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28. February 2008

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***JEL Classification: O3, O4***

***Keywords: economic growth, technical efficiency, telecommunications investment***

## Abstract

This study investigates the impact of telecommunications penetration on the aggregate production efficiency in a large cross-section of fifty countries. We show that higher levels of ICT capital stock penetration increase technical efficiency levels in the aggregate production function. However, depending on the geographical location the effects of ICT penetration are different. Our empirical findings suggest that increasing the per capita telecommunications capital in the form of land line and mobile telephones, computers, Internet access and the like is likely to considerably increase productive efficiency in case of the poorest nations, while in the more developed countries such gains have been largely exhausted. In the end we offer several avenues for more research based on the caveats discovered while working on this study.

## I. Introduction

Examining how the development of information and telecommunication technologies (ICT) has affected the process of economic growth has been the subject of a significant number of studies including recent contributions by Oliner and Sichel (1994), Schreyer (2000), Dewan and Kraemer (2000) and Jorgenson and Stiroh (2000). Corroborating the initial claim made much earlier in the research by e.g. Jipp (1963) and Hardy (1980), the general conclusion of these studies is that the high extent of telecommunications infrastructure is generally conducive to the high level of economic development.

Along with the empirical evidence in support of the above statement several mechanisms were identified through which telecommunications infrastructure is affecting economic performance. In its essence the telecommunications infrastructure is a social overhead capital that is a cost-effective and time-efficient medium of disseminating and accessing information, in this way producing the market efficiency effect. In other words, more telecommunications infrastructure facilitates the exchange of information between market participants such as buyers and sellers reducing business transaction costs, increasing aggregate productivity and boosting economic performance by improving organizational efficiency. Other indirect effects of telecommunications capital diffusion are related to the telecom's network nature that results in the creation of spillover and externalities effects. Among the most pronounced ones would be the increased arbitrage opportunities and lower search costs.

Recently the research emphasis has shifted away from assessing the direct contribution of ICT sector to economic growth and performance and towards the estimation of telecommunications infrastructure on economic efficiency. In fact, given the relatively small contribution of the ICT sector itself to the GDP and the variety of indirect (externality) effects outlined above, the key benefit of telecommunications investment is likely to be in the area of aggregate productivity and economic efficiency. Studies that have pursued this line of thinking such as Vu (2005) and Barry and Triplett (2000) have demonstrated that the indirect effects of ICT investment on economic performance are by far no less important than the direct ones. For example, Vu (2005) conducts a detailed growth accounting analysis in a cross-section of more than fifty countries and finds that the ICT investment produces a significant impact on economic growth not only as traditional investment, but also as a factor contributing to economic efficiency.

This study applies a *stochastic frontier* approach to estimating the effect of telecommunications penetration on aggregate productive efficiency (Aigner et al., 1977). Using this technique we estimate the global and regional aggregate production functions in order to see how investments into the telecommunication infrastructure are affecting production efficiency. Since, as discussed above, the network nature of telecommunications infrastructure is crucial to the link between ICT capital and economic performance, it is the ICT capital level *and* accessibility that together are boosting the latter. For that reason our main hypothesis is that the level of ICT penetration measured as the per capita level of ICT capital positively influences aggregate productivity.

Methodologically there are two basic ways in which the level of ICT penetration can be estimated. One is to compute it in terms of the physical units such as the number of landline telephones or mobile subscriptions per e.g. 1000 people and the like (the approach chosen e.g. in Thompson and Garbacz, 2007). The advantage of this approach is that the extent of ICT penetration is easily computable, but the price to pay is that the *amount* of telecommunications equipment units per capita says nothing about the *quality* thereof. Simply stated, the difference in quality between a disk dial-up telephone device and a modern multi-functional communicating terminal will not get accounted for when applying the physical units approach.

Measuring the extent of ICT penetration in monetary units makes much more economic sense since the equilibrium market prices represent economic agents' willingness to pay for the products' intrinsic value, so that both quantity and quality are accounted for. However, the estimation problem with this approach is that one cannot deflate telecom investment flows measured in current prices by a CPI, PPI or similarly aggregated price index. Indeed, it is well known that for the past several decades the quality of communications equipment has been rising, while the prices thereof have been falling, so that the price indices in general follow quite a different path compared to the deflators for more conventional commodities. In this study we circumvent this problem by deflating telecommunications investment flows by the rather narrowly defined "equipment and software" GDP component price index so that we are able to obtain monetary estimates of the level of ICT capital stock in our sample.

