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A Production Frontier Approach

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Abstract

The growth experience of virtually all but the very rich countries is best explained as a combination of high and low growth episodes. Therefore, there is a need to understand the sources of growth during high and low growth regimes and in particular the influences as growth regimes change. This paper approaches the issue by combining the derivation of structural breaks in economic growth with nonparametric growth accounting that enables the decomposition of productivity changes into technological and efficiency changes. The results show that even in the medium run growth rate changes are mainly the result of productivity changes whereas factor accumulation plays only a minor role. Except for high income countries productivity changes usually represent efficiency changes. A comparison of growth take-offs and growth collapses reveals that factor accumulation is even less important in periods of accelerating growth.

Keywords: Growth, Structural Breaks, Data Envelopment Analysis
JEL Classification: O11, O47

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1 Introduction

The focus of the empirical growth literature has shifted from explaining differences in average growth rates across countries to analyzing the responsible factors for growth regime changes, i. e. variations of the growth rates within countries. This shift of focus is necessary because most countries do not experience high or low periods of growth consistently but rather a combination of high and low growth episodes, thus making the average growth rate a vulnerable concept (Pritchett(2000, 2001)). This paper aims at identifying the causes of growth transitions by combining a statistical method to identify growth regime changes with a nonparametric approach to growth accounting.

The paper is inspired by a recent contribution by Jones and Olken (2005). The authors analyze the proximate causes of growth regime switches by means of traditional growth accounting. They find that growth accelerations and decelerations are asymmetric events in that changes in factor accumulation are significantly more important for growth decelerations. For both types of growth transitions, however, factor accumulation plays a surprisingly little role: less than ten percent of growth accelerations and about thirty percent of growth decelerations are explained by factor accumulation, leaving the major explanatory power to productivity changes. While the importance of total factor productivity changes for long run growth is by now widely accepted (Hall and Jones (1999), Easterly and Levine (2001), Prescott (1998), Caselli (2004)) and consistent with the neoclassical growth models (Solow (1956), Barro (2003)), the importance of these changes in the short run is somewhat surprising. Transitional dynamics in the neoclassical growth models are driven by changes in the capital stock. Poverty trap models often focus on a nonconvexity in factor accumulation to explain why some nations fail to escape poverty (Murphy, Shleifer, and Vishny (1989), Acemoglu and Zilibotti (1997)). Finally, there is some agreement that industrialization in the initial phase is about capital accumulation (Galor and Moav (2004), Porter (1990), Ch. 10). Therefore, one would expect to see an important role for capital accumulation in initializing episodes of fast economic growth at least in low income countries.

This paper applies a nonparametric methodology to reassess the findings by Jones and Olken (2005). Their use of growth accounting implicitly assumes that the economies are organized competitively, that the production technology follows the suggested Cobb-Douglas form and that technological progress is Hicks neutral. Nonparametric growth accounting does not need these assumptions. All that is required is an assumption about the returns to scale. A further advantage lies in the procedure's ability to decompose changes in total factor productivity into changes in the efficiency of production and technological changes. Growth accounting simply assumes that production is efficient at any point in time and attributes all changes in total factor productivity to technological change. Apart from this change in methodology four further refinements compared to Jones and Olken (2005) are implemented. First, the growth regimes are determined using the combined double maximum $\sup F_T(\ell + 1|\ell)$ testing procedure, which increases the power of the statistical tests. Second, the minimum duration of growth episodes is set to ten years, thus ensuring that growth regime changes are not confounded with business cycles.[1] Third, production is specified in terms of capital per worker and not capital per inhabitant. Furthermore, by using the Penn World Tables Mark 6.2 the length of the data series is extended.

Despite the differences in methodology and its tendency to attribute a larger fraction of growth to factor accumulation (Kumar and Russel (2002), Henderson and Russell (2005)) my results closely match those of Jones and Olken (2005). Growth regime changes are common across countries and time periods and are predominantly driven by changes in total factor productivity. Changes in total factor productivity chiefly represent changes in the efficiency of production as opposed to technological change. With regard to growth accelerations only high income countries grow faster because of technological change, low income countries rely completely on catch-up growth, i. e. the application of existing technologies that serve to increase the efficiency of production. In phases of decelerating growth changes in technological progress become unimportant even for high income countries. The present analysis, too, points to an asymmetry between growth accelerations and decelerations: Capital deepening is more important around growth decelerations than around accelerations. In all types of countries growth accelerations tend to happen at lower levels of efficiency than decelerations.

The paper is organized as follows. Section 2 relates the analysis more thoroughly with the existing literature. In Section 3 the statistical method used to calculate the growth regime changes is described. In Section 4 the nonparametric growth accounting analysis follows. Section 5 deals with the robustness of the results before section 6 concludes.

[1] Jones and Olken (2005) use a minimum duration of five years.

2 Review of Related Literature

Starting with the seminal contributions by Barro (1991) and Mankiw, Romer, and Weil (1992), the majority of empirical growth studies has tried to uncover the sources of growth by means of cross-country growth regressions. Typically, the average growth rate of per capita income over several decades for a large number of countries is regressed on variables thought to affect growth or the steady-state output of countries. Examples are the investment or government expenditure shares, population growth rates, variables related to education, trade openness or the quality of institutions. In addition to these variables the initial period per capita income is included to account for conditional convergence of countries. Following the contribution by Islam (1995) the cross-country growth regression approach has subsequently been extended to panel data. A major problem of these growth regressions is their fragility: depending on the exact model specification with regard to sample period, sample coverage or growth correlates the significance of variables varies (Levine and Renelt (1992), Pritchett (2006)). Some part of the fragility of growth regressions can be explained by the (in-)stability of growth rates and correlates: whereas growth rates are highly instable across periods, in particular in developing countries, growth correlates exhibit a high degree of persistence (Easterly, Kremer, Pritchett, and Summers (1993)). Pritchett (2000) elaborates on this point and shows that the evolution of GDP per capita in most countries is not characterized by a single exponential trend but rather by a multitude of structural breaks and growth episodes. Therefore, instead of focusing on explaining the average growth rate of countries he suggests to focus on three questions related to the observed structural breaks: What drives accelerations and decelerations of growth? What happens with growth after major policy reforms? Why do some countries deal with shocks so much better than others? The resulting literature on growth transitions has so far quite strictly adhered to this program.

An essential ingredient in the analysis of growth transitions as suggested by Pritchett (2000) is the definition of growth spells, i. e. periods during which the growth rate remains reasonably stable. There are three different approaches that have been used in the literature: the episodic approach, the threshold approach and the statistical approach. The episodic approach, which has been employed by Rodrik (1999) or Sahay and Goyal (2006), compares a sufficiently long (e.g. 10 or 15 years) period of high growth with a sufficiently long period of low growth. The periods of growth are determined by relying on some kind of a priori knowledge or on the calculation of average growth rates over a defined number of years. The threshold approach is based solely on economic criteria. A time period is classified as a low or high growth spell if the growth rates during this period remain above or below a certain magnitude. For instance, Hausmann, Pritchett, and Rodrik (2005) define a growth acceleration to be a period of at least 8 years during which the growth rate exceeds the previously experienced growth rate in a country by at least two percentage points and is in absolute terms at least 3.5 percent. Moreover, only periods ending with higher income per capital than ever before qualify for growth accelerations. The statistical approach amounts to testing a time series for the presence of structural breaks. In the growth context this approach has been pioneered by Ben-David and Papell (1998), who apply tests allowing for only one structural break point in a time series. The econometric method suggested by Bai and Perron (1998, 2003) allows for the presence of multiple structural breaks and has subsequently been applied for example by Jones and Olken (2005). The literature features also combinations of the different methods. Berg, Ostry, and Zettelmeyer (2006), for instance, combine the threshold and the statistical approach to define a growth spell.

Once the growth spells are identified, essentially three different methods are used to analyze the research questions proposed by Pritchett (2000). Rodrik (1999) focuses on the question why some countries respond to shocks so much more quickly than others. To that end he uses regression techniques resembling cross-country growth regressions, but using the differences in the growth rates between growth regimes as the dependent variable. A second approach that focuses on the effect of major policy changes analyzes the bivariate relationship between certain variables and different growth regimes. For instance, if the conjecture is that low US interest rates are conducive to high growth performances and if the US interest rate differs significantly between high growth and low growth regimes, the conjecture is seen to be confirmed (Sahay and Goyal (2006)). A third approach draws on microeconometric methods on discrete choice and duration analysis to determine factors initiating growth transitions or sustaining growth regimes. Based on observables such as the investment rates, external shocks or political institutions either the likelihood of a certain kind of growth spell or the likely duration of a growth spell is derived. A large number of papers has implemented a probit-type analysis. Among them are Hausmann, Pritchett, and Rodrik (2005), Dovern and Nunnenkamp (2006), Becker and Mauro (2006) and Hausmann, Rodriguez, and Wagner (2006). Duration analysis has been employed by Berg, Ostry, and Zettelmeyer (2006).

The contribution by Jones and Olken (2005) is a contribution to the literature on growth transitions that uses a statistical approach to determine structural break points in the GDP per capita time series. It is unique in the sense that it applies growth accounting before turning to a comparison of the proximate causes of growth across high and low growth regimes. As an alternative to traditional growth accounting a nonparametric approach to growth accounting based on data envelopment analysis (DEA) has been suggested in the literature. DEA as a tool of macroeconomic analysis has been introduced by Färe, Grosskopf, Norris, and Zhang (1994) to analyze productivity growth in OECD countries during the time period from 1979 to 1988. The authors decompose observed changes in productivity into changes in efficiency and technological change,[2] and find that productivity growth in the researched period is mainly attributable to technological change originating from the USA. Subsequently, these kinds of decomposition have become popular to reassess the relative importance of productivity growth in the Asian context (Cook and Uchida (2002), Krüger, Cantner, and Hanusch (2000)).

Kumar and Russel (2002) extend the DEA analysis to allow for growth accounting. The extension is based on the assumption of constant returns to scale and allows to determine how much of a change in growth rates between periods can be attributed to efficiency changes, technological changes and changes in factor accumulation.[3] DEA growth accounting results are usually used to determine the responsible factors for the wide differences that are observed in labor productivity across countries. The main instrument for this analysis is the use of counterfactual distributions of labor productivity. Kumar and Russel (2002) have started this type of analysis, which was subsequently extended to include more input factors or more broadly defined input factors of production or to refer to different time periods (Henderson and Russell (2005), Badunenko, Henderson, and Zelenyuk (2005) and Salinas-Jimenez, Alvarez-Ayuso, and Delgado-Rogriguez (2006)). The analysis has also been extended to account for statistical properties of the calculations (Enflo and Hjertstrand (2006)) or to include the calculation of an intertemporal DEA frontier (Henderson and Russell (2005), Enflo and Hjertstrand (2006), Los and Timmer (2005)). So far, no consensus has been achieved on which factor is the driving force for the observed differences in labor productivity.

In terms of the reviewed literature the contribution of this paper can be integrated as follows. The statistical approach is used to determine episodes of high and low growth. Nonparametric growth accounting is applied to derive the proximate causes of growth regime changes. The results of high growth and low growth regimes will

[2] The efficiency changes are further decomposed into pure efficiency and scale efficiency changes.
[3] The original decomposition uses only capital and labor as inputs, but has subsequently been extended to incorporate human capital as well (Henderson and Russell (2005)).

be compared so that this method is most closely related to the bivariate relationship method as described above.

3 Identifying Structural Breaks in Growth Series

3.1 Methodological considerations

The aim of the following section is to determine whether the average growth rate in countries has changed significantly over the years and if so in which years. In order to derive these structural breaks the econometric method proposed by Bai and Perron (1998, 2003) is used. The intuition for the method is straightforward: In a first step the optimal timing of a given number of structural break points (up to a maximum number of allowed breaks) is derived by minimizing the sum of squared residuals resulting from a regression of the actual growth rate on the average growth rate during the specified growth regimes. In a second step a sequential testing procedure is implemented to determine the required number of break points. Starting from the hypothesis that the time series contains no structural break at all, the test opts for the introduction of an additional break point whenever the resulting reduction in the sum of squared residuals is sufficiently large as indicated by the relevant asymptotic distribution of the test statistic. This sequential test is repeated until it no longer decides in favor of introducing an additional break.

Let g_t denote the annual growth rate of income per capita expressed in purchasing power parity, β_i the mean growth rate during growth regime i and ε_t a disturbance term drawn from possibly different distributions across growth regimes. The assumed data-generating process takes the following form:

$$g_t = \beta_i + \varepsilon_t. \qquad (1)$$

Assume in a first step that the number of structural breaks in the time series is known. Consider a time series containing m structural breaks, i. e. $m+1$ growth regimes. The break points are denoted $(T_1, ..., T_m)$, whereby the actual break that initiates growth regime i $(1 \leqslant i \leqslant m+1)$ occurs after the completion of period T_{i-1}. The new growth regime lasts until period T_i.[4] Between breakpoints, a minimum distance of h periods is imposed. The total sum of squared residuals for the m-partition $(T_1, ..., T_m)$ of the

[4] When T periods are observed, the convention $T_0 = 0$ and $T_{m+1} = T$ is used.

time series is given by

$$S_T = \sum_{i=1}^{m+1} \sum_{t=T_{i-1}+1}^{T_i} [g_t - \beta_i]^2. \tag{2}$$

The estimated break points $(\hat{T}_1, ..., \hat{T}_m)$ are chosen such that S_T is minimized subject to the minimum distance h between break points. The break point estimator is thus a global minimizer of the objective function and can be conveniently determined by an algorithm based on least squares residuals and a dynamic programming approach. Given a matrix which contains the sum of squared residuals for every conceivable growth regime, the optimal partition of a time series can be found by solving the following recursive problem:

$$SSR(T_{m,T}) = \min_{mh \leqslant j \leqslant T-h} [SSR(T_{m-1,j}) + SSR(j+1, T)]. \tag{3}$$

$SSR(T_{r,n})$ denotes the sum of squared residuals associated with the *optimal* partition of the time series containing r breaks and using the first n observations, $SSR(j+1, T)$ denotes the sum of squared residuals resulting from a partition starting in $(j+1)$ and lasting until T. The procedure starts by evaluating optimal one-break partitions. The earliest possible break date is period h and the break has to occur the latest in $T-h$ to accommodate the minimum duration h of a growth spell. These optimal one-break partitions are stored. For a two-break partition, the earliest possible ending date of growth regime 2 is $2h$, whereas the latest admissible ending date is again $T-h$. For each admissible ending date of growth regime 2, the procedure determines the minimum sum of squared residuals that can be achieved by inserting one of the optimal one-break partitions. This search is continued sequentially until m breaks are accommodated.[5]

The recursive procedure is able to determine the optimal break points only under the condition that the total number of break points in the time series is known. Of course, in the actual problem the number of break points is unknown. Therefore, test statistics are required that assist with deriving the correct number of break points. In principle, different test statistics can be used. Bai and Perron (1998) recommend to use the $\text{supF}_T(\ell+1|\ell)$ approach, which tests the null hypothesis of the time series containing $(\ell+1)$ breaks against the alternative of the time series containing only ℓ breaks. The approach is based on the calculation of the supF_T test statistic. The supF-test considers the null hypothesis of no structural break $(m = 0)$ versus the alternative hypothesis of $m = k$ structural breaks. A conventional F-statistic testing

[5] For a detailed description regarding the empirical implementation of the Bai-Perron methodology, see Bai and Perron (2003) and Appendix A.

the equality of growth rates across $(k+1)$ growth regimes is given by

$$F_T(\lambda_1, ..., \lambda_k) = \frac{1}{T}\left(\frac{T-(k+1)}{k}\right)\hat{\beta}' R'(R\hat{V}(\hat{\beta})R')^{-1}R\hat{\beta}. \quad (4)$$

$\hat{\beta}$ is a vector containing the estimated mean growth rates for each growth regime, $\hat{V}(\hat{\beta})$ is the estimated and if necessary robust covariance matrix of $\hat{\beta}$ and R is the linear restriction matrix such that $(R\beta)' = (\beta_1 - \beta_2, ..., \beta_k - \beta_{k+1})$. λ_i is defined as T_i/T and is necessary to derive the asymptotic distribution of the test statistic. The supF_T test statistic is the supremum of all admissible $F_T(\lambda_1, ..., \lambda_k)$-statistics. However, if the break points of the time series are already known, this test statistic is asymptotically equivalent to

$$\text{supF}_T(k) = F_T(\hat{\lambda}_1, ..., \hat{\lambda}_k), \quad (5)$$

i. e. the resulting F-statistic using the calculated break points. The asymptotic distribution of the $\text{supF}_T(k)$ test statistic depends on the number of break points as well as on the minimum duration of a growth regime relative to the entire time period under consideration, i. e. $\epsilon = h/T$.[6] ϵ is referred to as the trimming parameter of the estimation.[7]

Suppose that the presence of ℓ break points in the time series is confirmed. The $\text{supF}_T(\ell+1|\ell)$ proceeds by testing each growth regime for the presence of an additional structural break. Hence, a new structural break is introduced in each of the $(\ell+1)$ growth regimes and the resulting supF_T statistic for $k = 1$ is calculated.[8] Then the overall maximum value of all supF_T test statistics across regimes is selected and compared to the critical values derived by Bai and Perron (2003). A large test statistic indicates that an additional break point significantly improves the fit of the model and should therefore be introduced.[9] The testing procedure starts from testing zero against one break point. Then the number of breakpoints is increased one by one until the $\text{supF}_T(\ell+1|\ell)$ test fails to reject the null hypothesis of ℓ breaks.

