0.100*** (0.011)	0.096*** (0.016)	0.101*** (0.013)	0.077*** (0.016)	0.094*** (0.022)	0.078*** (0.016)
Test *d* = 1	0.000	0.000	0.71	0.000	0.006	0.007	0.059
No. of Countries	77	23	10	18	10	12	4

Table 11: Cointegration Test of Technology over Global Technology Frontier with Labor Share

8. Conclusions

The main contribution this paper is introduce new data to the measurement of the dynamics of economic growth across countries. This new data, on labor and capital inputs in many countries in the new PWT data set, enable us to calculate total factor productivity across many countries for an extended period of time of more than forty years. We then examine two important issues. First, we examine how does output follows the path of total factor productivity over time. We find that it follows it and the rate of convergence of output to the long run productivity is around 2 percent. Second, we examine whether productivities of individual countries follow the global frontier, and we show that many countries lag behind and actually diverge away from the frontier.

These two main results have an important implication. It means that the result of the rich literature on β-convergence cannot be interpreted as implying convergence across countries. According to this paper this finding only implies that output of each country converges to its own productivity, while this productivity might diverge significantly from the global frontier. Hence, this paper supports previous findings on divergence across countries.

On the theoretical side this paper supplies a justification to gradual adjustment of output to productivity in open economies, as a result of adjustment costs to investment. The main contribution of this model, which is presented in the appendix, is that it implies that the rate of convergence of output per worker to productivity should be around 2 percent, as found in the empirical part of the paper and also in many other studies.

This paper can also be related to some claims that analyzing differences in levels of output across countries is more important than analyzing differences in rates of growth. It is true that if rates of growth are similar across countries in the long-run, then the main important differences across countries are in levels. But if long-run rates of growth differ significantly across countries over a long period of time, as shown by this paper, then the distribution of output levels changes continuously. In other words, countries are poor because they have followed the frontier only partially for a long time. This view is also reflected in the recent survey by Jones (2015).

The empirical result of the paper on divergence of productivity and of output per worker across countries holds of course during the period we study, which is 1970-2014. We hope that future data, over more years to come, will enable us to reach better estimates on divergence and convergence. The reason is that our regressions measure by how much a country follows the global frontier during the period, but sometimes less developed countries follow what used to be the global frontier many years ago, as they have to catch up with many past technologies. Such catching up can be revealed by using longer periods of data.

Finally, we hope that this result of significant divergence during the period 1970-2014 might change soon. It is possible that the coming years will experience greater convergence if some countries in East Asia, Africa and Latin America will continue to catch up with the frontier, or if other countries might join them. Hence such studies should be repeated once in a while in order to track changes in the growth performance of countries. Future research should also try to find why countries diverge, namely why the coefficient d differs so much across countries.

Appendix:

1. Growth Accounting If Total Factor Productivity is Labor Augmenting

Assume that productivity is labor augmenting, as in equation (1) in the paper.

$$Y(t) = F[K(t), A(t)L(t)].$$

The differential of the change in output between period t – 1 and t is described by the following equation, where the derivatives are taken in period t – 1:

$$\begin{aligned} Y(t)-Y(t-1) &= F_K(t-1)[K(t)-K(t-1)]+ \\ &+F_L(t-1)A(t-1)[L(t)-L(t-1)]+F_L(t-1)L(t-1)[A(t)-A(t-1)]. \end{aligned}$$

Divide by output at time t – 1 and get:

$$\begin{aligned} \frac{Y(t)-Y(t-1)}{Y(t-1)} &= \frac{F_K(t-1)K(t-1)}{Y(t-1)}\frac{K(t)-K(t-1)}{K(t-1)}+ \\ &+\frac{F_L(t-1)A(t-1)L(t-1)}{Y(t-1)}\frac{L(t)-L(t-1)}{L(t-1)}+\frac{F_L(t-1)A(t-1)L(t-1)}{Y(t-1)}\frac{A(t)-A(t-1)}{A(t-1)}. \end{aligned} \quad \text{(A.1)}$$

Note that the elasticities of output with respect to labor and to capital are:

$$\eta_{Y,L}(t-1) = \frac{F_L(t-1)L(t-1)}{Y(t-1)}, \textit{ and } \eta_{Y,K}(t-1) = \frac{F_K(t-1)K(t-1)}{Y(t-1)}.$$