Overall, this study covers fifty countries over the period of twenty-four years which is the period of rapid development and adoption of ICT technology into most of the world's economies. We find that globally, more ICT penetration increases aggregate production efficiency, but not uniformly so in the geographical sense. Thus, in the most developed economies efficiency benefits of ICT penetration have most likely been exhausted, while in the poorest African nations the potential of telecommunications equipment to boost productive efficiency is most evident. Our results are thus corroborating the idea that more incentives should be given to boosting the ICT investment in the poorest countries.

This paper is organized as follows. Section II presents methodology and the data. Section III presents the results and provides discussion. Section IV concludes.

## II. Estimation Methodology and the Data

We start by postulating the basic Cobb-Douglas aggregate production function: $Y_{it} = A_{it} K_{it}^{\alpha} L_{it}^{\beta}$ where $Y_{it}$ is output, $K_{it}$ is capital and $L_{it}$ is labor in country $i$ in year $t$ and $A_{it} = A_0 D_i e^{\lambda t}$. Technology level $A_{it}$ is a function of global technological level $A_0$, country-specific characteristic $D_i$ and the global technological time component $e^{\lambda t}$. Taking the logarithm of the above specification, we obtain the following expression for our aggregate production function:

$$\ln Y_{it} = \alpha \ln K_{it} + \beta \ln L_{it} + \lambda \quad (1)$$

The empirical stochastic frontier specification of (1) with the technical inefficiency component will assume the following form:

$$\ln Y_{it} = \alpha \ln K_{it} + \beta \ln L_{it} + \lambda + \varepsilon_{it} \quad (2)$$

where $\varepsilon_{it} = v_{it} - u_{it}$ is a stochastic term with $v_{it}$ being standard i.i.d normal and $u_{it} > 0$ distributed as a truncated normal variable and representing the inefficiency of the aggregate growth process. The efficient production frontier corresponding to (2) will be then represented by

$$\ln Y_{it} = \alpha \ln K_{it} + \beta \ln L_{it} + \lambda + v_{it} \tag{3}$$

or, equivalently, (2) under the condition that $u_{it} = 0$. Technical efficiency of economic growth will then be given by the ratio of the right hand side of (3) to that of (2).

In this study we hypothesize that higher levels of per capita telecommunications capital stock increases technical efficiency of aggregate production relative to the efficient production frontier. In terms of specification (2) we are expecting to find a negative association between the term $u_{it}$ (representing technical *inefficiency* of aggregate production) and per capita telecommunications capital stock. Using our estimates of (3) we test the hypothesis that $u_{it}$ is a decreasing function of $\frac{K_{ICT}}{L}$ where $K_{ICT}$ is the real telecom capital stock.

In order to estimate (3) we need to estimate the levels of conventional and telecommunications equipment capital stock. The data at our disposal come from two sources. The Penn World Table, version 6.2, provides data on real output, labor and investment flows. The International Telecommunications Union world telecommunications database provides us with the total annual investments in telecom defined as capital expenditure in the sector. In either database we do not have the capital stock levels either for the conventional capital or for the telecom capital. For that reason, before estimating (3) empirically we need to estimate stocks of conventional and telecom capital $K_{it}$ and $K_{ICT,it}$, respectively.

We estimate the latter two stocks by employing the perpetual inventory method that allows one to estimate capital stocks as a sum of the past real investment flows weighted by the extent to which these investments depreciate over time. Assuming the finite useful lifetime of an investment equal to $m$ (equivalent to saying that an asset becomes useless $m$ years after purchase) and a yearly depreciation rate $\delta$, we obtain the following expression for the value of a stock variable $S_{it}$ that is characterized by investment flow $I_{it}$:

$$S_{it} = \sum_{\tau=0}^{m-1} (1-\delta)^{\tau} I_{t-\tau} \qquad (4)$$

To use (4) for our computation, we assume useful lifetime of conventional investment to be equal to thirty years, while that of the telecom investment to be equal to seven years (see e.g. Fraumeni, 1997 or Vu, 2005). Depreciation rates $\delta$ that correspond to these values are 7.5% and 20%, respectively.