Alternatively, the number of break points can be determined by using the Bayesian

[6] It is also possible to estimate breakpoints in the presence of several regressors. Then the distribution of the test statistics additionally depends on the number of regressors.

[7] The limiting distributions of the test statistics have only been derived for situations in which the global sum of squared residuals is minimized. This needs not be the case in a sequential procedure. However, Bai and Perron (1998) argue that the limiting distributions of all tests are the same in the sequential setup because the rate of convergence remains unchanged.

[8] A new breakpoint can only be introduced if the distance between the two endpoints of a growth regime are far enough from each other, i. e. at least $2h$ periods from each other. Otherwise, no breakpoint is introduced and the supF_T statistic is assumed to be zero.

[9] The asymptotic distributions of all tests in this section depend on the trimming parameter and are only determined in terms of λ_i.

Information criterion (BIC). The BIC for k break points is defined as

$$BIC(k) = \ln\left(\frac{\hat{e}'\hat{e}}{T}\right) + \frac{(k+1)\ln(T)}{T}, \tag{6}$$

where $\hat{e}$ is the vector of estimated residuals. If the series contains k break points, $(k+1)$ average growth rates in the growth regimes are estimated (see equation (1)), hence the factor $(k+1)$ in the second term. Denote by M the highest number of break points allowed in the time series. The optimal number of break points k^* minimizes the BIC, i. e.

$$k^* = \text{argmin}_{k \leqslant M} BIC(k). \tag{7}$$

The BIC-criterion performs reasonably well in the absence of serial correlation. However, it tends to opt for too many breaks in the presence of autocorrelation (Bai and Perron (2003)).

Berg, Ostry, and Zettelmeyer (2006) use the so called double maximum test to derive the number of growth regime changes. The double maximum test tests the null hypothesis of no structural break versus the alternative of an unknown number of structural breaks up to an upper bound of M. The (asymptotic) test statistic also rests upon the supF_T statistic and is defined as

$$\text{UD}max\text{F}_T = \max_{1 \leqslant k \leqslant M} F_T(\hat{\lambda}_1, ..., \hat{\lambda}_k). \tag{8}$$

The testing procedure resembles that of the $\text{supF}_T(\ell|\ell+1)$ test: Instead of applying the $\text{supF}_T(\ell+1|\ell)$-test in each growth regime, Berg, Ostry, and Zettelmeyer (2006) apply the double maximum test in each growth regime. As long as the test indicates that the null of no break should be rejected, they introduce an additional break into the tested growth regime. This procedure finds more break points than the $\text{supF}_T(\ell+1|\ell)$ procedure because it is easier to achieve a seizable reduction in the sum of squared residuals by introducing *several* additional breaks than by introducing *exactly one* additional break.

In a recent simulation study Bai and Perron (2004) compare the adequacy of different testing strategies in finite samples and in the presence of autocorrelation and/or heteroscedasticity. They show that even though the BIC works reasonably well in the absence of autocorrelation, sequential methods are still preferable. The preferred strategy is to first use the double maximum test in order to determine the presence of at least one break and then apply the $\text{supF}_T(\ell+1|\ell)$-test to determine the actual number of breaks. This testing procedure is preferred to the original $\text{supF}_T(\ell+1|\ell)$-

testing procedure because the power of the double maximum test is almost as high as the power of a test of no breaks versus the alternative hypothesis specifying the true number of breaks. If the true number of breaks were known, the $\sup F_T$-test would of course be preferable. Bai and Perron (2004) also recommend to correct – if present – for heteroscedasticiy and serial correlation in the data to further increase the power of the tests.

3.2 Estimation Strategy and Data

In light of the preceding discussion the combined double maximum $\sup F_T(\ell + 1|\ell)$ testing procedure is used to determine the structural breaks in the growth rate series. The growth rates of per capita income expressed in purchasing power parity are obtained from the Penn World Tables version 6.2 (PWT 6.2).[10] Across growth regimes separate covariance matrices are estimated so as to control for potential heteroscedasticity. The Breusch-Godfrey test is used to verify the absence of autocorrelation. If there are indications for autocorrelation in a time series, the estimation of break points is repeated using the HAC covariance matrix for each growth regime.[11] A growth regime is required to last for at least ten years in order to ensure that growth regimes changes and not only standard business cycles are captured. This requirement automatically limits the maximum number of breaks to four since the longest data series run from 1950 to 2004. With regard to the sample the following choices were

[10] GDP per capita in purchasing power parity in PWT 6.2 is expressed in year 2000 international dollars, once deflated by a fixed-base Laspeyres deflator ($RGDPL$) and once deflated by a chain deflator ($RGDPCH$). For time series analysis Summers and Heston (1991) recommand using the chain deflated GDP series. Despite the need to switch to fixed-base variables later on due to the non-availability of investment as a chain deflated series, I follow this advice in this section because the time series under consideration are very long and relative prices for the different components of GDP have changed (Summers and Heston (1991)). Consequently, the time series relying on the Laspeyres index are suffering from a substitution bias, which renders reported growth rates far from the base year unreliable and thus unsuitable to determine structural break points. To clarify the issue, suppose in country j the price of investment goods continuously fell from 1950 to 2000. If the country steadily increased its capital stock it follows that GDP at the beginning of the time series grew faster than captured by the Laspeyres growth rates because the price of investment goods was higher in the 1950s than in 2000. Hence, GDP growth using the Laspeyres deflator is understated, which might result in missing structural break points in the growth rate series (Cf. Nuxoll (1994), Nordhaus (2005), Summers and Heston (1991), and Schreyer (2004) for detailed considerations of substitution bias and Gerschenkron effects.). Therefore, the chain deflated series of GDP is used for the determination of structural breaks, thus ensuring that the correct break points are found. The break points will than later on be used in the production frontier analysis even though the latter uses fixed-base deflated variables. The results of this paper do not hinge on this decision. The calculations have also been carried out using the Laspeyres deflated GDP for the determination of structural break points. While the break points are somewhat different, the overall results remain unchanged. Results are available on request.

[11] Autocorrelation is only an issue for 13 of the 105 countries at a significance level of 5 %. The HAC variance estimator was not generally used, because it is only correct asymptotically whereas a data segment contains only a comparatively small number of observations.

made: only countries that were already available in the Penn World Tables version 6.1 were used, because many of the additional countries introduced in version 6.2 suffer from implausibly high historical levels of income.[12] To ensure sufficient data for the calculation of structural breaks the minimum number of data points has been set to 30. Moreover, following Hausmann, Pritchett, and Rodrik (2005) only countries with a population exceeding one million in the final year of available data are considered. Instead of the united Germany, for which not enough data points are available, data for the former West Germany between 1950 and 1989 has been included. These rules leave 105 countries for the analysis.

3.3 Results

Upon implementation a total number of 90 breaks is found in the included 105 countries.[13] As expected, the number of breaks exceeds that of Jones and Olken (2005), who use the less sensitive $\sup F_T(\ell+1|\ell)$ testing procedure, but falls below the number of breaks found by Berg, Ostry, and Zettelmeyer (2006), who rely on multiple applications of the double maximum test for similar samples. The breaks are classified as upbreaks or downbreaks as follows: if the average growth rate after a breakpoint is higher than before, the break is named an upbreak, otherwise a downbreak. The terms growth accelerations and growth decelerations are used interchangeably with upbreaks and downbreaks.[14] Table 1 contains the summary statistics for the calculated structural breaks.

The statistics indicate that downbreaks account for 62% of all breaks and are thus more common than upbreaks. The upper part of Table 1 shows that structural breaks prevail in all regions of the world: 19 of the breaks can be found in Africa, 19 in Asia, 23 in Europe, 16 in North America, 11 in South America and 2 in Oceania. The middle part of Table 1 gives the impression that structural breaks happened in particular in the 1970s and 1980s. However, the detected breaks in the 1950s and 2000s are low because our procedure requires the first and the last growth regime to last for at least ten years, effectively allowing the first break point in 1959 and the last break point in 1994 if a country has the longest conceivable series going back to 1950 and lasting until 2004. Moreover 37 time series start only in 1960 or later, thus further limiting

[12] This fact is pointed out by the Center for International Comparisons in the notes accompanying the launch of PWT 6.2.

[13] The calculations were carried out in Stata. I implemented the Bai-Perron procedure following existing implementations in RATS and GAUSS.

[14] Other authors in this literature distinguish between statistically significant breakpoints and growth accelerations and decelerations. Cf. for example Hausmann, Pritchett, and Rodrik (2005) or Berg, Ostry, and Zettelmeyer (2006).

Table 1: Summary Statistics for Structural Breaks

Structural Breaks by Region

	Total	Africa	Asia	Europe	North America	South America	Oceania
Total number of breaks	90	19	19	23	16	11	2
Upbreaks	34	7	9	6	7	4	1
Downbreaks	56	12	10	17	9	7	1

Structural Breaks by Decade

	Total	1950s	1960s	1970s	1980s	1990s
Total number of breaks	90	3	15	35	23	14
Upbreaks	34	3	10	4	7	10
Downbreaks	56		5	31	16	4

Structural Breaks by Initial Income

	Total	High Income	Middle Income	Low Income
Total number of breaks	90	27	22	41
Upbreaks	34	4	6	24
Downbreaks	56	23	16	17

The structural breaks are derived using the Bai-Perron methodology described in the text. The minimum duration of a growth spell equals 10 years, the trimming parameter follows from the number of observations, the size of the tests is 10 %. Upbreaks are those breaks where the growth rate in the regime after the break exceeds the growth rate in the regime before the break. Downbreaks are defined conversely.

the number of structural breaks that can be found in the 1960s. Despite these reservations regarding the relative importance of structural breaks in different decades, the large number of downbreaks recorded in the 1970s supports the hypothesis of a major productivity slowdown in industrialized countries during that era. The fact that 26 of 31 downbreaks during that era happened in Europe and North America, the regions where most of the industrialized countries are found, further corroborates this hypothesis. In the lower part of Table 1 the structural breaks are classified by the stage of development of the respective countries in the year preceding the break. Since the sample period comprises more than 50 years a dynamic definition of the state of development is used. A static definition would not be able to account for countries like Taiwan, Ireland, Japan or Korea, that have developed rapidly over the last decades and hence changed positions. The definition applied in this study is similar to one suggested by Becker and Mauro (2006). All countries that have at least half of the US per capita income belong to the high income countries. The middle income countries comprise all countries with an income per capita that is at least as high as one half of the highest per capita income of the non-high income countries. All other countries are classified as low income countries. Upbreaks happen mainly in countries with relatively low income while downbreaks are more evenly distributed across all levels of development. Unlike commonly assumed positive growth experiences are not limited to Asia and Latin America, but quite a large number of upbreaks happen in Africa, a continent that is traditionally linked with abysmal growth records. According to these numbers low income countries are not locked in growth traps. Rather they have a problem with sustaining growth.

Figure 1 contains examples of structural breaks. The log of the purchasing power parity income per capita is plotted against time for China, Mexico and Portugal to illustrate that the determined break points do indeed coincide with major policy changes or other remarkable events. The example of Poland serves to outline the merits and limits of the chosen approach. A table containing all calculated break points as well as the average growth rates during the different growth regimes can be found in appendix B.

For China, an upbreak is detected in 1978. This breakpoint coincides with Deng Xiaoping's ascension and the start of economic reforms such as the liberalization of agriculture and the opening of the economy. Similarily, the low growth regime in Mexico starting in 1982 can be linked to a severe currency crisis starting in that year. As far as Portugal is concerned, the high growth regime starting in 1974 can be related to the Carnation Revolution, which took place in 1974 and which entailed a change of

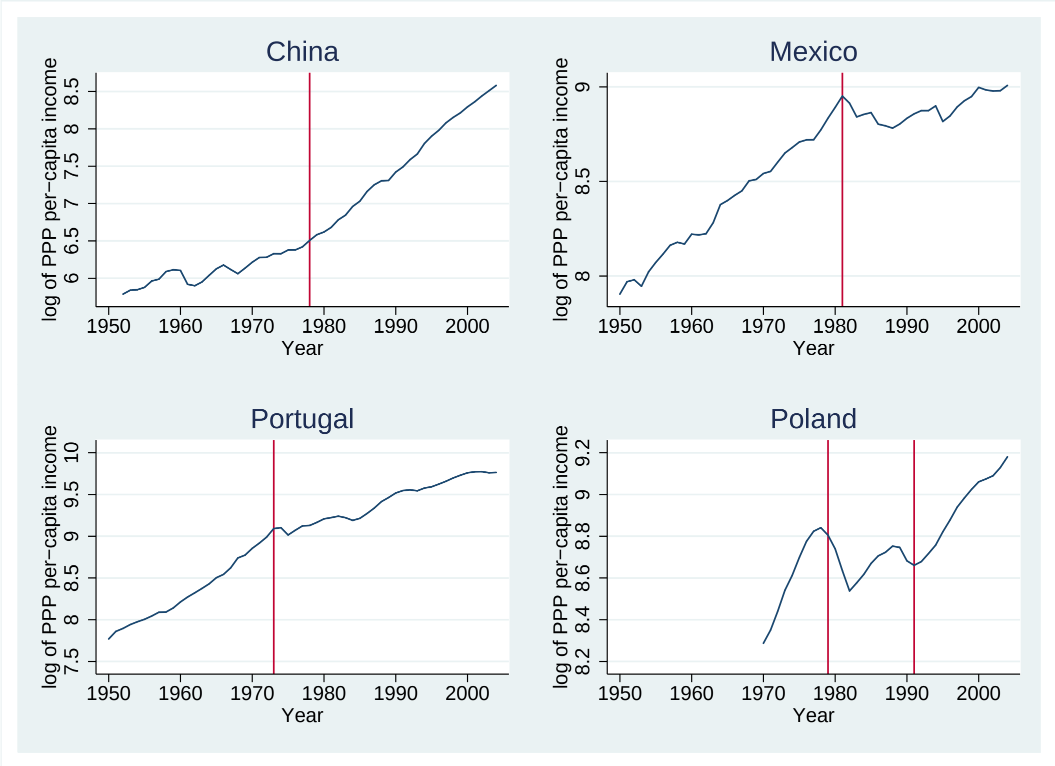

Figure 1: Examples of Structural Breaks

the political system and far reaching economic changes. Finally, a downbreak in 1980 and an upbreak in 1992 is recorded for Poland. The upbreak coincides with Poland being the first country to return to a growth path after the collapse of the communist system. The break in 1980 is in line with the economic crisis started by the attempt to increase meat prices in 1980. However, a look at the graph indicates that ”better” turning points might have been 1978, 1982 and 1992. The Bai-Perron-method, however, is unable to detect these turning points due to the requirement that a growth regime has to last for at least 10 years. While this requirement prevents a confusion of business cycle movements with growth regime movements, it also implies that the turning points found by the procedure are not turning points that would have been chosen by mere inspection of the series if there are several turning points in the neighborhood of each other.

