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Lei Zhou
Utah State University

Basudeb Biswas
Utah State University

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OF PER CAPITA INCOME

by

LEI ZHOU

BASUDEB BISWAS

Department of Economics
Utah State University
3530 Old Main Hill
Logan, UT 84322-3530

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Lei Zhou, Research Assistant
Basudeb Biswas, Professor

Department of Economics
Utah State University
3530 Old Main Hill
Logan, UT 84322-3530

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TRADE AND INTERNATIONAL CONVERGENCE
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Lei Zhou and Basudeb Biswas

ABSTRACT

Do countries that are more open achieve higher growth rates than countries which are less open? With the same degree of openness do poor countries tend to grow faster than rich countries? If they do, the poor countries will move toward equalizing the level of per capita income and there will be income convergence. The objective of this paper is to investigate empirically the role of trade in the process of convergence. International flows of goods and factors tend to result in convergence of factor prices among partner countries. Moreover, international trade serves as an important channel through which ideas and technology flow from one country to another country. Some empirical studies show that the countries trading intensively with each other tend to converge in per capita income. In this paper, we use the Penn World Data from 1950 to 1992 to study the role of trade in convergence. The average growth rate of real per capita gross domestic product (GDP) is regressed on the starting level of log real per capita GDP. This approach, known as \( \beta \) convergence, is used in the literature. If the growth rate of real per capita GDP is negatively related to the starting level of log real per capita GDP, it means that countries with lower per capita income grow faster and hence there will be movement toward equality in the level of per capita income. We estimate the coefficient by both linear and nonlinear least squares methods. The results show that convergence takes place among developed countries and trade helps in the process for the group of developed countries. As far as trade between developed and developing countries is concerned, there is no evidence of convergence.
TRADE AND INTERNATIONAL CONVERGENCE
OF PER CAPITA INCOME

I. Introduction

The purpose of this paper is to examine empirically the role of international trade in the cross-country convergence of per capita incomes. Today there exists in a world of great material prosperity tremendous difference in per capita income among countries. The per capita income of the wealthiest country is more than fifty times that of the poorest one. For example, in 1998, the per capita GDP of the United States was $29,605, while that of Sierra Leone was $458. Will the poorer countries ever catch up with the richer countries? Does trade help or hinder in this respect? To analyze convergence we need to focus at the first stage on the factors which determine the level of output per worker. The recent literature has identified physical capital, human capital, technology and infrastructure as the primary determinants of the level of per capita output. Therefore the difference in output per worker or per capita income can be attributed to cross-country differences in these determinants. The main objective of this paper is to examine whether international trade can serve as a contributing factor toward narrowing the differences in these factors. That is, could the existing difference in technology, knowledge and infrastructure be reduced through trade and hence will there be convergence by different countries to the same level of output per person?

There are two approaches in the empirical literature on cross-country convergence analysis. $\beta$ convergence refers to the situation where poorer economies grow faster than richer economies, hence poorer economies can catch up with richer ones. $\sigma$ convergence refers to the situation that the dispersion of income per capita across economies shrinks
over time. In this empirical study of convergence, we will take the \( \beta \) approach and explain briefly in the introduction the econometric formulation. Often the following regression equation (Aghion and Howitt, 1999) is used:

\[
\frac{1}{T} \cdot \log \left( \frac{y_{i,t_0+T}}{y_{i,t_0}} \right) = \alpha - \beta \cdot \log (y_{i,t_0}) + \gamma x_{i,t} + \epsilon_{i,t_0,t_0+T}
\]

where \( i \) denotes the \( i^{th} \) country and \( x_{i,t} \) is a vector of such variables as the saving rate \( s \), rate of depreciation \( \delta \) and the rate of growth of population \( n \). The expression on the left-hand side is the average annual growth rate of income of the country \( i \) over the \( T \) years. According to the above equation we can say that cross country variation in growth rate can be attributed to differences in \( s, \delta \) and \( n \) (the saving rate, the depreciation and the rate of growth of population). This part is captured in the term \( \gamma x_{i,t} \). Within the frame work of the Solow model these determine steady-state output per person. There is another factor – differences in initial positions which can explain the variation in growth rates. The term \( -\beta \cdot \log (y_{i,t_0}) \) captures this source of variation. If \( \beta > 0 \), the coefficient of initial income is negative. Since the dependent variable is the average annual growth rate, a negative relationship between the initial income and the growth rate means that the poor country will grow faster and hence there will be convergence. In this study we take this approach. Economies are grouped as the basis of the extent of trade that takes place among them.
II. Convergence and the Role of Trade