We obtain real values of investment flows into the conventional capital by combining the information on real GDP per capita (*rgdpl*), investment share of real GDP per capita (*ki*) and population (*pop*) provided by the Penn World table, version 6.2. Flows of investment into the telecommunications capital are defined by the ITU database as the annual investment in telecom (including mobile service) for acquiring property and plant [1]. Since the deflator for telecommunications investment is not explicitly provided by the ITU database, we employ the National Income and Product Account Tables provided by the U.S. Bureau of Economic Analysis (Table 1.1.4, price index for equipment and

[1] The term investment means the expenditure associated with acquiring the ownership of property (including intellectual and non-tangible property such as computer software) and plant. These include expenditure on initial installations and on additions to existing installations where the usage is expected to be over an extended period of time. Also referred to as *capital expenditure*. (ITU, Telecom Indicators)

software under gross private fixed domestic investment). We then deflate the ITU data on telecom investments in international U.S. dollars by this index.

Having combined the series of real stocks of conventional and telecommunications capital, we then maximize the likelihood function based on the following:

$$\ln Y_{it} = \alpha \ln K_{it} + \beta \ln L_{it} + \lambda + v_{it} - u_{it}, u_{it} \geq 0 \tag{5}$$

$$\mu(u_{it}) = \delta_1 + \delta_2 \left( \frac{K_{ICT,it}}{L_{it}} \right)$$

where $\mu(u_{it})$ is the mean of inefficiency term $u_{it}$ conditioned on the level of telecom capital penetration. We avoid running OLS regressions of inefficiency terms $u_{it}$ on the levels of ICT penetration (the so-called two-stage approach) since it is not clear whether the estimated inefficiency terms in (5) are indeed independent.

To complete this section, a few remarks must be made on the scope of the countries and years covered by this study. As mentioned before, the Penn World Table provides the data on output, capital and labor, while the ITU provides the telecommunications investment data. The World Table data normally cover the period from 1950 through 2004, while the ITU data coverage is only from 1975 through 2004 for telecom investment. Since we take the useful lifetime for conventional capital stock to be thirty years, while that of the telecom capital stock to be seven years, the earliest year for which both conventional and telecom capital stocks could be constructed is 1981, which is the beginning year of the sample.

Since the program we used in order to produce our estimations can deal with unbalanced panels, in principle it was possible to include those countries for which some observations were missing. However, in order to keep the panel reasonably balanced we did not include those countries where capital stocks could be calculated for only a few years such as the Eastern European countries and countries of the Former Soviet Union. For that reason, for example, Germany was not included into the sample. As a result, we ended up with fifty countries listed below by their geographical location.

**Table 1: The Geographical Coverage**

| Europe | OECD | Asia | Latin America | Africa |
|---|---|---|---|---|
| 1. Austria | Europe | 1. China | 1. Brazil | 1. Egypt |
| 2. Belgium | and | 2. Hong Kong | 2. Colombia | 2. Kenya |
| 3. Denmark | 1. Australia | 3. India | 3. Costa Rica | 3. Morocco |
| 4. France | 2. Canada | 4. Indonesia | 4. Ecuador | 4.South Africa |
| 5. Greece | 3. Japan | 5. Israel | 5. El Salvador | 5. Zambia |
| 6. Iceland | 4. New Zealand | 6. Malaysia | 6. Jamaica | |
| 7. Ireland | 5. United States | 7. Philippines | 7. Mexico | |
| 8. Italy | 6. Turkey | 8. Singapore | 8. Paraguay | |
| 9. Luxembourg | 7. Mexico | 9. Sri Lanka | 9. Uruguay | |
| 10. Netherlands | 8. Korea | 10. Taiwan | 10. Venezuela | |
| 11. Norway | | 11.Thailand | | |
| 12. Portugal | | | | |
| 13. Spain | | | | |
| 14. Sweden | | | | |
| 15. Switzerland | | | | |
| 16. United Kingdom | | | | |

In the next section we present and discuss our empirical results. Section IV concludes.