4 Nonparametric Growth Accounting

In this section the nonparametric approach to growth accounting is described and implemented. In the first subsection the traditional growth accounting methodology and its shortcomings are described so as to motivate the use of the nonparametric approach. A detailed depiction of DEA and the accounting decomposition follows. After a short description of the data used the results of DEA growth accounting are presented.[15]

4.1 Traditional Growth Accounting and Its Shortcomings

Standard growth accounting is based on an aggregate production function that exhibits constant returns to scale in the (rival) input factors and Hicks-neutral technological change.[16] As a minimum, the aggregate physical capital stock in use and the aggregate labor force in use are considered as factor inputs.[17] Often the labor force is weighted by some measure of human capital in order to obtain a measure of the quality adjusted workforce. Assume the following simple aggregate production function

$$Y = AF(K, L), \tag{9}$$

where Y is the aggregate output of the economy, A represents the level of technology, K is the aggregate physical capital stock in use and L is aggregate labor used. Taking logarithms and differentiating equation (9) with respect to time results in the well known growth accounting formula

$$g_Y = g_A + \frac{F_K K}{Y} g_K + \frac{F_L L}{Y} g_L. \tag{10}$$

g_x denotes the growth rate of x, F_x is the derivative of the production function with respect to x, with $x \in \{L, K, Y, A\}$. The logic of growth accounting is straightforward: The growth of inputs that occurs within a period is weighted by the respective elasticities over the same period yielding the output growth that can be attributed to factor accumulation. In the presence of competitive markets and constant returns to scale with respect to factor inputs the elasticities are equal to the respective factor shares. Hicks neutral technological progress is derived as the difference between the observed growth rate of output and the growth that can be attributed to the use of rival inputs.

[15] Both standard growth accounting and nonparametric growth accounting rely on the existence of aggregate factor inputs, aggregate outputs and aggregate production functions and are vulnerable to the Cambridge capital theory controversies and aggregation problems per se. In the Cambridge debate the logic of treating a quantity expressed in value terms (i. e. the capital stock) in the same way as other aggregate quantities expressed in physical terms (i. e. labor) is questioned. The aggregation literature argues that aggregate quantities and production functions only exist under very restrictive conditions which are not met in reality. An analysis of these objections is beyond the scope of this paper. A comprehensive survey of this issue can be found in Felipe and Fisher (2003).

[16] Barro (2003) describes how growth accounting can be interpreted assuming labor augmenting technological change. This, however, is rarely done.

[17] More precisely, it should be the services derived from the capital stock and labor in use, i. e. hours worked, that should enter the production function. The stock values are used due to lack of better data.

Following the majority of growth accounting studies Jones and Olken (2005) specify the production technology to be Cobb-Douglas and assume the capital share to equal 1/3.

As the exposition above has clarified the analysis by Jones and Olken (2005) is based on a multitude of assumptions which are not beyond dispute. To reiterate, the most important assumptions are the following: The aggregate production function is assumed to be of the constant returns to scale Cobb-Douglas form implying an elasticity of substitution between factors of one. Production takes place in a competitive environment, which is reflected in the use of factor shares as output elasticities. All growth that is not explained by factor accumulation is interpreted as technological change, thus effectively assuming that all countries produce efficiently, i. e. on the borders of their production possibility sets.

Going through the assumptions one by one it will become clear that they are contestable but at the same time determine the growth accounting results. Methods relying on less assumptions are preferable and necessary for robustness checks. The assumption of constant returns to scale is convenient, but if endogenous growth theory (Romer (1990), Aghion and Howitt (1992)) is to be believed, the aggregate production function is characterized by increasing returns to scale. The assumption of Hicks-neutral technological change is assailable on two grounds: First, steady state growth requires technological progress to be labor-augmenting. Steady state growth and Hicks-neutral technological progress are only compatible in the special case of a Cobb-Douglas production function (Barro (2003)). However, Duffy and Papageorgiou (2000) find that aggregate production functions are not well characterized by the Cobb-Douglas form. Moreover, a large literature exists that argues in favor of skill-biased technological change indicating that not all factors profit equally from technological change.[18] Regarding the approximation of output elasticities with factor shares this approximation is only valid in a competitive environment. Yet, market power and externalities exist. Furthermore, measured factor shares do not properly account for self-employment (Crafts (2003)). These issues make it likely that factor shares do not properly reflect output elasticities. Often this issue is dealt with by imposing constant factor shares at an appropriately deemed number following Gollin (2002), who argues that appropriately adjusted labor shares are indeed constant over time and across countries. Yet, other contributions show that labor and capital shares have not been constant in the past so that the jury on this issue is still out (Harrison

[18] Examples of this literature include Acemoglu (1998, 2002), Caselli (1999), Machin and Van Reenen (1998), Autor, Levy, and Murnane (2003), and Card and DiNardo (2002).

(2002), Blanchard, Nordhaus, and Phelps (1997)). However, the most serious shortcoming is the assumption of the unit elasticity of substitution between capital and labor, which is embodied in the Cobb-Douglas production function. A high elasticity of substitution between capital and labor implies that capital deepening alone is sufficient to increase output by a large amount. When the elasticity of substitution decreases ceteris paribus, the growth attributable to total factor productivity growth increases ceteris paribus. In this sense, the results of growth accounting are predetermined by the assumed production function (Cf. Rodrik (1997) and Nelson (1973)). The assumption of a unit elasticity of substitution is often justified by the observation that despite capital deepening the capital share and thus the marginal product of capital have remained approximately constant. However, this case is observationally equivalent to a case where the diminishing returns of capital are cushioned by labor-saving technical change. Any growth accounting results are therefore subject to considerable doubt (Rodrik (1997)).

Nonparametric growth accounting avoids most of the mentioned debatable assumptions. It does not require the specification of a production technology, thus leaving the nature of technological progress and the magnitude of the elasticity of substitution between labor and capital to be determined by the data. It is entirely based on quantity measures so that no assumptions with respect to optimizing behavior, market structures, institutions and market imperfections are involved. It takes into account the possibility of inefficient production and decomposes the black box "total factor productivity change" into changes in efficiency and technological change. The only questionable assumption that is maintained is constant returns to scale.[19]

4.2 Nonparametric growth accounting

4.2.1 Data Envelopment Analysis

Data envelopment analysis in its original form allows measuring the efficiency of production for decision-making units with multiple inputs and outputs in the absence of market prices. In order to achieve the efficiency measurement the observed input-output bundles of the decision making units are used to construct a benchmark technol-

[19] Growth accounting based on stochastic frontier analysis was considered as an alternative to the chosen approach based on DEA. Like the DEA approach, it allows the decomposition of productivity into efficiency and technology. Moreover, it acknowledges the fact that random shocks outside the control of producers can affect output. However, in a long panel like in this article technological change and time-varying efficiency levels have to be allowed for. In the context of stochastic frontiers, this is only possible by severely restricting the evolution of the efficiency term such that the time path is either equal across countries or smooth over time (Kumbhakar and Lovell (2000)). Neither assumption is suited for an analysis that focuses on the behavior of growth components in the presence of structural breaks.

ogy under fairly general assumptions. Basically the data is enveloped in the "tightest fitting" convex cone, and the upper boundary of this set represents the best-practice production frontier. The efficiency of a decision making unit is measured with reference to the thus defined benchmark technology. The decision making units in this article are the individual countries.

The following weak assumptions are used for the construction of the benchmark technology: First, all actually observed input-output-combinations are feasible. Second, the production possibility set is a convex cone. Third, inputs as well as outputs are freely disposable. Forth, the production technology exhibits constant returns to scale.[20] As in section 4.1 aggregate physical capital in use (K) and aggregate labor in use (L) are the factor inputs by means of which the single aggregate output good in the economy (Y) is produced.[21] Ignoring for the moment the intertemporal nature of the problem and denoting the countries (decision making units) by subscript j, the production possiblity set of the world ($\mathcal{T}$) in a single year is defined as follows:

$$\mathcal{T} = \left\{ (Y, K, L) \in \mathbb{R}^3 : K \geqslant \sum_j \mu_j K_j \wedge L \geqslant \sum_j \mu_j L_j \wedge Y \leqslant \sum_j \mu_j Y_j \wedge \mu_j \geqslant 0 \forall j \right\}. \tag{11}$$

In words, all input-output bundles (Y, K, L) that are convex combinations of observed input-output bundles make up the production possibility set. The upper boundary of this set represents the best-practice production / technology frontier. In the following the terms best practice production frontier and world technology frontier will be used interchangeably (and abbreviated by technology frontier), even though it is likely that the true world technology frontier envelops more input-output bundles than the best-practice frontier does. This will always be the case if in reality the frontier-defining decision making units do not operate fully efficiently.[22]

[20] It is not necessary to assume constant returns to scale in DEA analysis. Assuming varying or non-increasing returns to scale requires only slightly different restrictions on the activity levels, which are denoted by μ later on. However, the assumption of constant returns to scale is exploited in the following growth accounting decomposition (Kumar and Russel (2002) and Ray (2004)).

[21] It is debateable whether in an economy-wide context aggregate physical capital and labor in use or available should be used. Unemployment of a factor can be interpreted as a source of inefficiency in itself. Usually, however, in analogy to the microeconomic background of DEA analysis only the employed factors are taken as inputs. I adopt this approach, being aware that the efficiency of production in the economy is a somewhat narrower concept than the efficiency of the whole economy if idle resources were taken into account as well.

[22] Enflo and Hjertstrand (2006) examine the amount of bias that is introduced by ignoring the difference between best practice and world technology frontier. While the best practice frontier is indeed a downwards biased version of the world technology frontier correcting the bias does not change qualitative results.

One way to extend DEA analysis intertemporally is to simply calculate world technology frontiers in each time period independently. In this case equation (11) would not change except for the need to add a time subscript. This approach has a serious disadvantage: the world technology frontier can implode if for example the frontier defining countries experience an economic collapse. Yet, it is difficult to imagine events where the world would forget or unlearn previously known production possibilities. It is important here to distinguish between observed production and production possibilities. While many events can prevent countries from actually producing on the technology frontier not many events are conceivable where the "blueprint" of how to produce efficiently is lost once it has been discovered. For this reason an intertemporal variant of DEA that precludes technological regress is preferred.[23] Effectively, technological regress can be prevented by taking into account *all* input-output bundles that have ever been observed until period t when calculating the production frontier in period t (Diewert (1980), Henderson and Russell (2005)). Equation (11) therefore becomes

$$\begin{aligned}\mathcal{T}_t = \{(Y,K,L) \in \mathbb{R}^3 : K \geqslant \sum_{\tau \leqslant t} \sum_j \mu_{j\tau} K_{j\tau} \wedge L \geqslant \sum_{\tau \leqslant t} \sum_j \mu_{j\tau} L_{j\tau} \\ \wedge Y \leqslant \sum_{\tau \leqslant t} \sum_j \mu_{j\tau} Y_{j\tau}, \mu_{j\tau} \geqslant 0 \forall j, \tau\}.\end{aligned} \tag{12}$$

Typically, many of the decision making units do not produce on the boundaries of the technology set. If a decision making unit does not produce on the technology frontier it is inefficient in that the same amount of output could be produced by less input. The amount of inefficiency is captured by the Farrell output-based measure of technical efficiency.[24] The technical efficiency (TE) of country j at time t is defined as ϕ_{jt} such that

$$TE_{jt} = \left\{ \min \phi_{jt} : (K_{jt}, L_{jt}, \frac{Y_{jt}}{\phi_{jt}}) \in \mathcal{T}_t \right\}. \tag{13}$$

The efficiency index is the inverse of the maximal amount by which output Y_{jt} could be expanded while still remaining technically feasible and while still requiring the

[23] However, something akin to technological regress is quite plausible in the presence of behavioral changes. Consider e. g. the recent interest in environment protection. Effective environment protection might result in a production possibility set where the same amount of inputs brings about less output. The assumption in this paper is that this kind of behavior is not yet important, which is partly corroborated by the ever increasing production possibilities in high income countries.

[24] The literature uses the Farrell output-based measure inconsistently in that it is sometimes defined as below, i. e. as ϕ or alternatively as $\frac{1}{\phi}$ (Cf. e. g. Grosskopf (1993) for the latter definition). Farrell himself only defines the input-based measure of technical efficiency in this seminal contribution (Farrell (1957)).

same input quantities K_{jt} and L_{jt}. The efficiency index takes the value 1 if a country is producing on the world technology frontier. Otherwise, $\phi_{jt} < 1$ holds.[25] Formally, the efficiency indices are calculated by solving the following linear program for every decision making unit:

$$\begin{aligned} \min \phi_{jt} \quad \text{s. t.} \quad & \frac{Y_{jt}}{\phi_{jt}} \leqslant \sum_{\tau \leqslant t} \sum_{j} \mu_{j\tau} Y_{j\tau} \\ & K_{jt} \geqslant \sum_{\tau \leqslant t} \sum_{j} \mu_{j\tau} K_{j\tau} \\ & L_{jt} \geqslant \sum_{\tau \leqslant t} \sum_{j} \mu_{j\tau} L_{j\tau} \\ & \mu_{j\tau} \geqslant 0 \ \forall j, \tau. \end{aligned} \tag{14}$$

These efficiency levels and the activity levels $\mu_{j\tau}$ are reported for every decision making unit as the output of a DEA analysis.[26]

4.2.2 Decomposing Productivity Growth

The DEA analysis introduced in the previous section showed how to determine the efficiency of production. Färe, Grosskopf, Norris, and Zhang (1994) showed how to account for productivity changes over time based on the Malmquist productivity index (Caves, Christensen, and Diewert (1982)). Under the assumption of constant returns to scale Kumar and Russel (2002) decomposed changes in income per worker into components attributable to efficiency change, technological change and capital accumulation. This section starts by presenting the originally proposed decomposition by Kumar and Russel (2002), extends the decomposition to integrate labor force participation and finally shows how to implement the approach in terms of distance functions.

Since constant returns to scale are assumed the decomposition of changes in income per worker can be derived in the (y, k) space, where $k = K/L$ and $y = Y/L$, i. e. capital stock and output per worker if labor in use is measured by the number of workers. Consider the base period b and the current period c. The world technology frontiers in the base period and the current period are shown in figure 2.