In the closed-economy Solow growth model, per capita income remains constant at the steady state. If countries have identical saving rate, identical labor force growth rate and identical technologies, there will be absolute convergence of income, that is, different countries will have the same level of output per person. If we assume that all countries are at the steady state, observed variation in cross country income per capita can be attributed to the differences in saving rate, growth rate of population, technology, human capital and the infrastructure. If economies are not at the steady state, they are at a state of transition. Given the infrastructure and technology the transitional dynamics according to Solow model can partly explain the difference in per capita income. If countries or regions of a country have the same production technology and the same type of infrastructure, then steady-state output per worker will tend to be equalized.

Let us assume that an economy has the Cobb-Douglas aggregate production function \( Y(t) = AK(t)^a L(t)^{1-a} \) where \( K, L \) and \( Y \) are the stock of physical capital, the supply of labor and the net national output respectively; \( A \) is the technology level that is exogenous by assumption in the neoclassical growth model. Labor grows at a constant rate \( n \). The law of motion of the capital stock is given by \( \dot{K} = I - \delta K = sAK^a L^{1-a} - \delta K \) where \( I \) is investment; \( \delta \) is the depreciation rate; \( s \) is the saving rate of the economy, which is also exogenous. Investment is assumed to come solely from savings; therefore, the change of capital stock is the difference between savings and depreciation. Using the
intensive form of the production function $y = f(k) = Ak^a$, the growth rate of capital per effective labor $k$ is $\gamma_k = \frac{\dot{k}}{k} = \frac{sAk^a}{k} - (n + \delta)$, hence the growth rate of income per labor is

$$\gamma_y = \frac{\dot{y}}{y} = \frac{f'(k)\dot{k}}{f(k)} = \gamma_k \frac{f'(k)}{f(k)} k = \alpha \gamma_k \quad (\text{Romer 1996}).$$

Figure 1. Capital per Labor and Convergence

Seen from Figure 1, all economies will end up with the same steady-state level $k^*$ if they have the same exogenous parameters. In the transitional dynamics, economies can display differences in per capita income even though they have the same parameters. During the state of transition, poorer economies that have lower capital per labor have higher growth rate than richer economies do. Therefore, neoclassical growth model generates absolute convergence in per capita income across economies.

Barro and Sala-i-Martin (1992) study the $\beta$ convergence among U.S. states and 98 countries. States or regions within one country can be considered to have identical saving
rate, identical labor force growth rate and identical technologies. The difference in per capita income comes from the fact that these states or regions are at different stages of transition. However, poorer economies have higher growth rates, which indicates poorer economies can catch up with richer economies and all economies should converge to the same steady-state income per labor. Barro and Sala-i-Martin’s (1992) results show that 48 U.S. states do converge in per capita income but at a very low speed, so do 20 OECD countries, but the sample of 98 countries shows evidence of divergence.

The failure of cross-country convergence points to the inappropriateness of the assumption of the same technology and the common rate of technological progress in different economies.

In early study of convergence, convergence was found only in the years after World War II. This period was also the period that international trade boomed (Figure 2). Trade can affect long-run growth through different channels. First, commodity exchange facilitates the transmission of new technology and technical information. Second, international competition is a great incentive for firms in each country to adopt new ideas and innovations. Thirdly, the size of market that each country faces is enlarged by global integration. Fourthly, international trade may affect the resource endowment and allocation of each country (Grossman and Helpman, 1991). Introducing trade into the Solow model generates medium-run economic growth because trade shifts the production function. Hence, capital per labor and per capita output move to a new steady state with higher levels. The long-run rate of technological progress is positively related to the
extent of specialization. Learning-by-doing, human capital accumulation and the research and development (R&D) models show that trade may induce permanent economic growth (Ven den Berg, 2001).