## III. Empirical Results

Table 2 below presents the results of a simultaneous maximum likelihood estimation of the aggregate production function and conditional mean in (5)[2]. It is worthwhile stressing that *negative* values of the estimate for $\delta_2$ (the

[2] We use the **frontier** command in **Stata** to perform this estimation.

coefficient for ICT penetration) correspond to the efficiency-enhancing role played by more ICT capital stock per capita. We split our countries into five groups, namely, the OECD, Developed European, Latin American, Developing Asian and African countries. We also present our results for the whole sample.

The shares of capital and labor in our estimates of the production function are reasonable exhibiting almost perfect constant returns to scale for the world as a whole, OECD, Europe and Latin American countries. In all six country groups the estimates of $\delta_2$, which measures the impact of ICT penetration on *inefficiency*, comes out negative and statistically significant, which is in line with our expectations, which is that increased levels ICT penetration lead to higher levels of aggregate productive efficiency.

We observe great contrast in the value of this coefficient for different groups of countries. Thus, we see that its absolute value is ten times higher in the economically less developed part of the world compared to the countries of OECD or Western Europe. Indeed, according to our results, an additional dollar invested into purchases of ICT capital per individual in the Latin American, developing Asian or African countries increases efficiency by almost ten times as much as it does in the more developed OECD world. That finding is consistent with the observation that, as the country reaches higher levels of economic development, gains of exploiting the positive network externalities provided by the ICT technology, gradually get exhausted. According to our results, greatest efficiency gains from investing more into the ICT equipment are to be reaped in Latin American countries, while lower gains will accrue in developing Asia or African countries. However, since no statistical tests were applied to the difference of $\delta_2$ coefficients in the three groups of countries, we cannot say whether the observed differences in values are due more to the fundamentals or are a mere statistical discrepancy.

**Table 2: ICT Penetration and Production Efficiency**

| | OECD | Europe | Latin America | Developing Asia | Africa | World |
|---|---|---|---|---|---|---|
| ***Aggregate Production Function: Dependent Variable*** $Ln(Y_{it})$ | | | | | | |
| $C$ | 2.16 (0.000) | 1.84 (0.000) | 5.61 (0.000) | 6.30 (0.000) | -4.02 (0.000) | 3.20 (0.000) |
| $Ln(K_{it})$ | 0.73 (0.000) | 0.76 (0.000) | 0.64 (0.000) | 0.46 (0.000) | 0.80 (0.000) | 0.65 (0.000) |
| $Ln(L_{it})$ | 0.27 (0.000) | 0.23 (0.000) | 0.36 (0.000) | 0.43 (0.000) | 0.76 (0.000) | 0.33 (0.000) |
| ***Inefficiency Function: Dependent Variable U*** $(u_{it} = \delta_1 + \delta_2 \left( \frac{K_{ICT,it}}{L_{it}} \right))$ | | | | | | |
| $\delta_1$ | -0.03 (0.002) | 0.14 (0.017) | 0.37 (0.000) | 0.69 (0.000) | 0.29 (0.000) | 0.26 (0.000) |
| $\left( \frac{K_{ICT,it}}{L_{it}} \right)$ | -0.003 (0.007) | -0.006 (0.008) | -0.08 (0.003) | -0.03 (0.000) | -0.04 (0.000) | -0.01 (0.000) |
| $\gamma$ | 0.24 | 0.27 | 0.08 | 0.58 | 0.999 | 0.86 |
| **Average Efficiency** | 96% | 93% | 90% | 75% | 58% | 80% |
| **Average Efficiency in the World Sample** | 87% | 86% | 78% | 73% | 70% | 80% |
| **# Obs** | 552 | 352 | 216 | 210 | 120 | 1098 |

*Note: the coefficient for the* $\frac{K_{ICT,it}}{L_{it}}$ *variable is entering the* ***inefficiency*** *function, so that the* ***negative*** *value for this coefficient corresponds to* ***increased*** *efficiency. P-values are in parentheses.*

It is also interesting to look at the average efficiency levels in our six country groups. As would be rationally expected, the more mature economies of OECD and Western Europe exhibit the highest average efficiencies at 93% and 96%, respectively. Again, no statistical tests are available to test the statistical significance of this difference. However, intuitively, this difference is likely to be the result of Mexico, Turkey and South Korea included in the OECD sample. Latin American countries in our sample are not much less efficient than the most developed country group at 90%. Quite expectedly, the lowest efficiency levels pertain to the African countries at 58% with the developing Asian countries standing in between at 75%.