[25] Since the Farrell output-based measure of technical efficiency is a radial measure of efficiency, $\phi = 1$ does not necessarily indicate Pareto-efficient production. ϕ only shows whether proportional increases in the output mix given the input mix are possible. It does not capture whether one component of the output mix could be individually increased more than proportionally nor does it capture whether reductions of some individual inputs are feasible without affecting output (Ray (2004)). In the present analysis only the input mix question arises.

[26] Unless otherwise noted, this section has drawn from Ray (2004) and Färe, Grosskopf, and Lovell (1994).

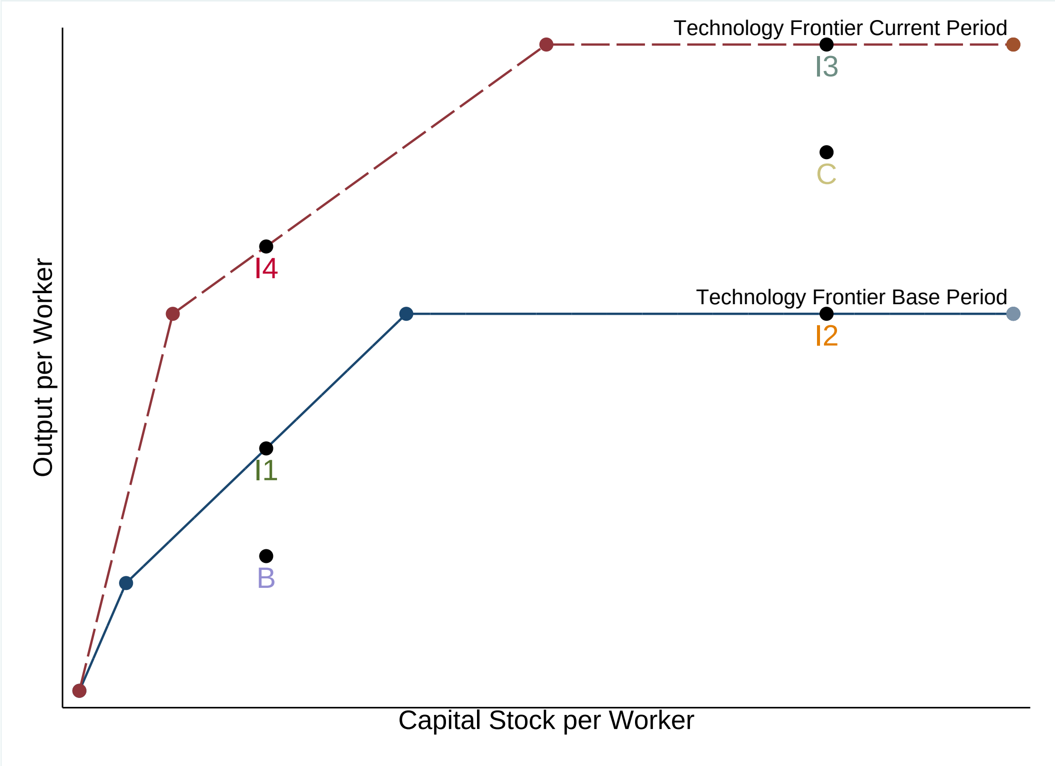

Figure 2: Illustration of Nonparametric Growth Accounting

Suppose the economy under consideration produces at point B in the base period using capital intensity k_b and at point C in the current period using capital intensity k_c. Then outputs y_b and y_c are produced, respectively. By definition, output on the production frontier for the respective capital intensities is given by $\bar{y}_c(k_c) = y_c/\phi_c$ and $\bar{y}_b(k_b) = y_b/\phi_b$, where ϕ again denotes the efficiency of production. Income per worker in the two periods is related via

$$\frac{y_c}{y_b} = \frac{\phi_c}{\phi_b}\frac{\bar{y}_c(k_c)}{\bar{y}_b(k_b)}. \tag{15}$$

Multiplying both the numerator and the denominator by $\bar{y}_b(k_c)$ and rearranging terms results in

$$\frac{y_c}{y_b} = \frac{\phi_c}{\phi_b}\frac{\bar{y}_c(k_c)}{\bar{y}_b(k_c)}\frac{\bar{y}_b(k_c)}{\bar{y}_b(k_b)}. \tag{16}$$

Changes in income per worker as measured by the growth factor of income per worker are decomposed into changes in efficiency (first term), changes in technology (second term) and the effect of changes in the capital intensity per worker (third term) via this identity. Graphically speaking, efficiency changes are changes in the distance from, technological changes are shifts of and the effect of changes in the capital intensity are movements along the production frontier. In terms of figure 2 the proposed decomposition measures technological change by shifts of the frontier at the current capital intensity - from point I_2 to point I_3 - and the effect of capital accumulation as movements along the base-period frontier - from point I_1 to point I_2. Of course the reverse decomposition resulting in

$$\frac{y_c}{y_b} = \frac{\phi_c}{\phi_b}\frac{\bar{y}_c(k_b)}{\bar{y}_b(k_b)}\frac{\bar{y}_c(k_c)}{\bar{y}_c(k_b)} \tag{17}$$

is equally valid. This time technological change is measured by shifts of the frontier at the base capital intensity - from point I_1 to point I_4 - and the effect of capital accumulation as movements along the current-period frontier - from point I_4 to point I_3. The choice between equation (16) and (17) is arbitrary. If technological change is Hicks-neutral, the production frontier shifts by the same amount at each capital intensity so that the point of measurement does not matter. If, however, technological change is not Hicks-neutral, the two decompositions yield different results because the shifts of the technology frontier at different capital intensities varies. Following Färe, Grosskopf, Norris, and Zhang (1994) and Kumar and Russel (2002) this ambiguity is resolved by adopting the "Fisher ideal" decomposition. The Fisher ideal decomposition uses the geometric averages of the measures of technological change and capital accumulation. Formally,

$$\begin{aligned}\frac{y_c}{y_b} &= \frac{\phi_c}{\phi_b}\left(\frac{\bar{y}_c(k_c)}{\bar{y}_b(k_c)}\frac{\bar{y}_c(k_b)}{\bar{y}_b(k_b)}\right)^{1/2}\left(\frac{\bar{y}_b(k_c)}{\bar{y}_b(k_b)}\frac{\bar{y}_c(k_c)}{\bar{y}_c(k_b)}\right)^{1/2} \\ &=: EFF \cdot TECH \cdot KACCUM,\end{aligned} \tag{18}$$

where again the first term denotes efficiency change (EFF), the second term technological change (TECH) and the third term the effect of capital deepening (KACCUM).

Since the ultimate objective of the paper is to decompose growth rates around structural breaks and since the structural breaks were calculated using the growth rates of income *per capita* it is necessary to extend equation (18) such that income per capita is decomposed. Let *lfp* denote the labor force participation measured as the number of workers per capita and $\tilde{y}$ income per capita. Since income per capita is nothing else than income per worker multiplied by the labor force participation it can be written as

$$\begin{aligned}\frac{\tilde{y}_c}{\tilde{y}_b} &= \frac{y_c}{y_b}\frac{lfp_c}{lfp_b} \\ &= \frac{\phi_c}{\phi_b}\left(\frac{\bar{y}_c(k_c)}{\bar{y}_b(k_c)}\frac{\bar{y}_c(k_b)}{\bar{y}_b(k_b)}\right)^{1/2}\left(\frac{\bar{y}_b(k_c)}{\bar{y}_b(k_b)}\frac{\bar{y}_c(k_c)}{\bar{y}_c(k_b)}\right)^{1/2}\frac{lfp_c}{lfp_b} \\ &=: EFF \cdot TECH \cdot KACCUM \cdot LFP.\end{aligned} \tag{19}$$

Since the only outputs from a DEA analysis are the efficiency levels ϕ and the activity levels μ the components of the suggested decomposition have to be expressed solely in terms of these and input-output measures. To this end, the distance function $D^b(k_b, y_b)$ for a single decision making unit is defined as follows:[27]

$$D^b(k_b, y_b) = \left\{ \min \phi_b : \left(K_b, L_b, \frac{Y_b}{\phi_b} \right) \in \mathcal{T}_b \right\}. \tag{20}$$

The distance function takes the same value as the efficiency measure ϕ_b and hence measures the maximal proportional change in outputs required to make (k_b, y_b) just feasible in relation to technology at time t. The superscript b indicates the reference period of the production possibility set, the main advantage of the distance function over the efficiency measure. According to the previous section efficiency in the base period is the fraction of actual to potential output as defined by the technology frontier. Hence,

$$\phi_b = D^b(k_b, y_b) = \frac{y_b(k_b)}{\bar{y}_b(k_b)} = \frac{Y_b(K_b, L_b)}{\bar{Y}_b(K_b, L_b)}. \tag{21}$$

The distance function $D^c(k_c, y_c)$ is defined analogously. However, in order to calculate the decomposition the additional distance functions $D^b(k_c, y_c)$ and $D^c(k_b, y_b)$, i. e. the efficiency of today's production in reference to tomorrow's technology frontier and vice versa, are also needed. These distance functions are defined as

$$\begin{aligned} D^b(k_c, y_c) &= \frac{y_c(k_c)}{\bar{y}_b(k_c)} \\ D^c(k_b, y_b) &= \frac{y_b(k_b)}{\bar{y}_c(k_b)}. \end{aligned}$$

In practice, these counterfactual distance functions or efficiency scores are obtained by solving two additional linear programs similar to (14). The difference is that the observation that is evaluated is not included in the reference set from which the production possibility frontier is derived.[28] Altogether, to obtain a decomposition for one period of growth and one country four linear programming problems have to be solved.

With the distance functions at hand all components of the suggested decomposition can be derived reverting only to distance functions and data on factor inputs and outputs. Consider the first term of equation (18) or (19). By definition, this term is

[27] For convenience, subscript i is dropped.
[28] A nice exposition dealing with how to calculate these counterfactual distance functions can be found in Grosskopf (1993).

nothing else than

$$\frac{\phi_c}{\phi_b} = \frac{D^c(k_c, y_c)}{D^b(k_b, y_b)}. \tag{22}$$

The term defining technological change in equation (18) can be rewritten as follows:

$$\begin{aligned}
\left(\frac{\bar{y}_c(k_c)}{\bar{y}_b(k_c)}\frac{\bar{y}_c(k_b)}{\bar{y}_b(k_b)}\right)^{\frac{1}{2}} &= \left(\frac{\frac{1}{\bar{y}_b(k_c)}}{\frac{1}{\bar{y}_c(k_c)}}\frac{\frac{1}{\bar{y}_b(k_b)}}{\frac{1}{\bar{y}_c(k_b)}}\right)^{\frac{1}{2}} \\
&= \left(\frac{\frac{1}{\bar{y}_b(k_c)}y_c(k_c)}{\frac{1}{\bar{y}_c(k_c)}y_c(k_c)}\frac{\frac{1}{\bar{y}_b(k_b)}y_b(k_b)}{\frac{1}{\bar{y}_c(k_b)}y_b(k_b)}\right)^{\frac{1}{2}} \\
&= \left(\frac{D^b(k_c, y_c)}{D^c(k_c, y_c)}\frac{D^b(k_b, y_b)}{D^c(k_b, y_b)}\right)^{\frac{1}{2}}.
\end{aligned} \tag{23}$$

Finally, the effect of capital deepening can be expressed as follows:

$$\begin{aligned}
\left(\frac{\bar{y}_b(k_c)}{\bar{y}_b(k_b)}\frac{\bar{y}_c(k_c)}{\bar{y}_c(k_b)}\right)^{\frac{1}{2}} &= \left(\frac{\frac{1}{\bar{y}_b(k_b)}\frac{y_b(k_b)}{y_b(k_b)}}{\frac{1}{\bar{y}_b(k_c)}\frac{y_c(k_c)}{y_c(k_c)}}\frac{\frac{1}{\bar{y}_c(k_b)}\frac{y_b(k_b)}{y_b(k_b)}}{\frac{1}{\bar{y}_c(k_c)}\frac{y_c(k_c)}{y_c(k_c)}}\right)^{\frac{1}{2}} \\
&= \left(\frac{D^b(k_b, y_b)}{D^b(k_c, y_c)}\frac{D^c(k_b, y_b)}{D^c(k_c, y_c)}\left(\frac{y_c}{y_b}\right)^2\right)^{\frac{1}{2}}.
\end{aligned} \tag{24}$$

After a description of the data the results of the decomposition around structural breaks according to equation (19) are reported. The values have been derived in the following way: Consider a break that occurs in the year t. For every adjacent pair of years in the ten years before the break and in the ten years after the break the growth factors of income per capita, labor force participation, efficiency change, technological change and changes resulting from capital accumulation are calculated. Based on these yearly growth factors, the average growth factors over the ten year period before and the ten year period after the break are derived by taking the geometric average.[29] Finally, the overall averages across countries are obtained by taking the arithmetic average.

[29] The order of calculation is reported because the Fisher type indices do not satisfy the circular test so that the results depend the order of calculation (Battese, Coelli, and Rao (1998), chap. 4.5).

4.3 Data

The data for the nonparametric growth accounting is also taken from the Penn World Tables version 6.2 (Heston, Summers, and Aten (2006)). Compared to other data sets the Penn World data has the advantage of being measured in a common set of prices, thus allowing real international quantity comparisons across countries and time (Summers and Heston (1991)). Using real quantities is important since growth accounting and DEA in particular are theoretically based on real quantities. The Penn World Tables contain data on output per capita and the population number so that total GDP can be derived. Unlike in section 3 GDP per capita is deflated using a Laspeyres index because the data needed for the construction of the capital stock is only available for a Laspeyres deflator.[30] Aggregate labor used in production is measured by the number of workers in the population.[31] While the number of workers is an imperfect measure of actual labor used (e. g. due to unemployment), it nevertheless captures some variation in capacity utilization. This adjustment is important in an analysis that focuses on *medium-term* changes in observed growth rates.[32] Total investment per period (I) is derived multiplying the investment rate with total GDP.[33] The capital stock is calculated via the perpetual inventory method (Nehru and Dhareshwar (1993)) assuming a constant depreciation rate δ of seven percent. Assuming for the moment that the initial capital stock is known the capital stock in subsequent periods is specified by

$$K_t = (1 - \delta)K_{t-1} + I_t. \tag{25}$$

The initial period capital stock is derived via

$$K_0 = \frac{I_1}{g_I + \delta}, \tag{26}$$

with g_I being the average investment rate[34] of the first ten observations.[35]

[30] In terms of the Penn World table variable names $RGDPL$ is used.

[31] Using the Penn World Table variable names the number of workers is derived via $RGDPCH * POP/RGDPWOK$. For Taiwan the number of workers is extrapolated from 1999 onwards based on the assumption that the labor force participation rate equals that of 1998.

[32] The effect of further adjustments for the quality of labor based on human capital are analyzed as part of the robustness check in section 5.

[33] Using the Penn World Table variable names, investment is calculated via $KI/100 * RGDPL * POP$.

[34] $g_I = (\frac{I_{10}}{I_0})^{\frac{1}{10}}$.

[35] If g_I is negative for the first ten observations, an investment rate of zero is assumed.

4.4 Results

In this section the preferred nonparametric growth accounting results are presented. The preferred basic results have been calculated excluding the countries Jordan and Gabon because the inclusion or exclusion of these countries proved to be quite influential.[36] Therefore, 88 growth regime changes have been considered in the analysis.