![Figure 2 Trade Index from 1950 to 2001](image)

(Source: WTO International trade statistics 2001)

Grossman and Helpman (1991) also state that more open countries have a greater ability to absorb advanced technology. The poorer economy imitates the new technology innovated in the advanced economy. If the cost of imitation is less than that of innovation, the poorer economy can have a higher growth rate than the advanced economy. Therefore, the poorer economy may catch up with the advanced economy through trade.
The object of this paper is to examine the relationship between openness and convergence. When economies are more integrated through exports and imports of goods, capital and ideas, we would like to examine the effect of openness on convergence. With openness there will be international diffusion of technologies. As a result, production technologies will tend to be the same. So one source of variation in steady-state output per head would tend to disappear and will contribute to movement toward equality.

Ben-David (1996) studies the convergence in trading partners by measuring the change of the dispersion of the logarithm of real per capita income across a group of economies over time -- Σ convergence. He uses the data from 1960 to 1985 for 25 trading groups. The trading groups are created in the following way: 25 individual source economies are selected by ranking, then trading partners are selected for each of the source economy based on import, export and import-and-export criteria respectively. Regression is carried on in each trading group. The results show that wealthier economies that trade intensively among themselves tend to converge in per capita income. Regressions are also carried on in all the possible random combinations of these economies. The distribution of the convergence coefficient indicates that the random grouping is more likely to generate divergence. Ben-David’s study gives indirect evidence that trade contributes to convergence in per capita income.

Ben-David’s (1993 and 1996) findings are criticized by Slaughter (1997) who states that although Ben-David’s results provide evidence that trade contributes toward
convergence, it cannot be concluded that trade plays the only role in helping convergence, and there are also contributions from other non-trade factors.
III. Methodology and Data

The concept that is employed in this paper to study convergence is $\beta$ convergence, that is, to test economies with lower initial levels of per capita income grow faster than economies with higher initial levels of per capita income. This relationship can be tested by a simple ordinary least squares (OLS) model.

$$\frac{1}{T} \cdot \log\left(\frac{y_{i,t_0+T}}{y_{i,t_0}}\right) = \beta_0 + \beta_1 \cdot \log(y_{i,t_0}) + \epsilon_{i,t_0,t_0+T} \quad \text{(Model 1)}$$

where $y_{i,t}$ is the real per capita GDP of the $i^{th}$ economy at time $t$ and $\epsilon$ is the error term. The dependent variable of the model is the average growth rate of real per capita GDP of one economy during a certain period of time. The explanatory variable is the initial value of the log of real per capital GDP of the economy. If convergence exists in this groups of economies, the coefficient of $\log(y_{i,t_0})$ should be negative, which means that the growth rate of real per capita GDP is inversely related to the initial level of the log of GDP per capita. If the coefficient is positive, divergence occurs and poorer economies will never catch up with richer economies.

Barro and Sala-i-Martin (1992) use the following model to analyze convergence, which is also adopted in this paper.

$$\frac{1}{T} \cdot \log\left(\frac{y_{i,t_0+T}}{y_{i,t_0}}\right) = B - \left(\frac{1 - e^{-\beta T}}{T}\right) \cdot \log(y_{i,t_0}) + \epsilon_{i,t_0,t_0+T} \quad \text{(Model 2)}$$
The above equation is derived from the Ramsey growth model by using a log-linearization of the growth rate of capital per labor and the law of motion of consumption per labor around the steady state, and then solve for the solution of the log-linearized approximation to the Ramsey model using the technique of solving ordinary differential equations (A detailed derivation based on Barro and Sala-i-Martin (1995) is given in the appendix). The constant $B$ in Model 2 is independent of different economies under the assumption of absolute convergence. The coefficient $\beta$ of the explanatory variable in Model 2 has different meaning from the $\beta_1$ in Model 1. In Model 2, $\beta$ measures the speed of convergence. $\beta_1$ is expected to be negative in Model 1 while a positive value of $\beta$ indicates tendency toward convergence.