One has to exercise caution when interpreting the average efficiency levels since the stochastic frontier approach is based on the existence of a benchmark efficient production frontier *within the sample of the estimated countries*. That is, a high level of average efficiency *per se* does not automatically mean that these same countries will be as efficient in the overall sample. For that reason we include average efficiency estimates for the sub-groups of countries in the whole sample as well. We observe all of the average efficiency levels drop down in all but one (African) country group compared to the within-subsample estimates, but this fall happens consistently leaving the relative efficiency ranking the same.

In interpreting the estimation results of (5) one can also infer the extent to which the deviation from the deterministic production frontier is random or is due to production inefficiency. Denoting $\sigma_u^2$ to be the variance of $u_{it}$ in (5) and $\sigma_v^2$ to be the variance of $\sigma_v^2$, we can infer the relative importance of inefficiency by computing $\gamma = \frac{\sigma_u^2}{\sigma_u^2 + \sigma_v^2}$. The values of $\gamma$ close to unity are indicative of the prevalence of inefficient production, while the values of the parameter close to zero are a sign that most deviations from the deterministic production frontier are of random nature.

As demonstrated by Table 2, in the more developed European and OECD countries, roughly one-quarter of the deviation from deterministic frontier is due to the inefficient production. In stark contrast is the African estimate of almost unity (0.999) and the developing Asian value of almost 60%. We are puzzled to have estimated the value of $\gamma$ very low at 0.08 in case of the developing Asian countries. As mentioned before, caution should be exercised when interpreting the efficiency estimation results made in the subsample since the best practice frontier is likely to be different in the overall (world) sample and the Latin American subsample. However, since we are unable to estimate $\gamma$ in the Latin American subsample *and* in the overall sample, we leave the clarification of this issue to later research. On average we can say that in the more mature economies of OECD and Western Europe deviations from the deterministic frontier are mostly of random nature while those in the developing world are more due to the inefficiencies in production.

In order to check for the robustness of our findings, we run the same type of estimations on the three equal-length sub-periods covering the original period of 1981-2004 where the production function also includes the time trend variable. We also consider three different groups of countries: the OECD countries, the developing countries that include Latin American, developing Asian and African countries, and as before, the world as a whole. The summary of these results is presented in Table 3 below.

**Table 3: ICT Penetration and Productive Efficiency in the Three Time Sub-Samples**

| | **1981-1988** | **1989-1996** | **1997-2004** | **1981-2004** |
|---|---|---|---|---|
| **OECD** | | | | |
| $\gamma$ | 0.37 | 0.076* | 0.78 | 0.24 |
| $\left(\frac{K_{ICT,it}}{L_{it}}\right)$ | -0.003 (0.278) | 0.004* (0.054) | 0.003 (0.322) | -0.03 (0.002) |
| **Median Efficiency** | 94.0% | 99.5% | 94.8% | 97.1% |
| **Developing Countries** | | | | |
| $\gamma$ | 1 | 0.83* | 0.58 | 0.83 |
| $\left(\frac{K_{ICT,it}}{L_{it}}\right)$ | -0.14 (0.000) | -0.31* (0.000) | -0.09 (0.000) | -0.21 (0.000) |
| **Median Efficiency** | 75.6% | 96% | 93.4% | 94.6% |
| **World** | | | | |
| $\gamma$ | 0.97* | 0.83 | 0.79 | 0.86 |
| $\left(\frac{K_{ICT,it}}{L_{it}}\right)$ | -0.02* (0.000) | -0.12 (0.000) | -0.04 (0.000) | -0.01 (0.000) |
| **Median Efficiency** | 84.6% | 84.7% | 83.0% | 83.5% |

*Note: P-values are in parentheses. * refers to the situation when the process of likelihood maximization failed to converge for a given set of countries and/or time period. In that case the maximization was done for the period excluding the initial year of the sample.*

For the world as a whole, we find the coefficient for ICT capital penetration to retain its negative sign as well as its statistical significance everywhere except for the OECD countries in the eight-year subsamples suggesting most of the efficiency gains due to increased ICT penetration are to be realized in the developing world. We also observe that parameter $\gamma$ is decreasing over time for the world as a whole, suggesting that the world economy's deviations from the best practice production frontier have become relatively more random in nature over the past two decades. Especially in the developing world we observe the same pattern with virtually all of such deviations being due to inefficient production in the beginning of the 1980-s, while in the latest years such inefficiency only accounting for half of the deviations.