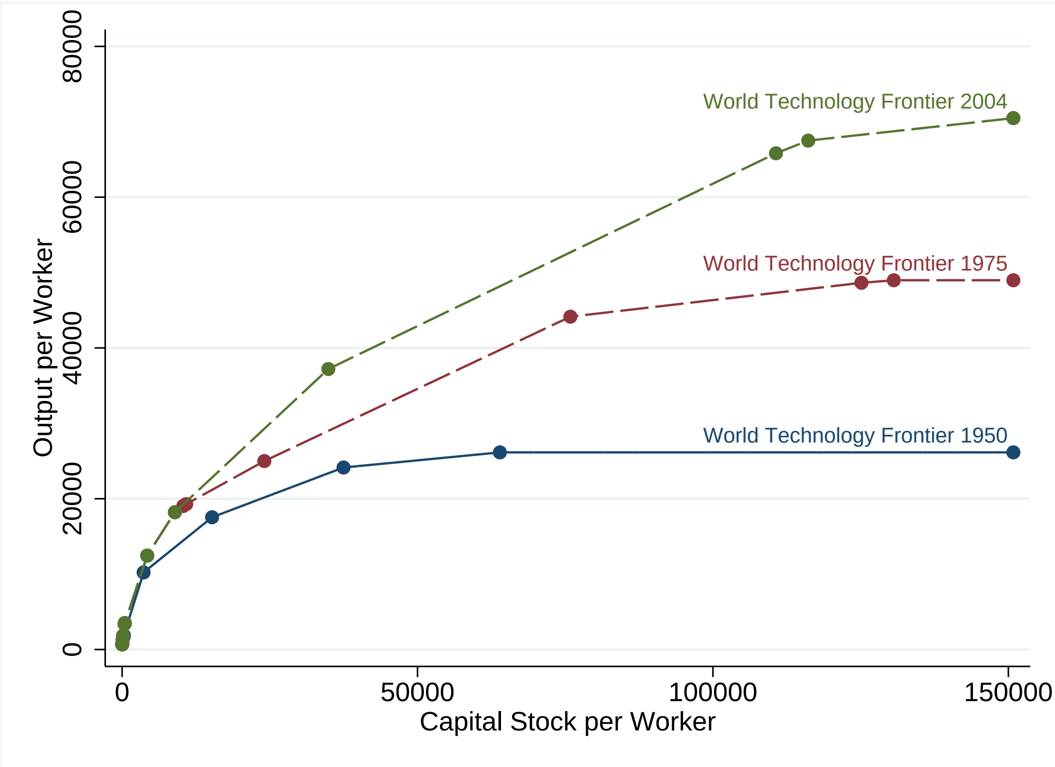

Figure 3: Prodution Frontiers for 1950, 1975 and 2004

In Figure 3 the calculated production frontiers for the years 1950, 1975 and 2004 are plotted in the (k, y)-space.[37] As expected the production possibility set expanded between 1950 and 2004. The production frontiers are virtually identical at low levels of capitalization (i.e. low levels of capital per worker). For higher levels of capitalization the production frontiers shift outwards indicating technological progress. The uneven shifts of the production frontiers indicate that technological progress is not neutral.[38] Rather, technological progress benefits predominantly countries that produce capital-intensively and have high levels of income per capita. These results are

[36] Cf. section 5.1.

[37] In 1950 and 1975 the last input-output combination has not been observed in the data. It has been plotted in order to ease the comparison of the different convex production possibility sets.

[38] Neutral technological progress would shift the production frontier equally at each capital intensity.

similar to those of Kumar and Russel (2002) and Henderson and Russell (2005).

In Table 2 the average growth rates of income per capita in the ten years before and after growth accelerations are decomposed into the contributions of efficiency, technology, capital deepening and labor force participation.[39] The third column comprises the differences in the contributions to growth between the regime changes. The contributions of efficiency and technology are summarized as productivity changes, which correspond loosely to Hicks-neutral technological progress calculated in growth accounting (see equation (10)).

Before a growth acceleration the average country experiences an annual growth rate in income per capita of 0.19%. If there were no changes in productivity and labor force participation the growth rate would be 1.16% owing to capital accumulation. However, productivity and labor force participation contribute negatively to the overall growth rate, reducing it by 0.87 and 0.07 percentage points, respectively. The negative contribution of productivity growth is a result of declining efficiency. After a growth acceleration the average yearly growth rate of income per capita exceeds 4%, accelerating by 3.97 percentage points. Productivity change contributes positively to the higher growth rate, explaining 1.16 percentage points. After the acceleration changes in efficiency, too, contribute positively to the observed growth rate. The difference in percentage points between the growth regimes is 2.28 for efficiency but only 0.19 for technology. Thus, while technological change occurs somewhat faster after an acceleration than before, efficiency change is the major driving force of the increased productivity. Capital deepening now contributes to the growth rate with 2.14 percentage points, almost one percentage point more than before. Labor force participation of the average country increases markedly after an acceleration. The lower part of Table 2 indicates how much of the increased growth rate can be explained by accelerated capital accumulation. Depending on whether the contribution of capital accumulation is calculated using the averages given in Table 2 or using the individual data first and averaging afterwards, the contribution amounts to 24.6% or 23.5%. It follows that 75 % of the observed growth rate changes are accounted for by other factors. Productivity changes alone account for 2.48 of the 3.97 percentage point increase in growth rates or 62.5% (based on average contributions).

[39] The values in one row do not add up exactly, because the original relationship is a product between growth factors. Focusing on productivity and capital accumulation only, we approximate $(1 + g_y) = (1 + g_{prod})(1 + g_{cap})$ by $g_y = g_{prod} + g_{cap}$, so that a slight inaccuracy of $g_{prod}g_{cap}$ is introduced. However, this inaccuracy is of little relevance as long as the growth rates are small.

Table 2: Nonparametric Growth Accounting around Growth Accelerations

	Before Upbreak	After Upbreak	Difference Between Growth Regimes
Average Annual Growth Rate of Income per Capita	0.19	4.16	3.97
Productivity Changes	-0.87	1.61	2.48
Efficiency Changes	-1.31	0.97	2.28
Technological Changes	0.45	0.64	0.19
Capital Deepening	1.16	2.14	0.98
Changes in Labor Force Participation	-0.07	0.39	0.46
Number of Observations	34	34	34
<u>Contribution to Growth</u>			
Capital Accumulation (based on individual contributions)	23.54 %		
Capital Accumulation (based on average contributions)	24.58 %		

Growth accelerations are derived using the Bai-Perron methodology as described in section 3. The growth rates before and after the structural breaks are the average growth rates in the ten years preceding and the ten years following the structural break.

In Table 3 the equivalent results for growth decelerations are presented. Growth decelerations are somewhat larger in magnitude than growth accelerations with the growth rate of income per capita falling from 4.63 % to 0.14 % between regimes. Both efficiency and technology contribute positively to economic growth preceding a downbreak. After a downbreak the contribution of efficiency change to growth becomes negative and technological change slows down. The growth contribution of capital deepening falls from 2.4 to 0.5 percentage points. Despite the deceleration of the growth rate, labor force participation increases slightly after the regime change, possibly indicating that survival especially in poor countries has become more difficult and requires more people to contribute to household earnings. Focusing once again on the importance of capital accumulation, the calculations indicate that slower capital accumulation can account for 40 – 50% of the observed fall in the growth rate. Capital accumulation is thus quantitatively more important around downbreaks than around upbreaks. Using the contributions of capital accumulation based on individual contributions, a t-test reveals that the contributions between upbreaks and downbreaks differ significantly from each other at the one percent significance level.[40]

[40] The t-statistic equals 2.9 and has a p-value of 0.0048. The test assumes unequal variances across the two samples.

Table 3: Nonparametric Growth Accounting around Growth Decelerations

	Before Downbreak	After Downbreak	Difference Between Growth Regimes
Average Annual Growth Rate of Income per Capita	4.63	0.14	-4.49
Productivity Changes	2.08	-0.62	-2.70
Efficiency Changes	1.39	-0.98	-2.37
Technological Changes	0.69	0.36	-0.33
Capital Deepening	2.40	0.47	-1.92
Changes in Labor Force Participation	0.12	0.30	0.18
Number of Observations	54	54	54
Contribution to Growth			
Capital Accumulation (based on individual contributions)	49.19 %		
Capital Accumulation (based on average contributions)	42.82 %		

Growth decelerations are derived using the Bai-Perron methodology as described in section 3. The growth rates before and after the structural breaks are the average growth rates in the ten years preceding and the ten years following the structural break.

Table 4 summarizes the importance of capital accumulation, efficiency changes and technological changes for growth accelerations and decelerations depending on the countries' level of development in the year preceding the structural break. The state of development is determined as explained in section 3.3. The table indicates the percentage of growth rate changes between regimes that can be explained by each growth component. As mentioned in the introduction, capital accumulation is expected to be more important in developing compared to developed countries based on the literature on industrialization and poverty traps. The literature on the diffusion of technology[41] predicts that rich countries are typically leader countries that innovate and develop new technologies. Poor countries, on the other hand, benefit mainly from imitating and implementing already discovered technologies. In terms of the production frontier, rich countries are therefore expected to shift the production frontier so that technological change should account for some part of their changing growth rates. Poor countries, on the other hand, are mainly expected to move towards the technology frontier so that efficiency changes should be more important.

Focusing on the importance of capital accumulation in phases of accelerating growth the theoretical considerations are not supported by the empirical findings.

[41] Important contributions are Nelson and Phelps (1966), Krugman (1979), Segerstrom (1991), and Barro and Sala-i Martin (1997).

Table 4: Nonparametric Growth Accounting and the State of Development

	Contribution to Growth Rate Change Between Regimes	High Income Countries	Middle Income Countries	Low Income Countries
Upbreaks				
	Efficiency Change	-8.09%	46.17%	66.25%
	Technological Change	39.68%	21.25%	-2.45%
	Capital Accumulation	34.09%	23.36%	23.97%
	Labor Force Participation Change	31.84%	7.90%	10.49%
	Observations	4	6	24
Downbreaks				
	Efficiency Change	40.14%	62.62%	53.84%
	Technological Change	9.71%	7.32%	5.10%
	Capital Accumulation	48.52%	35.65%	45.01%
	Labor Force Participation Change	-0.18%	-7.02%	-4.28%
	Observations	22	15	17

The structural breaks are derived using the Bai-Perron methodology as described in section 3. The contributions to growth indicated in the table are based on the average growth contribution of each component.

Capital accumulation proves itself most important in high income countries, where it explains 34% of the growth rate change. In middle and low income countries capital accumulation only explains roughly one fourth of the growth rate changes. The predictions concerning the diffusion of technology are supported. In high income countries 40% of the accelerating growth rate is explained by faster technological change. Efficiency, on the other hand, contributes negatively to the observed growth rate, which might reflect problems of adjusting to new technologies or problems of restructuring. Middle income countries profit much more from efficiency changes, which explain 46% of the increased growth rate. Faster technological advances are important, too, though on a lower scale than in high income countries. Low income countries, on the other hand, experience slower technological progress in accelerating growth episodes than before. Growth is primarily driven by improvements in efficiency, which explain 66% of the increased growth rate. For low income countries, a strategy aimed at adopting existing technology seems to pay off.

The second part of Table 4 deals with downbreaks. Capital accumulation accounts for roughly 50% of the lower growth rate in high and low income countries. It is less important for middle income countries, where only 35% of the growth rate difference is explained by capital accumulation. The negative evolution of productivity in growth decelerations is mainly due to a worsening of efficiency in all types of countries. Slower technological change only accounts for 10% of the growth rate change in high income countries and even less in middle and low income countries. Efficiency change, on the other hand, accounts for 40% of the difference in growth rates in high income countries, 63% in middle income countries and 54% in low income countries.

Finally, Table 5 presents the average levels of efficiency of the countries in the years preceding an upbreak or a downbreak, respectively. Intuition suggests that growth accelerations can happen most easily when countries find themselves far from the production frontier and have ample easy opportunities to catch up. Downbreaks, on the other hand, are likely to happen in situations in which increases in efficiency become more difficult to achieve, i. e. at relatively high levels of efficiency. Table 5 confirms this intuition. For instance, if all countries are considered, upbreaks on average happen at an efficiency level of 0.54, whereas downbreaks are linked with a considerably higher efficiency level of 0.72.

To sum up, the calculations point at the paramount importance of productivity changes both for the explanation of growth accelerations and decelerations. Upbreaks and downbreaks are asymmetric events in the sense that decelerations of growth are to a larger extent driven by capital accumulation changes than accelerations of growth. The consideration of efficiency scores and changes supports the idea that high income countries are innovators whereas low income countries are imitators in terms of the technology diffusion literature. Moreover, growth accelerations tend to happen when countries find themselves at relatively low levels of efficiency and catching up is therefore easier, whereas downbreaks tend to happen at relatively high levels of efficiency.

4.5 A comparison to the literature

In this section the deviations between my nonparametric growth accounting results and the results obtained by Jones and Olken (2005) are shortly analyzed. Table 6 summarizes the contributions of capital accumulation and productivity changes to observed growth rate changes in income per capita as obtained by the different meth-

Table 5: Average Level of Efficiency Preceding Structural Breaks

	All Countries	High Income Countries	Middle Income Countries	Low Income Countries
Upbreak	0.53 (34)	0.81 (4)	0.67 (6)	0.45 (24)
Downbreak	0.72 (54)	0.84 (22)	0.71 (15)	0.59 (17)

The structural breaks are derived using the Bai-Perron methodology as described in section 3. The number in parentheses indicates the number of observations available for each category.

ods. In order to ensure as much comparability as possible, the numbers reported for Jones and Olken (2005) refer to their growth accounting specification including adjustments for labor force participation, but excluding adjustments for human capital and electricity consumption. However, the calculated contributions of capital accumulation and productivity changes would be similar if other specifications were chosen.

In the chosen growth accounting approach Jones and Olken (2005) decompose the per capita growth rate changes into the part accounted for by growth in capital stock per capita (as opposed to this paper using capital per worker), the part accounted for by changing labor force participation and the part accounted for by Hicks-neutral technological progress. The resulting explanatory power of capital accumulation to growth rate changes is low: if the five years before and after an upbreak are compared, only seven percent of the growth rate change between regimes can be explained by capital accumulation. The same is true if the long-run, i. e. the whole duration of a growth regime, is considered. With regard to downbreaks the respective contributions of capital are 19% and 25.6%. A comparison of the short-run contributions of capital to those obtained by nonparametric growth accounting reveals that Jones and Olken's (2005) contribution of capital is more than 15 percentage points lower both for upbreaks and for downbreaks. Accordingly, their contributions of productivity changes are higher.

This paper and the paper by Jones and Olken (2005) differ both in the determination of break points and the method of growth accounting. To understand the influence of the growth accounting methods, traditional growth accounting was replicated with the new data and newly calculated structural breaks.[42] The contribution of capital to growth rate changes in the case of upbreaks remains much higher (17.8%) than the one obtained by Jones and Olken (2005) even though it falls somewhat compared to the nonparametric growth accounting results. For downbreaks the calculated

[42] The growth accounting formula in terms of the established notation runs as follows: $g_{\tilde{y}} = \alpha g_k + g_{lfp} + g_A$. α is set to 1/3.