The data used in this study are Summers-Heston data (1950-1992). We will use the trading groups set up by Ben-David (1996) to test the role of trade in the process of convergence. There are three criteria used to create trading groups, import-based groups, export-based groups and the union of import-based and export-based groups. Levine and Renelt (1992) in their research about the robustness of cross-country growth regression find out that the results are almost identical by using export share, import share or total trade share. In this paper, we will combine import-based and export-based groups to see how trade helps convergence. Based on this grouping, there are 25 trading groups of 43 countries in total. The legend of the abbreviations of countries is in Table 1.
## Table 1  Legend of Countries

<table>
<thead>
<tr>
<th>Code</th>
<th>Country</th>
<th>Code</th>
<th>Country</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARGN</td>
<td>Argentina</td>
<td>JAP</td>
<td>Japan</td>
</tr>
<tr>
<td>AUSTL</td>
<td>Australia</td>
<td>MEX</td>
<td>Mexico</td>
</tr>
<tr>
<td>AUSTR</td>
<td>Austria</td>
<td>MOZ</td>
<td>Mozambique</td>
</tr>
<tr>
<td>BELLU</td>
<td>Belgium-Luxemburg</td>
<td>NETH</td>
<td>Netherlands</td>
</tr>
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<td>Bolivia</td>
<td>NOR</td>
<td>Norway</td>
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<tr>
<td>BOTS</td>
<td>Botswana</td>
<td>NZ</td>
<td>New Zealand</td>
</tr>
<tr>
<td>BRAZ</td>
<td>Brazil</td>
<td>PNG</td>
<td>Papua New Guinea</td>
</tr>
<tr>
<td>CAN</td>
<td>Canada</td>
<td>PARA</td>
<td>Paraguay</td>
</tr>
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<td>CHIL</td>
<td>Chile</td>
<td>PHIL</td>
<td>Philippines</td>
</tr>
<tr>
<td>CONG</td>
<td>Congo</td>
<td>PORT</td>
<td>Portugal</td>
</tr>
<tr>
<td>DEN</td>
<td>Denmark</td>
<td>SAFR</td>
<td>South Africa</td>
</tr>
<tr>
<td>ETHI</td>
<td>Ethiopia</td>
<td>SKOR</td>
<td>South Korea</td>
</tr>
<tr>
<td>FIN</td>
<td>Finland</td>
<td>SPA</td>
<td>Spain</td>
</tr>
<tr>
<td>FRA</td>
<td>France</td>
<td>SWAZ</td>
<td>Swaziland</td>
</tr>
<tr>
<td>GER</td>
<td>Germany</td>
<td>SWED</td>
<td>Sweden</td>
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<td>GHAN</td>
<td>Ghana</td>
<td>SWIS</td>
<td>Switzerland</td>
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<td>Guatemala</td>
<td>TAIW</td>
<td>Taiwan</td>
</tr>
<tr>
<td>GUYA</td>
<td>Guyana</td>
<td>UK</td>
<td>United Kingdom</td>
</tr>
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<td>HK</td>
<td>Hong Kong</td>
<td>URUG</td>
<td>Uruguay</td>
</tr>
<tr>
<td>ICE</td>
<td>Iceland</td>
<td>US</td>
<td>United States</td>
</tr>
<tr>
<td>IRE</td>
<td>Ireland</td>
<td>ZIMB</td>
<td>Zimbabwe</td>
</tr>
<tr>
<td>ITAL</td>
<td>Italy</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
IV. Empirical Results

Regression results for Model 1 and Model 2 are given in Table 2. $\hat{\beta}_1$, which is estimated by linear least squares method, is the estimator of the coefficient of the log of initial income per labor in Model 1. $\hat{\beta}$ is the estimator of converging speed in Model 2, which is estimated by Guass-Newton nonlinear least squares method. The $t$-value of the estimator is listed in the parenthesis.