The group of OECD countries is special in the sense that increasing the level of ICT penetration in these countries does not appear to produce any efficiency gains. We interpret this as being due to the fact that the OECD countries are the world's leading economies where efficiency gains from the ICT investments have been already exhausted.

In terms of the median efficiency the world does not undergo any drastic changes staying between 80% and 85% off the best practice production frontier. The OECD countries are by far the most efficient producers whose efficiency level does not appear to be changing with time. It is only the developing countries that appear to have been increasing their production efficiency levels. Our empirical results thus lead us to conclude that most of the discussion on the relevance of ICT investment for the aggregate production efficiency should be concentrated on the developing countries of Africa, Latin America and Asia.

The discussion in this section would be incomplete without mentioning the limitations and caveats of the approach we have undertaken. First, even if the ICT investment data provided by the ITU are to our knowledge the most comprehensive cross-country dataset on ICT indicators to date, the annual investment flows are not disaggregated into the various kinds of telecommunications investments such as, say, hardware and software. Since the latter two groups have different useful lifetimes, such disaggregation would allow us to be more precise in deflating the reported investment flows in order to obtain real capital stock data. Second, the hedonic price index that we are using is not disaggregated across countries, which reduces the accuracy with which ICT capital stock levels are computed for the individual countries. However, the hedonic price indices provided by the BEA are definitely the second-best solution since the conventional CPI or PPI provided by the ITU and WDI are not capturing the rapid decrease in the price-quality ratio that has occurred in the domain of telecom products over the past two decades. Constructing the country- and product-specific hedonic price deflators for telecommunications-related investment flows is in itself an area of future research.

## IV. Conclusion

The main idea behind the present study is that the network nature of telecommunications capital and the relatively small contribution of the ICT sector itself to the GDP reveals itself much stronger in the indirect effects on production such as productive efficiency improvements rather than in the direct contribution as one of the production factors. While the direct effect of ICT sector on both economic growth and productive efficiency has been amply explored in the literature, it is exactly the link between productive efficiency improvements and ICT capital stock accumulation that we have focused upon in this study.

In order to capture the network and overhead capital properties of the ICT capital we are measuring the extent of ICT development by the ICT penetration, which is the per-capita ICT capital stock in the country. With this purpose in mind we use hedonic telecom price indices to construct ICT real capital stock levels and combine those levels with the stochastic production frontier framework applying it to the sample of fifty countries over the period of twenty-four years.

Our main result that comes robust across different country samples and time periods is that for the world economy in general and the developing world in particular, increased levels of ICT capital stock per capita are conducive to increased production efficiency. However, more detailed analysis reveals that most of these gains are to be reaped in the developing countries of Africa, Latin America and developing Asia (in particular, excluding Japan). In contrast, we find that in the world's most developed OECD countries the potential for such gains has been most likely already exhausted since the estimated marginal contributions to productive efficiency of more ICT penetration are either very low or even statistically insignificant in this group of country. Also most deviations in these countries from the best practice frontier are estimated to be of random nature rather than being due to production inefficiencies.

For those reasons we suggest that the focus of future research in the area linking the ICT sector and economic performance be shifted to the developing countries of Asia, Africa and Latin America where the potential of ICT-related efficiency improvement is indeed there. Another important area of research would be the construction of ICT capital-specific hedonic price indices for specific countries. Finally, the causality link between ICT investment and productive efficiency has not been much investigated so far. Indeed, even the existence of a strong positive association between higher levels of ICT penetration or development in general and productive efficiency does not guarantee the existence of causality between the two. On the one hand, more efficient economies might choose to invest more into the ICT sector so that there is a problem of reverse causality. On the other hand, both production efficiency and ICT capital accumulation might be influenced by a third factor such as e.g. improved institutional environment in the country or increase in the level of political stability. The latter is especially relevant for the less developed part of the world.

This study thus presents general results on the positive link between ICT capital stock accumulation and productive efficiency for a comprehensive set of countries and a long time period, which can be a basis for more detailed work in the future along the directions outlined above.

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