Table 6: Comparison of Growth Accounting Around Structural Breaks

	Upbreaks			Downbreaks		
Contribution to Growth Rate Change:	Capital accumulation	Productivity Change	Obs.	Capital accumulation	Productivity Change	Obs.
Jones und Olken (2005) (short-run)	6.9%	91.2%	29	19.0%	83.8%	39
Jones und Olken (2005) (long-run)	6.9%	90.2%	29	25.6%	80.0%	39
Nonparametric Growth Accounting	24.6%	62.5%	34	42.8%	60.2%	54
Traditional Growth Accounting with Capital Stock per Worker	17.8%	70.7%	34	32.7%	71.0%	54
Traditional Growth Accounting with Capital Stock per Capita	21.8 %	70.5 %	34	31.4 %	71.3 %	54

The contributions of capital accumulation and productivity changes to growth rate changes in the case of Jones and Olken (2005) are calculated using the averages reported in their Tables 4A and 4B. The calculations assume that GDP and capital per capita growth rates in the somewhat smaller labor force participation sample are identical to those observed in the full sample. When the contributions of capital accumulation and productivity changes to growth rate changes do not add up to one, changes in labor force participation have occurred (not reported here). All parametric growth accounting calculations assume a physical capital share of 1/3.

contribution of the capital stock diminishes to 32.7%, a number that is lower than in the nonparametric growth accounting case but still higher than the one obtained by Jones and Olken (2005). These results indicate that the use of nonparametric growth accounting is responsible for some of the increased explanatory power of capital accumulation.[43] Yet, the change of methodology only explains roughly one half of the differences between the results, so that something else has to be of importance, too.

An obvious candidate to explain the differences is Jones and Olken (2005)'s use of capital stock per capita instead of capital stock per worker. Therefore, traditional growth accounting using the capital stock per capita and the new data has been implemented, too.[44] The difference between the two growth accounting specifications is negligible. While the explanatory power of capital accumulation decreases for growth

[43] This finding is common. Cf. Henderson and Russell (2005) or Kumar and Russel (2002) as prominent examples.

[44] The growth accounting formula now runs $g_{\tilde{y}} = \alpha g_{\tilde{k}} + (1-\alpha) g_{lfp} + g_A$ with $\tilde{x}$ representing per capita values and α equal to 1/3. Since both this and the previous growth accounting formula are based on a Cobb Douglas production function using the aggregate capital stock and the number of workers as factor inputs, the contribution of productivity changes should remain unchanged. The slight observed changes point at minor inaccuracies in the data base.

decelerations, it increases for growth accelerations (see last row of Table 6). Since the remaining data is comparable between the two studies[45] and the same method is used for the construction of the capital stock, a reasonable conjecture is that the differing testing procedures used to determine the structural breaks are partly responsible for the differences in results. It seems unlikely that the length of time before and after a structural break can account for much of the deviations, because, as Jones and Olken (2005) show, their results hardly change even when the very long run is considered.

5 Robustness of the Results

In this section the robustness of the results is analyzed from two angles. First, some considerations regarding the sample choice are reported. Second, the importance of adjusting labor for quality is considered.

5.1 Choice of sample

Methods based on DEA have the merit of requiring very few assumptions. This flexibility, however, has the drawback that the calculations are by construction very sensitive to extreme values and outliers. Therefore, the results of the previous section should be checked for their robustness. The literature has developed some methods such as the use of influence functions or the order-m approach that help with identifying potentially atypical observations (Wilson (1993), Simar (2003), and Cazals, Florens, and Simar (2002)). Unfortunately, the influence function approach becomes computationally prohibitive in larger samples. The order-m approach is well suited for frontiers involving many observations for a single period. Its implementation is more difficult in an intertemporal context such as in this paper, so that the application of the order-m approach is left as a future research task. Nevertheless, even without using a formal method to flag potential outliers a robustness check of the results is possible. The suggested methods are not automatic procedures but only give indications as to which observations should be scrutinized. It is always up to the researcher to determine what to do with a flagged observation and the decision is ultimately based on the influence an observation has on the overall results (Simar (2003)). Therefore, a valid approach to check the robustness of the results is to focus on frontier defining countries, i. e. those countries that are potentially suspiciously efficient and bias the production possibility set upwards, and analyze how the results change if some of these countries are eliminated from the sample. The focus of the

[45] Unfortunately, it is not clear whether Jones and Olken (2005) used GDP deflated by the Laspeyres or by the chain index.

robustness check in this paper is on low income countries. It seems unreasonable to check the robustness of the results by leaving out high income countries as these are precisely the countries that are expected to determine the production frontier.

As a starting point of the robustness check all countries used in section 3 are included in the initial calculations. After that, observations determining the boundaries of the production possibility set for very long periods of time and the respective countries are identified. These potentially influential countries are then stepwise eliminated from the sample and the results are recalculated in order to analyze the extent of influence of the respective observations. If the results change markedly by the elimination of a country, this indicates unusual input-output combinations so that the country should indeed be dropped to avoid biased technology frontiers. If, on the other hand, the results change little despite the elimination of a country, similar countries have to be available in the sample and the values of the dropped country are not extreme. For ease of exposition, the following discussion focuses on the stability of capital's contribution to growth rate changes. Of course, the other components of the growth accounting decomposition are also sensitive to the choice of sample. Therefore, a more detailed compilation regarding the impact of sample changes can be found in Appendix B.

If all countries of section 3 are used in the nonparametric growth accouting calculations, the frequency and persistency of Jordan as a frontier defining country arouses suspicion. The input-output combinations of the years 1954, 1958, 1959 and 1967 define the boundaries of the production possibility set up to the year 2004. Therefore, the calculations are repeated without Jordan. As a result, the contribution of capital deepening to growth rate changes increases markedly - in upbreaks it accounts for 30 % instead of 22 % and in downbreaks it accounts for 46 % instead of 42 % (Table 7). Once Jordan is dropped from the sample, other countries such as Nicaragua, Costa Rica or El Salvador start to determine the boundaries of the production set for small capital stocks per worker for long periods of time. However, dropping these countries does not change the results of the tripartite decomposition nearly as much as the elimination of Jordan. Apparently, there are enough countries in the sample that are similar enough to yield comparable production frontiers. Therefore, only Jordan is identified as a potential extreme value and left out in the preferred specification.

The case to eliminate Gabon from the sample is most obvious in Figure 4. Gabon becomes a frontier defining country in 1976 and remains so until the end of the sample. In 1976 income per worker in Gabon is the highest in the world, even exceeding that of

Table 7: The Effect of Eliminating Countries From the Original Sample on the Importance of Capital Deepening

Contribution of Capital Deepening to Growth Rate Changes		
	Upbreaks	Downbreaks
All Countries from Section 2	21.86%	41.99%
All countries excluding Jordan	30.11%	46.19%
All Countries excluding Jordan, Nicaragua	31.79%	46.81%
All Countries excluding Jordan, Nicaragua and Costa Rica	28.03%	49.54%
All Countries excluding Jordan, Nicaragua, Costa Rica and El Salvador	27.97%	48.68%

This table shows the sensitivity of results with respect to the sample choice. Countries were excluded if observations of a particular country defined the world technology frontiers for long periods of time.

advanced Western economies such as the United States or Switzerland. Capital stock per worker, on the other hand, is of a magnitude generally found in middle income countries. It is unreasonable to assume that this observation is not driven by extraordinary factors. And indeed, the high income per worker can be explained by offshore oil production in Gabon. Clearly, if Gabon is retained in the sample, the results will be biased. Suppose that the technology frontier for the next year remains unchanged and suppose that a country extends its capital stock per worker and experiences growth. If the country in question is, for instance, the United Kingdom, none of the resulting growth would be attributed to the enlarged capital stock, because the technology frontier would be flat from Gabon onwards. On the other hand, if the country had a lower capital stock per worker than Gabon, a large part of the resulting growth would be attributed to capital deepening because the technology frontier would be very steep in this region. If Gabon were eliminated from the sample, the technology frontier would be less steep for the low capital stock country and steeper for the high capital stock country. Therefore, the contribution of capital accumulation to growth would become less and more important, respectively. It follows that Gabon heavily influences the growth accounting results and should be excluded from the preferred sample.[46] Figure 4 also provides further support for the exclusion of Jordan in the preferred sample. The figure includes the input-output combinations of Jordan for the years 1954, 1958 and 1959. Even in 1976, i. e. 20 years later than the original data were collected, no country comes close to a comparably high income per worker with a comparably low capital stock per worker. The exclusion of Jordan is corroborated.

[46] Table 7 shows the impact of Jordan on the capital contribution with Gabon included in the sample. Qualitatively, the results do not change if Gabon is excluded.

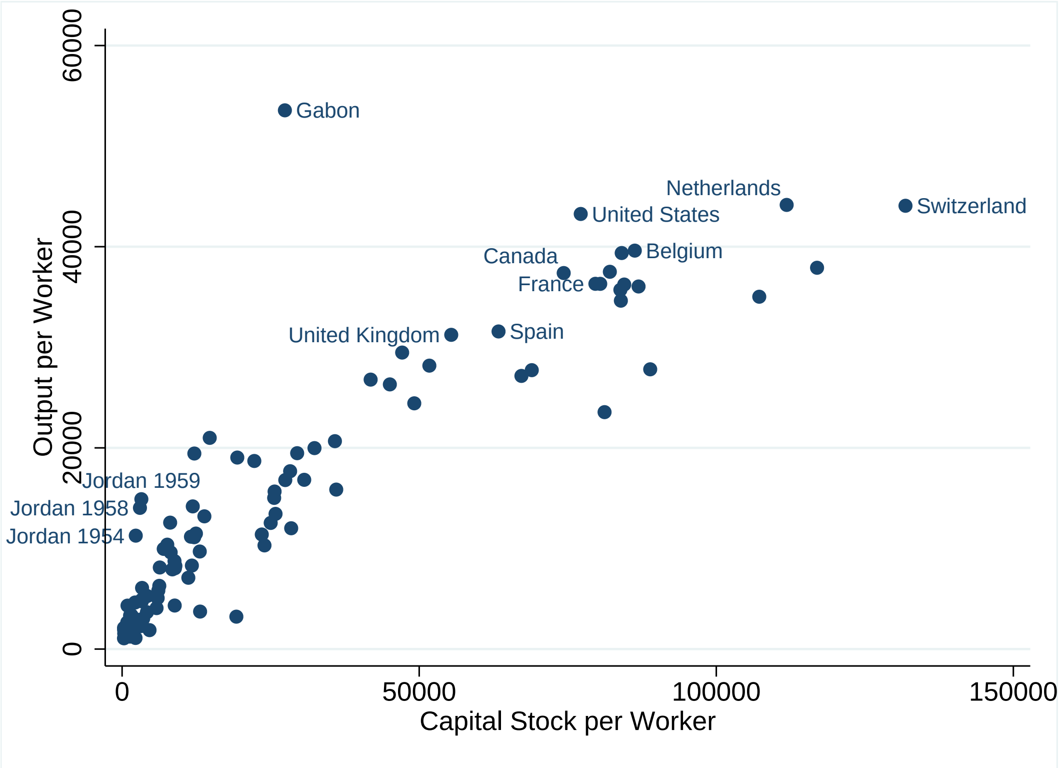

Figure 4: Input-Output combinations in 1976

5.2 Quality Adjusted Workforce

This section investigates the robustness of the nonparametric growth accounting results with regard to quality adjusted labor inputs. The parametric growth accounting literature has started very early to use more sophisticated measures of labor in order to reduce the magnitude of the growth accounting residual (Denison (1962), Jorgenson and Griliches (1967)). Subsequently, theoretical contributions such as Lucas (1988) or Romer (1990) as well as empirical contributions (Barro (1991), Mankiw, Romer, and Weil (1992), Benhabib and Spiegel (1994)) identified human capital as an important determinant of growth. Therefore, it is a natural question to ask whether the results of the previous section continue to hold if labor is quality adjusted. The usual approach to incorporate human capital in a cross-country analysis is to focus on education only, because otherwise the data constraint becomes insurmountable. Even this modest approach leads to a considerable loss of data points because education data is only available for a subset of countries and time periods.

Human capital is constructed following Hall and Jones (1999), and Bils and Klenow (2000). By assumption, the efficiency of labor increases proportionally with wages and wages rise with the years of schooling. Following Psacharopoulos (1994) and evidence from Mincerian wage equations, the returns to education exhibit diminishing returns. Formally, the human capital stock H of a worker in economy j at time t is defined as

$$H_{jt} = e^{\xi(s_{jt})}, \tag{27}$$

where s denotes the years of schooling an average worker is endowed with. ξ is a piecewise linear function with zero intercept and a slope of 0.134 for the first four years of education, 0.101 for the fifth to eighth year of education and 0.068 for education beyond the eighth year. Thus, economy j at time t uses a total amount of $\hat{L}_{jt} = L_{jt}e^{\xi(s_{jt})}$ efficiency units of labor. The production frontier in this context is calculated as in equation (12) with $L_{j\tau}$ being replaced by $\hat{L}_{j\tau}$. The decomposition in equation (19) is reformulated in terms of efficiency units of labor (denoted by the hat symbol) and extended by yet another factor that accounts for the growth of human capital. The final decomposition becomes

$$\begin{aligned} \frac{\tilde{y}_c}{\tilde{y}_b} &= \frac{\hat{y}_c}{\hat{y}_b}\frac{lfp_c}{lfp_b}\frac{H_c}{H_b} \\ &= \frac{\phi_c}{\phi_b}\left(\frac{\hat{\bar{y}}_c(\hat{k}_c)}{\hat{\bar{y}}_b(\hat{k}_c)}\frac{\hat{\bar{y}}_c(\hat{k}_b)}{\hat{\bar{y}}_b(\hat{k}_b)}\right)^{1/2}\left(\frac{\hat{\bar{y}}_b(\hat{k}_c)}{\hat{\bar{y}}_b(\hat{k}_b)}\frac{\hat{\bar{y}}_c(\hat{k}_c)}{\hat{\bar{y}}_c(\hat{k}_b)}\right)^{1/2}\frac{lfp_c}{lfp_b}\frac{H_c}{H_b} \\ &:= EFF \cdot TECH \cdot KACCUM \cdot LFP \cdot HACCUM. \end{aligned} \tag{28}$$

The data on the average years of schooling is taken from Barro and Lee (2000) and is available at five year intervals. Between data points the average years of schooling are obtained via linear interpolation.[47]

The availability of education data reduces the sample used in this section to 87 countries that experience a total of 66 of the previously calculated breaks. The total years of schooling are only available from 1960 onwards so that only breaks occuring in 1970 or later can be considered.[48] Against this background it is unreasonable to expect the exact numbers from section 4 to hold. However, it would be reassuring if the main conclusions as summarized at the end of section 4.4 continued to hold. Table 8 summarizes the relative contributions to growth attributable to the different factors in equation (28) and the average level of efficiency in the year preceding a growth regime change.

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47 Although unusual, linear interpolation of education data has also been used by Bassanini and Scarpetta (2001) and Engelbrecht (1997).

48 As this section is meant to test the robustness of the previous results, the break dates were not calculated anew for the shorter time series. Rather, all breaks occuring before 1970 were simply discarded.

The upper part of Table 8 relates to upbreaks, the lower part to downbreaks. In the first column the average of growth regime changes in all countries is reported. The paramount importance of productivity changes for both accelerations (65 %) and decelerations (67 %) and the finding that upbreaks happen at lower levels of efficiency (0.51) than downbreaks (0.69) are supported. The asymmetry between upbreaks and downbreaks, however, no longer holds. The importance of capital accumulation increases in upbreaks and decreases in downbreaks, making it essentially equally important for both types of breaks (32 %). Human capital explains less than 7% of the increased growth rate around upbreaks. Around downbreaks, human capital contributes negatively to the explanation of growth rate changes, indicating that human capital continued to grow even in times of economic downturn.