The sum of these elasticities is equal to 1, due to CRS. Hence, we get from equation (A.1):

$$\begin{aligned} \frac{Y(t)-Y(t-1)}{Y(t-1)} &= [1-\eta_L(t-1)]\frac{K(t)-K(t-1)}{K(t)}+ \\ &+\eta_L(t-1)\frac{L(t)-L(t-1)}{L(t)}+\eta_L(t-1)\frac{A(t)-A(t-1)}{A(t)}. \end{aligned}$$

From this equation we can derive the rate of change of productivity:

$$\begin{aligned} \frac{A(t)-A(t-1)}{A(t-1)} &= \frac{1}{\eta_L(t-1)}\left[\frac{Y(t)-Y(t-1)}{Y(t-1)}-\frac{K(t)-K(t-1)}{K(t-1)}\right]+ \\ &+\frac{K(t)-K(t-1)}{K(t-1)}-\frac{L(t)-L(t-1)}{L(t-1)}. \end{aligned} \quad \text{(A.2)}$$

Under the assumption of perfect competition, $F_L(t-1)A(t-1) = MPL(t-1)$ and hence the elasticity of output with respect to labor is equal to the share of labor in output: $\eta_L(t-1) = s_L(t-1)$. We can rewrite equation (A.2) as following:

(A.3)
$$\frac{A(t)-A(t-1)}{A(t-1)}=\frac{1}{s_L(t-1)}\left[\frac{Y(t)-Y(t-1)}{Y(t-1)}-\frac{K(t)-K(t-1)}{K(t-1)}\right]+ \\ +\frac{K(t)-K(t-1)}{K(t-1)}-\frac{L(t)-L(t-1)}{L(t-1)}.$$

In the empirical analysis we examine two options, one is to use the share of labor in PWT 9.0 as a measure for the elasticity $\eta_L(t-1)$, and the second is to assume that it is constant and equal to 2/3, as suggested by Jones (2015). Note, that the rate of growth of labor augmenting productivity is very similar to the rate of growth of productivity, which is multiplicative in the production function as in 'Solow's Growth Accounting.' It can be shown that it is equal to (A.3) multiplied by $s_L(t-1)$. Namely, the rate of growth of labor augmenting productivity should be around 1.5 higher than the rate of growth of the standard TFP.

2. Convergence in a Small Open Economy with Adjustment Costs

Consider a small open economy with full capital mobility facing a constant global interest rate *r*. Output in the economy in period *t* is described by the Cobb-Douglas production function:

(A.4) $$Y(t)=K(t)^{\alpha}\left[A(t)L(t)\right]^{1-\alpha},$$

where $Y(t)$ is output, $L(t)$ is labor and $K(t)$ is the amount of capital invested prior to *t*. Capital depreciates at a rate *dep*. Productivity *A* and population *N* increase at constant rates:

(A.5) $$A(t)=A(0)e^{gt}, \text{ and } N(t)=N(0)e^{nt},$$

where *g* and *n* are positive numbers.[15] Each person supplies 1 unit of labor per period, so *L* = *N*. Investment has adjustment costs, which are assumed to be quadratic and of CRS:

(A.6) $$a(t)=\frac{1}{2m}\frac{[K(t+1)-K(t)]^2}{K(t)}.$$

The parameter *m* is an inverse measure of the intensity of these costs. Also assume that the economy is open and has full capital mobility. The global interest rate is *r*.

Due to the constant returns to scale of the production and the adjustment cost functions, the value of each firm is proportional to its capital and marginal *q* is equal to average *q*, as shown in Hayashi (1982). Hence, the market value of capital *V*(*t*) satisfies:

[15] This open economy model fits exactly the canonical growth model of DJT. It can also be adjusted to the estimations of this paper. An economy that follows the global frontier by a rate *d* and the global frontier grows at a constant rate *gg*, then productivity in this country grows at an average rate *g* = *dgg*.

$$V(t) = q(t)K(t+1),$$

where $q(t)$ is the economy wide value of one unit of capital. Denote the wage rate in period t by $w(t)$. Profit maximization by firms leads to the following two first order conditions. The first is with respect to labor:

(A.7) $$w(t) = (1-\alpha)K(t)^{\alpha} A(t)^{1-\alpha} L(t)^{-\alpha}.$$

The second is with respect to capital so that the rate of capital accumulation is:

(A.8) $$\frac{K(t+1)-K(t)}{K(t)} = z[q(t)-1].$$

We next introduce the equilibrium conditions. Labor market equilibrium requires:

$$L(t) = N(t).$$

Due to capital mobility and lack of risk, the returns on capital and on lending are equal, so that:

(A.9) $$q(t)(1+r) = MPK(t+1) + q(t+1) - dep + \frac{m}{2}\left[q(t+1)-1\right]^2.$$

This is the condition of equilibrium in the capital market.