<table>
<thead>
<tr>
<th>Source Country</th>
<th>Trade Partners</th>
<th>$\hat{\beta}_1$ (Model 1)</th>
<th>$\hat{\beta}$ (Model 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAN</td>
<td>JAP US</td>
<td>-0.0213*</td>
<td>0.0582*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(-26.478)</td>
<td>(10.245)</td>
</tr>
<tr>
<td>NOR</td>
<td>FRA GER NETH SWED UK US DEN FIN JAP</td>
<td>-0.0222*</td>
<td>0.0713</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(-11.596)</td>
<td>(1.938)</td>
</tr>
<tr>
<td>SWED</td>
<td>DEN FIN FRA GER NETH NOR UK US JAP</td>
<td>-0.0222*</td>
<td>0.0713</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(-11.596)</td>
<td>(1.938)</td>
</tr>
<tr>
<td>FIN</td>
<td>DEN GER NOR SWED UK US JAP</td>
<td>-0.0221*</td>
<td>0.0705*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(-10.314)</td>
<td>(3.872)</td>
</tr>
<tr>
<td>JAPI</td>
<td>SKOR US AUSTL</td>
<td>-0.0183*</td>
<td>0.0320</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(-5.385)</td>
<td>(1.833)</td>
</tr>
<tr>
<td>ICE</td>
<td>GER JAP UK US DEN NETH NOR SWE</td>
<td>-0.0224*</td>
<td>0.0773</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(-11.636)</td>
<td>(1.640)</td>
</tr>
<tr>
<td>GER</td>
<td>AUSTR BELLU FRA ITAL NETH SWISS UK US JAP</td>
<td>-0.0175*</td>
<td>0.0326*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(-6.068)</td>
<td>(3.104)</td>
</tr>
<tr>
<td>AUSTR</td>
<td>GER ITAL SWIS UK US</td>
<td>-0.0179*</td>
<td>0.0341*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(-8.377)</td>
<td>(4.513)</td>
</tr>
<tr>
<td>Source Country</td>
<td>Trade Partners</td>
<td>$\hat{\beta}_1$ (Model 1)</td>
<td>$\hat{\beta}$ (Model 2)</td>
</tr>
<tr>
<td>---------------</td>
<td>------------------------------------</td>
<td>--------------------------</td>
<td>--------------------------</td>
</tr>
<tr>
<td>DEN</td>
<td>FRA GER NOR SWED UK US JAP NETH</td>
<td>-0.0226* (-12.812)</td>
<td>0.0827 (1.520)</td>
</tr>
<tr>
<td>FRA</td>
<td>BELLU GER ITAL NETH SWIS UK US</td>
<td>-0.0118* (-3.437)</td>
<td>0.0165* (2.723)</td>
</tr>
<tr>
<td>SWIS</td>
<td>FRA GER ITAL UK US BELLU NETH</td>
<td>-0.0118* (-3.437)</td>
<td>0.0165* (2.723)</td>
</tr>
<tr>
<td>NZ</td>
<td>AUSTL JAP UK US GER</td>
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<td>0.1536 0.098</td>
</tr>
<tr>
<td>AUSTL</td>
<td>JAP NZ US GER UK</td>
<td>-0.0235* (-8.550)</td>
<td>0.1536 0.098</td>
</tr>
<tr>
<td>ITAL</td>
<td>FRA GER SWIS UK US NETH</td>
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<td>0.0337 4.200</td>
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<td>BELLU</td>
<td>FRA GER ITAL NETH UK US</td>
<td>-0.0113* (-3.050)</td>
<td>0.0155 2.539</td>
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<td>NETH</td>
<td>BELLU FRA GER ITAL UK US</td>
<td>-0.0113* (-3.050)</td>
<td>0.0155 2.539</td>
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<tr>
<td>UK</td>
<td>BELLU FRA GER IRE ITAL NETH US JAP NOR</td>
<td>-0.0156* (-4.918)</td>
<td>0.0260 2.989</td>
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<tr>
<td>IRE</td>
<td>BELLU FRA GER NETH UK US</td>
<td>-0.0087* (-2.421)</td>
<td>0.0108 2.249</td>
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<tr>
<td>SPA</td>
<td>FRA GER ITAL NETH UK US MEX</td>
<td>-0.0120* (-3.049)</td>
<td>0.0169 2.399</td>
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<tr>
<td>US</td>
<td>CAN GER JAP MEX UK</td>
<td>-0.0171* (-3.004)</td>
<td>0.0310 1.757</td>
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<tr>
<td>URUG²</td>
<td>ARGN BRAZ GER UK US</td>
<td>-0.0058 (-0.645)</td>
<td>0.0070 (0.688)</td>
</tr>
</tbody>
</table>
### Table 2  Coefficients for 25 Trade Groups (Continued)