The more detailed decomposition of upbreaks and downbreaks depending on the level of development reveals that low income countries continue to experience catch-up growth around upbreaks. 59 % of the observed growth rate changes are results of improved efficiency. Technological progress slows down during an upbreak, which is mirrowed in its negative relative contribution. The results for high and middle income countries differ from those in the previous section. Productivity changes and therein efficiency changes are much more important than before (more than 80 % and 60 %, respectively). However, the result for high income countries is generated by one observation, namely Ireland, where a structural break was recorded for 1994. Middle income countries have four observations with the earliest upbreak occurring in 1984 and the other upbreaks occuring in 1993 or 1994. Due to the small number of observations the results for high and middle income countries cannot be well interpreted. They might indicate that recent upbreaks in relatively well-off countries are driven by different forces than earlier upbreaks. However, the results may equally well be an artefact of the sample restrictions. For low income countries and hence for the only category comprising enough observations to reasonably draw conclusions, it is justified to say that the results around upbreaks do not change radically with the introduction of human capital.

With regard to downbreaks, it seems that the introduction of human capital has boosted the importance of technological change and diminished the contribution of capital deepening as explanatory factors of growth rate declines in high and middle income countries. Productivity changes now explain around 80 % of the growth rate decline, whereas the contribution of capital accumulation to growth rate changes di-

Table 8: Source of Growth Rate Changes Including Human Capital

Relative Contributions	Total Average	High Income Countries	Middle Income Countries	Low Income Countries
Upbreaks				
Annual Growth				
Productivity	64.75%	88.61%	87.59%	57.52%
Efficiency	63.24%	61.59%	81.69%	58.71%
Technology	1.37%	25.91%	5.66%	-1.25%
Capital Deepening	32.09%	16.84%	13.13%	37.81%
Human Capital	6.70%	19.91%	8.97%	5.31%
Labor Force Participation	8.59%	12.44 %	7.0 %	8.75 %
Level of Efficiency	0.51	0.68	0.62	0.47
Observations	20	1	4	15
Downbreaks				
Annual Growth				
Productivity	66.84%	83.14%	75.44%	40.14%
Efficiency	44.12%	45.12%	51.10%	34.89%
Technology	22.50%	37.43%	24.20%	5.33%
Capital Deepening	31.58%	13.38%	28.40%	53.83%
Human Capital	-4.67%	-3.11%	-2.06%	-9.32%
Labor Force Participation	-4.36%	-0.90%	-7.47%	-4.22%
Level of Efficiency	0.69	0.80	0.63	0.59
Observations	46	19	14	13

minishes to 13 % in high income countries and 30 % in middle income countries.[49] In low income countries capital deepening now explains more than 50 % of the growth rate changes and efficiency changes become less important (35 % instead of the former 53 %). Nevertheless, the asymmetry of growth accelerations and growth decelerations is no longer observable. Human capital continues to grow in all types of countries despite growth decelerations as the negative contribution rates of human capital show.

6 Conclusion

This article has been inspired by Jones and Olken's (2005) finding that capital deepening has little impact on the acceleration or deceleration of growth rates, but that it is rather productivity changes that are important. Since the importance of productivity change in the medium run is both a novel and theoretically unexpected finding and since Jones and Olken (2005) derive their results conditional on the strict assumptions of parametric growth accounting, a validation of the results relying on a different method seems desirable. To this end, this paper applies the combined double maximum $\text{supF}_T(\ell+1|\ell)$ testing procedure for the derivation of structural breaks in economic growth, which has more power than the originally used $\text{supF}_T(\ell+1|\ell)$ test. Afterwards, the proximate sources of growth are determined using a nonparametric growth accounting approach. This approach has the advantage of requiring fewer assumptions than parametric growth accounting. In particular, the functional form of the production function is not defined beforehand so that the elasticity of substitution between factors is determined by the data. The same is true for the nature of technological progress. Furthermore, no assumption regarding the market structure is involved. The approach is therefore well suited to test whether the results by Jones and Olken (2005) are a consequence of the assumptions implicit in their calculations or whether they continue to hold in a much more flexible environment.

Notwithstanding the increased flexibility of nonparametric growth accounting the results by Jones and Olken (2005) are largely confirmed. Despite a somewhat increased ability of capital accumulation to explain growth regime changes, productivity changes remain the crucial part of the explanation. This finding is robust not only to the method, but also to the state of development, to the inclusion of human capital and to changes in the choice of countries. The asymmetry between growth accelerations

[49] This change in results is not an effect of the sample change: if the productivity frontier is calculated without human capital for the smaller sample the relative contribution of capital deepening and technology are similar to those reported in Table 4. A table containing these results is available upon request.

and decelerations with respect to the importance of capital deepening is confirmed in the absence of human capital, but not in the presence of it. The ability of nonparametric growth accounting to discriminate between productivity changes due to technological progress or productivity changes due to efficiency changes further shows that growth accelerations in poor countries are catch-up growth episodes whereas in middle and high income countries they are (partly) a result of genuine technological progress. It follows that policy measures aimed at increasing growth should differ between the types of countries. Whereas policies facilitating catch-up should be implemented in low income countries, middle and high income countries should also rely on policy measures supporting innovation capacities.

Several extensions of this paper are conceivable. As indicated in the main text the robustness of nonparametric growth accounting is an issue. While it is reassuring that parametric and nonparametric growth accounting reach the same conclusions, it would nevertheless be of interest to implement a nonparametric growth accounting approach based on robust frontier estimation. Another obvious question concerns appropriate policy measures. While it is nice to know that developing countries tend to experience catch-up growth in growth accelerations whereas high and middle income countries also benefit from innovation, it would be fruitful to know more about what kind of policy measure can assist with the acceleration of growth. In particular, it would be interesting to differentiate between measures that are supporting catch-up growth and measures that are supporting technological progress in the sense of frontier shifts. The decomposition of productivity changes into technological and efficiency changes is a prerequisite to progress in this direction. Finally, the finding of manifold structural breaks in the countries' growth rates and the varying importance of efficiency and technological changes or factor accumulation changes depending on the countries' state of development underlines the need for a theory of growth that explicitly allows countries to be in different states. A state should at the very least be characterized by the typical level of income and by the prevailing rate of growth. As the frequent structural breaks indicate countries have to be able to switch between states. The challenge lies in defining how growth in particular states and growth transitions between states are governed.[50] As Pritchett (2006) points out such a flexible model would be of much use for finding growth strategies that are suited to the particulars and constraints different countries find themselves in.

[50] A first attempt at the empirical estimation of transition probabilities has been made by Jerzmanowski (2006).

References

Acemoglu, D. (1998). Why do New Technologies Complement Skills: Dircted Technical Change and Wage Inequality. *Quarterly Journal of Economics 113*, 1055–1089.

Acemoglu, D. (2002). Technical Change, Inequality, and the Labor Market. *Quarterly Journal of Economics 40*, 7–72.

Acemoglu, D. and F. Zilibotti (1997). Was Prometheus Unbound by Chance? Risk, Diversification, and Growth. *Journal of Political Economy 105*, 709 – 751.

Aghion and Howitt (1992). A Model of Growth Through Creative Destruction. *Econometrica 60*, 323–351.

Autor, D. H., F. Levy, and R. J. Murnane (2003). The Skill Content Of Recent Technological Change: An Empirical Exploration. *Quarterly Journal of Economics 118*, 1279–13333.

Badunenko, O., D. J. Henderson, and V. Zelenyuk (2005). Technological Change and Transition: Relative Contributions to Worldwide Growth During the 1990's. *Institute of Statistics, University Catholique de Louvain, Discussion Paper 0509*.

Bai, J. and P. Perron (1998). Estimating and Testing Linear Models with Multiple Structural Changes. *Econometrica 66*, 47–78.

Bai, J. and P. Perron (2003). Computation and Analysis of Multiple Structural Change Models. *Journal of Applied Econometrics 18*, 1–22.

Bai, J. and P. Perron (2004). Multiple Structural Change Models: A Simulations Analysis. *Manuscript, Department of Economics, Boston University*.

Barro, R. (2003). *Economic Growth*. Cambridge: MIT Press.

Barro, R. and X. Sala-i Martin (1997). Technological Diffusion, Convergence, and Growth. *Journal of Economic Growth 2*, 1–26.

Barro, R. J. (1991). Economic Growth in a Cross Section of Countries. *Quarterly Journal of Economics 106*, 407–443.

Barro, R. J. and J.-W. Lee (2000). International Data on Educational Attainment: Updates and Implications. *NBER Working Paper*.

Bassanini, A. and S. Scarpetta (2001). Does Human Capital Matter for Growth in OECD Countries? Evidence from Pooled Mean-Group Estimates.

Battese, G., T. Coelli, and D. Rao (1998). *An Introduction to Efficiency and Productivity Analysis*. London: Kluwer Academic Publisher.

Becker, T. and P. Mauro (2006). Output Drops, and the Shocks that Matter. *IMF Research Department*.

Ben-David, D. and D. H. Papell (1998). Slowdowns and Meltdowns: Postwar Growth Evidences From 74 Countries. *Review of Economics and Statistics 0*, 561–571.

Benhabib, J. and M. M. Spiegel (1994). The Role of Human Capital in Econmic Development: Evidence From Aggregate Cross–Country Data. *Journal of Monetary Economics 34*, 143–173.

Berg, A., J. Ostry, and J. Zettelmeyer (2006). What Makes Growth Sustained? *Manuscript, IMF*.

Bils, M. and P. J. Klenow (2000). Does Schooling Cause Growth? *American Economic Review 90*, 1160 – 1183.

Blanchard, O., W. Nordhaus, and E. Phelps (1997). The Medium Run. *Brookings Papers on Economic Activity 1997*, 89–158.

Brown, R. L., J. Durbin, and M. Evans (1975). Techniques for Testing the Constancy of Regression Relationships over Time. *Journal of the Royal Statistical Society, Series B 37*, 149–192.

Card, D. and J. DiNardo (2002). Skill-Biased Technological Change and Rising Wage Inequality: Some Problems and Puzzles. *Journal of Labor Economics 20*, 733–783.

Caselli, F. (1999). Technological Revolutions. *American Economic Review 89*, 78–102.

Caselli, F. (2004). Accounting for Cross-Country Income Differences. *NBER Working Papers 10828*.

Caves, D. W., L. R. Christensen, and E. W. Diewert (1982). The Economic Theory of Index Numbers and the Measurement of Input, Output and Productivity. *Econometrica 50*, 1393–1414.

Cazals, C., J.-P. Florens, and L. Simar (2002). Nonparametric Frontier Estimation: A Robust Approach. *Journal of Econometrics 106*, 1–25.

Cook, P. and Y. Uchida (2002). Productivity Growth in East Asia: A Reappraisal. *Applied Economics 34*, 1195–1207.

Crafts, N. F. R. (2003). Quantifying the Contribution of Technological Change to Economic Growth in Different Eras: A Review of Evidence. *London School of Economics 79/03*.

Denison, E. (1962). *The Sources of Economic Growth in the United States and the Alternatives Before Us*. Committee for Economic Development.

Diewert, W. (1980). Capital and the Theory of Productivity Measurement. *The American Economic Review 70*, 260–267.

Dovern, J. and P. Nunnenkamp (2006). Aid and Growth Accelerations: An Alternative Appraoch to Assess the Effectiveness of Aid. *Kiel Working Paper 1296*.

Duffy, J. and C. Papageorgiou (2000). A Cross–Country Empirical Investigation of the Aggregate Production Function Specification. *Journal of Economic Growth 5*, 87–120.

Easterly, W., M. Kremer, L. Pritchett, and L. H. Summers (1993). Good Policy or Good Luck? Country Growth Performance and Temporary Shocks. *Journal of Monetary Economics 32*, 459–483.

Easterly, W. and R. Levine (2001). It's Not Factor Accumulation: Stylized Facts and Growth Models. *The World Bank Economic Review 15*, 177–219.

Enflo, K. and P. Hjertstrand (2006). Relative Sources of European Regional Productivity Convergence: A Bootstrap Frontier Approach. *Manuscript, Lund University*.

Engelbrecht, H. (1997). International R&D Spillovers, Human Capital and Productivity in OECD Economies: An Empirical Investigation. *European Economic Review 41*, 1479–1488.

Farrell, M. (1957). The Measurement of Productive Efficiency. *Journal of the Royal Statistical Society. Series A 120*, 253–290.

Felipe, J. and F. M. Fisher (2003). Aggregation in Production Functions: What Applied Economists Should Know. *Metroeconomica 54*, 208–262.

Färe, R., S. Grosskopf, and C. K. Lovell (1994). *Production Frontiers*. Cambridge: Cambridge University Press.

Färe, R., S. Grosskopf, M. Norris, and Z. Zhang (1994). Productivity Growth, Technical Progress, and Efficiency Change in Industrialized Countries. *American Economic Review 84*, 66–83.

Galor, O. and O. Moav (2004). From Physical to Human Capital Accumulation: Inequality and the Process of Development. *Review of Economic Studies 71*, 1001–1026.

Gollin, D. (2002). Getting Income Shares Right. *Journal of Political Economy 110*, 458–474.

Grosskopf, S. (1993). Efficiency and Productivity. In H. Fried, C. Lovell, and S. Schmidt (Eds.), *The Measurement of Productive Efficiency: Techniques and Applications*, pp. 160–194. Oxford: Oxford University Press.

Hall, R. and C. I. Jones (1999). Why Do Some Countries Produce So Much More Output per Worker than Others? *Quarterly Journal of Economics 114*, 83–116.

Harrison, A. E. (2002). Has Globalization Eroded Labor's Share? Some Cross-Country Evidence . *Manuscipt, UC Berkeley*.

Hausmann, R., L. Pritchett, and D. Rodrik (2005). Growth Accelerations. *Journal of Economic Growth 10*, 303–329.

Hausmann, R., F. Rodriguez, and R. Wagner (2006). Growth Collapses. *CID Working Paper 136.*

Henderson, D. J. and R. R. Russell (2005). Human Capital and Convergence: A Production–Frontier Approach. *International Economic Review 46*, 1167–1205.

Heston, A., R. Summers, and B. Aten (2006). Penn World Table Version 6.2. *Center for International Comparisons of Production*.

Islam, N. (1995). Growth Empirics: A Panel Data Approach. *The Quarterly Journal of Economics 110*, 1127–1170.

Jerzmanowski, M. (2006). Empirics of Hills, Plateaus, Mountains and Plains: A Markov–Switching Approach to Growth. *Journal of Development Economics 81.*

Jones, B. F. and B. A. Olken (2005). The Anatomy of Start-Stop Growth. *NBER Working Paper 11528.*

Jorgenson, D. and Z. Griliches (1967). The Explanation of Productivity Change. *The Review of Economic Studies 34*, 249–283.

Krüger, J., U. Cantner, and H. Hanusch (2000). Total Factor Productivity, the East Asian Miracle and the World Production Frontier. *Weltwirtschaftliches Archiv 136*, 111–36.

Krugman, P. (1979). A Model of Innovation, Technology Transfer, and the World Distribution of Income. *The Journal of Political Economy 87*, 253–266.

Kumar, S. and R. R. Russel (2002). Technological Change, Technological Catch–up, and Capital Deepening: Relative Contributions to Growth and Convergence. *American Economic Review 92*, 527–548.

Kumbhakar, S. and C. Lovell (2000). *Stochastic Frontier Analysis.* Cambridge: Cambridge University Press.