To better describe the dynamics of the economy we transform the dynamic variables to better fit the empirical model. Instead of the price of capital we use: $Q(t) = q(t) - 1$, and instead of capital we use the natural logarithm of its marginal productivity: $x(t) = \ln[MPK(t)]$. From (A.9) we get:

(A.10) $$Q(t)(1+r) = \exp[x(t+1)] + Q(t+1) - (r+dep) + \frac{m}{2}Q(t+1)^2.$$

The dynamics of x are derived from (A.5) and (A.8):

(A.11) $$x(t+1) = x(t) + (1-\alpha)\{g + n - \ln[1 + mQ(t)]\}.$$

The equilibrium solution to this dynamic system, (A.10) and (A.11), is a saddle path, which is described by the function: $Q(t) = Q[x(t)]$, where Q is monotonic increasing. Using a linear approximation we get that the steady state of the system is described by:

(A.12) $$Q^* = \frac{g+n}{m},$$

And:

(A.13) $$x^* = \ln(r+dep) + \ln\left[1 + \frac{g+n}{m}\frac{r-(g+n)/2}{r+dep}\right].$$

We next turn to connect this model more to the convergence assumption in the paper. Note that efficiency output per worker, $y^E(t)$, satisfies:

(A.14) $$\ln y^E(t) = -\frac{\alpha}{1-\alpha}[x(t) - \ln \alpha].$$

Hence, efficiency output per worker converges to a steady state $\ln y^E(\infty)$ along the saddle path. This steady state efficiency output per worker can be calculated from (A.12) and (A.13) and is equal to:

(A.15) $$\ln y^E(\infty) = \frac{\alpha}{1-\alpha}\left\{\ln \alpha - \ln(r + dep) - \ln\left[1 + \frac{g+n}{m}\frac{r-(g+n)/2}{r+dep}\right]\right\} \cong$$
$$\cong \frac{\alpha}{1-\alpha}\left[\ln \alpha - \ln(r + dep)\right].$$

Note that although r is the same for all countries, and α and dep are technological parameters that should also be the same for all countries, the long-run efficiency output per worker depends negatively on the rate of growth of productivity g, as found in the paper. But equation (A.15) show that this effect is small in size.

From (A.11) and (A.14) we derive the dynamics of efficiency output per worker:

(A.16) $$\ln y^E(t+1) = \ln y^E(t) + \alpha z Q\left[\ln \alpha - \frac{1-\alpha}{\alpha}\ln y^E(t)\right] - \alpha(g+n).$$

Hence, the efficiency output per worker follows dynamics of convergence similar to those described by equation (10) in the paper. The rate of convergence of y^E in the neighborhood of the steady state is:

$$b = (1-\alpha)mQ'(x^*).$$

We next try to estimate the size of b. One way to find it is to calculate the slope of the saddle path at the steady state, $Q'(x^*)$. This slope is the positive solution of the following quadratic equation:

$$(1-\alpha)m(1+g+n)[Q'(x^*)]^2 + \left[r - g - n + (1-\alpha)me^{x^*}\right]Q'(x^*) - e^{x^*} = 0.$$

Another way to estimate the rate b is to examine the dynamics of capital accumulation using a first order approximation around the steady state. We get:

$$\ln K(t+1) - \ln K(t) = n + g + mQ'(x^*)\frac{MPK(t) - MPK^*}{MPK^*}.$$

Hence:

(A.17) $$b = (1-\alpha)MPK^*\frac{\partial[\ln K(t+1) - \ln K(t)]}{\partial MPK(t)} \cong (1-\alpha)(r+dep)\frac{\partial[\ln K(t+1) - \ln K(t)]}{\partial MPK(t)}.$$

This equation enables us to roughly estimate the expected size of b. We can assume, for example by comparing China today with the US, that the effect of MPK on the rate of growth of capital should be somewhere between 0.3 and 0.5. According to standard assumptions $r + dep$ is around 0.1 and

$1-\alpha = 0.65$. Hence, the rate of convergence b should be somewhere between 1.7% and 3.2%. Therefore, the open economy model yields a rate of convergence that fits the data well, unlike the closed economy models used in many other growth regressions, as shown by DJT.

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