<table>
<thead>
<tr>
<th>Source Country</th>
<th>Trade Partners</th>
<th>$\hat{\beta}_1$ (Model 1)</th>
<th>$\hat{\beta}$ (Model 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MEX</td>
<td>JAP SPA US</td>
<td>-0.0169 (-1.988)</td>
<td>0.0303 (1.368)</td>
</tr>
<tr>
<td>ARGN</td>
<td>BRAZ JAP NETH US BOLI FRA GER ITAL</td>
<td>-0.0061 (-0.690)</td>
<td>0.0071 (0.669)</td>
</tr>
<tr>
<td>CHIL$^2$</td>
<td>AUSTR BRAZ GER ITAL JAP UK US GUYA</td>
<td>-0.0043 (-0.381)</td>
<td>0.0048 (0.391)</td>
</tr>
<tr>
<td>SAFR</td>
<td>CONG ETHI GHAH JAP UK US FRA GER</td>
<td>0.0055 (1.225)</td>
<td>-0.0055 (-0.019)</td>
</tr>
</tbody>
</table>

$^1$ Data are from 1953 to 1991
$^2$ Data are from 1950 to 1990
$^3$ Data are from 1951 to 1992
* means significant different from zero at the 5% level.

Results of Model 1 indicate that among these 25 trading groups, 20 of them have statistically significant coefficients, and all of the significant coefficients have the expected negative sign. 20 trade groups show strong evidence that trading partners converge in per capita income. Ben-David (1996) measures the standard deviation of log real per capita GDP and gets 16 converging groups using Summers and Heston data from 1960 to 1985. In Ben-David (1996), the groups of UK, Ireland, Spain and the United States show divergence, but these groups show convergence in this study.

The nonlinear least squares estimates of Model 2 give us different results. There are 12 significant estimators out of 25 at the 5% level and 18 significant estimators at the 10% level. Same as estimators of Model 1, all the significant coefficients have the expected positive sign. In some cases the speed of convergence is less than 2%, while in some other cases, it is as high as 7%, which indicates a half life of about 10 years. The
results show that for trading partners, poorer economies grow faster than richer ones, that is, convergence happens among trading partners. Compared to the results of Barro and Sala-i-Martin (1992), the converging speed is faster among trading partners. This might be evidence that trade contributes to convergence in per capita income.

In contrast for the last 5 trading groups in Table 2, headed by Uruguay, Mexico, Argentina, Chile and South Africa, the estimated coefficients are not significant and the group of South Africa has the opposite sign in both Model 1 and Model 2. These 5 groups consist of one or more developing economies, while the first 20 groups in Table 2 consist only of developed economies. We need to pay special attention to the difference between developed and developing economies. Much research work has shown that the difference in production functions and parameters cannot fully explain the discrepancy among economies. More recent study focuses on the underlying factor that relates to the huge difference in productivity and output per worker.