Levine, R. and D. Renelt (1992). A Sensitivity Analysis of Cross–Country Growth Regressions. *American Economic Review 82*, 942–963.

Los, B. and M. P. Timmer (2005). The 'Appropriate Technology' Explanation of Productivity Growth Differentials: An Empirical Approach. *Journal of Development Economics 77*, 517–531.

Lucas, R. E. (1988). On the Mechanics of Economic Development. *Journal of Monetary Economics 22*, 3–42.

Machin, S. and J. Van Reenen (1998). Technology and Skill Structure: Evidence from Seven OECD Countries. *Quarterly Journal of Economics 109*, 367–397.

Mankiw, G. N., D. Romer, and D. N. Weil (1992). A Contribution to the Empirics of Economic Growth. *Quarterly Journal of Economics 107*, 407 – 437.

Murphy, K., A. Shleifer, and R. Vishny (1989). Income Distribution, Market Size, and Industrialization. *Quarterly Journal of Economics* (3), 537–64.

Nehru, V. and A. Dhareshwar (1993). A New Database on Physical Capital Stock: Sources, Methodology and Results. *Revista de Analisis Economico 8*, 37–59.

Nelson, R. (1973). Recent Exercises in Growth Accounting: New Understanding or Dead End? *American Economic Review 63*, 462–468.

Nelson, R. and E. Phelps (1966). Investment in Humans, Technological Diffusion, and Economic Growth. *American Economic Review 56*, 69–75.

Nordhaus, W. (2005). Alternative Measures of Output in Global Economic-Environmental Models: Purchasing Power Parity or Market Exchange Rates? *Report for Meeting of IPCC Expert Meeting on Emission Scenarios, January 12-14, 2005*.

Nuxoll, D. A. (1994). Diffrences in Relative Prices and International Differences in Growth Rates. *American Economic Review 84*, 1423–1436.

Porter, M. (1990). *The Competitive Advantage of Nations*. New York: Free Press.

Prescott, E. (1998). Needed: A Theory of Total Factor Productivity. *International Economic Review 39*, 525–552.

Pritchett, L. A Toy Collection, a Socialist Star and a Democratic Dud? (Growth Theory, Vietnam and the Philippines). In D. Rodrik (Ed.), *In Search of Prosperity*. Princton: Princeton University Press.

Pritchett, L. (2000). Understanding Patterns of Economic Growth: Searching for Hills among Plateaus, Mountains, and Plains. *The World Bank Economic Review 14*, 221–250.

Pritchett, L. (2006). The Quest Continues. *Finance and Development 43*, 18–22.

Psacharopoulos, G. (1994). Returns to Investment in Education: A Global Update. *World Development 22*, 1325–1343.

Ray, S. (2004). *Data Envelopment Analysis: Theory and Techniques for Economics and Operations Research*. Cambridge: Cambridge University Press.

Rodrik, D. (1997). TFPG Controversies, Institutions, and Economic Performance in East Asia. *NBER Working Paper 5914*.

Rodrik, D. (1999). Where Did All the Growth Go? External Shocks, Social Conflict, and Growth Collpses. *Journal of Economic Growth 4*, 385–412.

Romer, P. M. (1990). Endogenous Technological Change. *Journal of Political Economy 98*, 71–102.

Sahay, R. and R. Goyal (2006). Volatility and Growth in Latin America: An Episodic Appraoch. *IMF Working Paper 06/287*.

Salinas-Jimenez, M., I. Alvarez-Ayuso, and J. Delgado-Rogriguez (2006). Capital Accumulation and TFP Growth in the EU: A Production Frontier Approach. *Journal of Productivity Analysis 28*, 195–205.

Schreyer, P. (2004). Chain Index Number Formulae in the National Accounts. *8th OECD-NBS Workshop on National Accounts*.

Segerstrom, P. (1991). Innovation, Imitation, and Economic Growth. *The Journal of Political Economy 99*, 807–827.

Simar, L. (2003). Detecting Outliers in Frontier Models: A Simple Approach. *Journal of Productivity Analysis 20*, 391–424.

Solow, R. (1956). A Contribution to the Theory of Economic Growth. *The Quarterly Journal of Economics 70*, 65–94.

Summers, R. and A. Heston (1991). The Penn World Table (Mark 5) : An Expanded Set of International Comparisons, 1950 –1988. *Quarterly Journal of Economics*, 327–368.

Wilson, P. W. (1993). Detecting Outliers in Deterministic Nonparametric Frontier Models with Multiple Outputs. *Journal of Business & Economic Statistics 11*, 319–323.

Appendix A

In the main text, the Bai-Perron methodology (Bai and Perron (1998, 2003)) has been introduced in order to identify the number and dates of structural breaks in the growth rate series of different countries. In this appendix, the empirical implementation of how to determine the break dates for a *given* number of breaks is presented in more detail. Afterwards, the actual number of breaks is derived using the double maximum $\text{supF}_T(\ell + 1|\ell)$ testing procedure as described in the main text.

A pure structural change model of the form given in equation (1) is considered. For ease of exposition, the equation is repeated here.

$$g_t = \beta_i + \varepsilon_t. \tag{A1}$$

As in the main text, g_t denotes the annual growth rate of income per capita expressed in purchasing power parity, β_i marks the mean growth rate during growth regime i and ε_t is a disturbance term. There are $i = 1, ..., m + 1$ growth regimes, i. e. m break points $(T_1, ..., T_m)$ need to be determined. The break dates for a given m are determined such that the sum of squared residuals for the m-partition $(T_1, ..., T_m)$ given by (A2) is minimized subject to the minimum distance h between breakpoints.

$$S_T = \sum_{i=1}^{m+1} \sum_{t=T_{i-1}+1}^{T_i} [g_t - \beta_i]^2. \tag{A2}$$

Empirically, the optimal partition of the growth rate series is found by solving the recursive problem as given in equation (3), which is repeated here for convenience.

$$SSR(T_{m,T}) = \min_{mh \leqslant j \leqslant T-h} [SSR(T_{m-1,j}) + SSR(j + 1, T)]. \tag{A3}$$

As before, $SSR(T_{r,n})$ denotes the sum of squared residuals associated with the *optimal* partition of the time series containing r breaks and using the first n observations, $SSR(j+1, T)$ denotes the sum of squared residuals resulting from a partition starting in $(j + 1)$ and lasting until T. In the following, the steps needed to implement the recursive procedure in practice are described.

In order to solve (A3), the sum of squared residuals (SSR) resulting from different partitions needs to be known. Therefore, an upper-triangular matrix M that contains the estimated SSR for every conceivable growth regime is defined. For a time series with $T = 25$ observations matrix M is a 25×25 matrix, where the information is recorded above the principal diagonal. The rows of the matrix denote the starting and the columns of the matrix denote the ending dates of a growth regime. Hence, the entry at position $(5, 10)$, for instance, contains the estimated SSR resulting from a growth regime lasting from period 5 to period 10. It follows that the associated estimated SSR for every conceivable growth regime can be read off matrix M. The estimated total SSR for every conceivable m-partition $(T_1, ..., T_m)$ of a time series can be derived by summing up the estimated SSR for each growth regime. The estimated SSR are obtained from regressing the growth rates for the period in question[51] on a constant and from summing up the resulting squared residuals.[52]

The next step concerns the implementation of equation (A3). To this end, two further matrices are created. The first matrix, matrix L, records the minimal estimated SSR for a sample running from period 1 to the column number for a given number of breaks, which equals the row number minus one. In practice, the first line of matrix L contains the estimated SSR for a sample running from period 1 to T, 1 to $(T-1)$ etc. with no break and is therefore equal to the first line of matrix M. The second line of matrix L contains the minimal estimated SSR for a sample running from 1 to T with one structural break, the minimal estimated SSR for a sample running from 1 to $T-1$ with one structural break and so on. The structural break is chosen such that the estimated total SSR is minimized. The timing of the break is recorded in a second matrix B, which looks the same as matrix M. The minimal estimated SSR for the series running from 1 to $(T-k)$ with one break is recorded in matrix M at position $(2, T-k)$, in short $M(2, T-k)$. It is the linear combination of $L(1, T_1)+M(T_1+1, T-k)$. Correspondingly, the break period is recorded in $B(2, T-k)$.

The third line in matrix L contains the minimal estimated SSR for samples running from period 1 to the column number with two breaks imposed upon. The line is derived using the recursive procedure (A3). Intuitively, at each admissible second break period j the procedure calculates the resulting estimated total SSR from matching the break point with the corresponding optimal one-break partition and selects the break point that yields the minimal overall result. The admissible second break dates are restricted by the requirement that each growth regime has to last for at least h periods. With the first break happening before the second one, the earliest earliest admissible break date is $2h$ to ensure that the previous two growth regimes

[51] The period in questions last from the time period as indicated by the row number to the time period as indicated by the column number of the entry under consideration.

[52] Bai and Perron (2003) originally propose to compute the matrix entries using the recursive residuals formula suggested by Brown, Durbin, and Evans (1975) in order to simplify the computation and to avoid too many matrix inversions. However, the use of estimated residuals instead of recursive residuals does not constitute a problem, since the original distributions and sequential procedures are derived in terms of estimated residuals.

are of length h each. Similarly, the latest admissible break date is $T - h$, otherwise the third growth regime could not last for h periods. The matrices L and M provide exactly the ingredients needed to execute the optimization. The estimated SSR for the optimal one-break partition spanning observations 1 to j is given by $L(2, j)$. The residuals for the remaining partition from observation j to T can be obtained from $M(j + 1, T)$. Hence, for every admissible j the estimated total SSR is given by $L(2, j) + M(j + 1, T)$. The optimal second break point is found by selecting the period j that minimizes $L(2, j) + M(j + 1, T)$, which is recorded in $L(3, T)$. The period of the break is collected in $B(3, T)$. The entries for $L(3, T - 1)$, $L(3, T - 2)$ etc. are obtained by carrying out the same calculations with the diminished sample running from 1 to $T - 1$, 1 to $T - 2$ and so on. The same routine is repeated until m breakpoints are imposed upon the time series. Once matrices L and B are derived, it is easy to read off the optimal break points. If m break points are determined, T_m is recorded in $B(m + 1, T)$. The period of next break point T_{m-1} is found in $B(m + 1 - 1, T_m)$, T_{m-2} is available in $B(m + 1 - 2, T_{m-1})$. One has to go back step by step until the timing of the first break is obtained from $B(m + 1 - m, T_{m-(m-2)})$.

Appendix B

Table 9: Structural Breaks in Growth

	Year Preceding Break by Type		Average Growth Rate in % in			
	Upbreak	Downbreak	Growth Regime 1	Growth Regime 2	Growth Regime 3	Growth Regime 4
Argentina		1974	1.91	0.25		
Australia	1961		1.36	2.29		
Austria		1973	5.01	2.11		
Belgium	1959	1974	2.15	4.56	1.86	
Bolivia	1959		-1.74	0.58		
Botswana		1989	8.40	3.82		
Brazil		1980	4.55	0.33		
Cameroon	1975	1985	0.21	6.06	-1.35	
Canada	1961		1.19	2.35		
Chile	1985		0.97	4.31		
China	1977		2.74	8.37		
Colombia	1967	1980	1.41	3.37	1.03	
Congo		1982	5.27	-2.63		
Costa Rica		1978	2.96	0.90		
Cote d'Ivoire		1989	2.45	-1.63		
Denmark		1973	3.21	1.49		
Dominican Republic	1991		2.39	4.32		
Ecuador		1980	3.42	-0.39		
El Salvador	1989	1978	2.01	-1.88	1.89	
Finland		1974	4.47	1.89		
France		1973	4.19	1.78		
Gabon		1976	9.94	-3.61		
Greece	1962, 1994	1973	4.61	7.86	0.59	3.21
Guatemala	1992	1980	1.96	-1.36	0.89	
Guinea	1994		-0.55	3.27		
Haiti		1980	4.12	-1.00		
Hong Kong		1994	6.40	1.18		
Hungary		1979	4.65	1.93		
India	1993		2.22	4.49		
Indonesia	1969		1.14	3.70		
Iran	1989	1976	5.86	-5.29	3.46	
Ireland	1993		2.79	6.72		
Israel		1973	4.85	1.38		
Italy		1974	4.99	1.84		
Jamaica	1985	1972	4.21	-2.35	1.39	
Japan		1970, 1991	8.64	3.29	0.77	
Jordan		1965	5.48	-0.67		

Table 9 continued

	Year Preceding Break by Type		Average Growth Rate in % in			
	Upbreak	Downbreak	Growth Regime 1	Growth Regime 2	Growth Regime 3	Growth Regime 4
Korea	1962		1.04	6.25		
Lesotho		1978	4.53	2.33		
Madagascar		1971	0.89	-1.79		
Malawi		1979	2.20	0.65		
Malaysia	1970		2.81	4.94		
Mauritius	1960		-4.15	3.66		
Mexico		1981	3.47	0.31		
Morocco	1960		-0.24	2.82		
Mozambique	1986	1976	2.15	-3.08	3.54	
Netherlands		1970	3.47	1.66		
New Zealand		1966	2.48	1.20		
Nicaragua	1993	1976	2.87	-4.24	0.50	
Nigeria		1960	4.48	0.45		
Norway		1986	3.24	2.25		
Pakistan	1960	1988	-0.39	3.63	1.41	
Panama		1981	3.68	1.43		
Paraguay	1971	1981	1.06	5.47	-0.38	
Peru		1974	3.20	-0.38		
Philippines		1977	3.17	0.92		
Poland	1991	1979	6.01	-1.05	4.09	
Portugal		1973	5.95	2.25		
Romania		1979	8.14	0.87		
Singapore		1994	5.39	1.99		
South Africa	1994	1983	1.97	-0.61	2.27	
Spain	1984	1974	6.04	0.49	2.72	
Sweden		1970	3.15	1.62		
Switzerland		1973	3.42	0.80		
Taiwan	1962	1994	4.41	7.21	3.82	
Thailand	1959		-1.12	4.74		
Togo		1969	5.72	-1.46		
Trinidad & Tobago	1993	1981	4.69	-2.96	7.46	
Uganda	1988		-0.54	3.78		
Venezuela		1977	2.78	-1.06		
West Germany		1960	6.77	2.58		

The structural breaks are derived using the Bai-Perron methodology described in the text. The minimum duration of a growth spell equals 10 years, the trimming parameter follows from the number of observations, the size of the tests is 10 %. Upbreaks are those breaks where the growth rate in the regime after the break exceeds the growth rate in the regime before the break. Downbreaks are defined conversely.

Table 10: The Effect of Eliminating Countries From the Original Sample

	Upbreaks				Downbreaks			
	Productivity	Efficiency	Technology	Capital	Productivity	Efficiency	Technology	Capital
All Countries from Section 2	65.07%	72.99%	-9.22%	21.86%	60.59%	31.83%	28.94%	41.99%
All countries excluding Jordan	57.28%	53.81%	3.24%	30.11%	56.59%	26.36%	30.69%	46.19%
All Countries excluding Jordan, Nicaragua	55.18%	52.12%	2.83%	31.79%	55.95%	26.39%	30.05%	46.81%
All Countries excluding Jordan, Nicaragua and -Costa Rica	58.60%	47.31%	11.50%	28.03%	53.38%	17.49%	36.99%	49.54%
All Countries excluding Jordan, Nicaragua, Costa Rica and El Salvador	58.55%	49.56%	9.06%	27.97%	54.16%	17.88%	37.42%	48.68%

This table shows the sensitivity of results with respect to the sample choice. Countries were excluded if observations of a particular country defined the world technology frontiers for long periods of time.

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