One of the most important differences between developing and developed economies is the infrastructure. Hall and Jones (1999) find a large amount of variation lies in the level of Solow residual across countries on an accounting basis. The differences in factors that affect the growth rate of per capita income, such as capital accumulation and productivity, are driven by differences in institutions and government policies, which are called social infrastructure by Hall and Jones. Jimenez (1995) reviews the evidence that infrastructure plays an important role in the development process.
In this study, we use an indirect method to analyze the role of trade in convergence. Our results give evidence that trade contributes to convergence in per capita income among trading partners. However, this conclusion does not hold for all the trading groups that are studied, especially for the groups which include both developed economies and developing economies. Globalization or integration of the countries of the world may raise the per capita income of all countries. But for nations with low per capita income is there any possibility that they will be able to catch up with high income countries in a world of increasing interdependence?
V. Conclusion and Discussion

The indirect method used in this empirical study shows that within groups of developed countries there is strong evidence of convergence. Results are based on the data for the period from 1950 to 1992. Our results also indicate that trade among developed and developing countries does not contribute to convergence. The difference in infrastructure between rich and poor nations may provide a clue to why trade does not help developing countries attain a higher rate of growth.
Appendix

Derivation of equation (Model 2) in page 11

Households
Each household maximizes overall utility, $U$, as given by

$$U = \int u[c(t)] \cdot e^{nt} \cdot e^{-\rho t} dt$$

where
- $L(t)$ is the adult population at time $t$;
- $C(t)$ is total consumption at time $t$;
- $c(t)$ is consumption per adult person;
- $n$ is the rate of growth of population;
- $\rho$ is the rate of time preference.

The budget constraint for the household is

$$\dot{a} = w(t) + ra(t) - c(t) - na(t)$$

where
- $a(t)$ is the assets per adult person;
- $w(t)$ is the wage income per adult person;
- $r$ is the interest rate;
- $r a(t)$ is interest income.

From the theory of optimal control, the level of consumption at each period of time must maximize the present-value Hamiltonian:

$$J = u(c)e^{-(\rho-n)t} + \nu[w + (r-n)a - c]$$

First order conditions
- $\frac{\partial J}{\partial c} = 0 \Rightarrow \nu = u'(c)e^{-(\rho-n)t}$
- $\dot{\nu} = -\frac{\partial J}{\partial a} \Rightarrow \dot{\nu} = -(r-n)\nu$ (A2)

Transversality condition:
- $\lim_{t \to \infty} [\nu(t) \cdot a(t)] = 0$ (A3)

Differentiate (A2) with respect to $t$ and substitute for $\nu$ from (A2) and for $\dot{\nu}$ from (A3),
\[ r = \rho - \left( \frac{d u'(t)}{d t} \right) = \rho - \left[ \frac{u''(c) c'}{u'(c)} \right] (c' / c) \]  

(A4)

Let \( u(c) = \frac{c^{(1-\theta)} - 1}{1 - \theta} \), where \( \theta \) is the elasticity of marginal utility.  

(A5)

From (A4), we get  

\[ \frac{c'}{c} = (1/\theta) \cdot (r - \rho) \]  

(A6)

**Firms**

\[ Y = F(K, L, t) \]

where  
- \( Y \) is the flow of output;  
- \( K \) is capital input;  
- \( L \) is labor input, \( t \) is time.

\[ Y = F(K, \hat{L}) \]

where  
- \( \hat{L} = L \cdot A(t) \),  
- \( A(t) = e^{xt} \),  
- \( \hat{L} \) is the effective amount of labor input.

Let \( \hat{y} = Y / \hat{L} \), \( \hat{k} = K / \hat{L} \)

\[ \hat{y} = f(\hat{k}) \]  

is the intensive form production function.

We can write \( Y = L \cdot f(\hat{k}) \), then

\[ \frac{\partial Y}{\partial K} = f'(\hat{k}) \quad \frac{\partial Y}{\partial L} = [f(\hat{k}) - \hat{k} \cdot f'(\hat{k})]e^{xt} \]  

(A7)

\[ \text{Profit} = F(K, \hat{L}) - (r + \delta) \cdot K - w \cdot L \]  

(A8)

where \( r \) is the interest rate;  
- \( \delta \) is the depreciation rate;  
- \( w \) is the wage rate.
Profit = \hat{L} \cdot [f(\hat{k}) - (r + \delta) \cdot \dot{k} - \omega e^{-\sigma t}] \quad (A9)

A competitive firm that takes \( r \) and \( w \) as given maximizes profit for given \( \hat{L} \) by setting

\[ f'(\hat{k}) = r + \delta \quad (A10) \]

\[ [f(\hat{k}) - \hat{k} \cdot f'(\hat{k})] e^{\sigma t} = w \quad (A11) \]

**Equilibrium**

In (A1), let \( a = k, \hat{k} = ke^{-\sigma t} \), also use (A10) and (A11) to get

\[ \dot{k} = f(\hat{k}) - \hat{c} - (x + n + \delta) \cdot \dot{k} \quad (A12) \]

From (A6), use \( r = f'(\hat{k}) - \delta \) and \( \hat{c} = ce^{-\sigma t} \), we get

\[ \dot{\hat{c}} / \hat{c} = \hat{c} / c - x = (1/\theta) \cdot [f'(\hat{k}) - \delta - \rho - \theta x] \quad (A13) \]

Use Cobb-Douglas Production Function \( f(\hat{k}) = A\hat{k}^\alpha \), rewrite (A12) and (A13), where \( A \) is technology.

\[ \frac{\dot{k}}{k} = \frac{A\hat{k}^\alpha}{\hat{k}} - \frac{\dot{c}}{\hat{c}} - (x + n + \delta) \]

\[ \frac{\dot{c}}{\hat{c}} = (1/\theta) \cdot [f'(\hat{k}) - \delta - \rho - \theta x] \]

Rewrite in terms of the logs of \( \hat{c} \) and \( \hat{k} \),

\[ \frac{d[\log(\hat{k})]}{dt} = A \cdot e^{-(1-\alpha) \cdot \log(\hat{k})} - e^{\log(\hat{c}) / \hat{k}} - (x + n + \delta) \quad (A14) \]

\[ \frac{d[\log(\hat{c})]}{dt} = (1/\theta) \cdot [\alpha A \cdot e^{-(1-\alpha) \cdot \log(\hat{k})} - (\rho + \theta x + \delta)] \quad (A15) \]

\[ \frac{d[\log(\hat{\hat{k}})]}{dt} = \frac{d[\log(\hat{c})]}{dt} = 0 \quad \text{at steady state, so} \]

\[ A \cdot e^{-(1-\alpha) \cdot \log(\hat{k}^*)} - e^{\log(\hat{c}^*) / \hat{k}^*} = x + n + \delta \quad (A16) \]

\[ \alpha A \cdot e^{-(1-\alpha) \cdot \log(\hat{k}^*)} = \rho + \theta x + \delta \quad (A17) \]
Take a first order Taylor expansion of (A14) and (A15) around the steady-state values determined by (A16) and (A17),

\[
\begin{bmatrix}
\frac{d[\log(k)]}{dt} \\
\frac{d[\log(\hat{c})]}{dt}
\end{bmatrix} =
\begin{bmatrix}
\zeta & x + n + \delta - (\rho + \theta x + \delta)/\alpha \\
-(1 - \alpha) \cdot (\rho + \theta x + \delta)/\theta & 0
\end{bmatrix}
\begin{bmatrix}
\log(\hat{k}/k^*) \\
\log(\hat{c}/c^*)
\end{bmatrix}
\]

where \( \zeta = \rho - n - (1 - \theta)x \)

Compute eigenvalues,

\[
\det\left[\begin{array}{cc}
\zeta - \varepsilon & x + n + \delta - (\rho + \theta x + \delta)/\alpha \\
-(1 - \alpha) \cdot (\rho + \theta x + \delta)/\theta & -\varepsilon
\end{array}\right] = 0
\]

\[
\Rightarrow \varepsilon^2 - \zeta \varepsilon - [x + n + \delta - (\rho + \theta x + \delta)/\alpha] \cdot [-(1 - \alpha) \cdot (\rho + \theta x + \delta)/\theta] = 0
\]

\[
\Rightarrow 2\varepsilon = \zeta \pm \sqrt{\zeta^2 + 4\left(\frac{1 - \alpha}{\theta}\right) \left(\rho + \theta x + \delta\right) \cdot \left[(\rho + \theta x + \delta)/\alpha - (x + n + \delta)\right]}^{1/2}
\]

let \( 2\beta = -2\varepsilon_2 = -\zeta + \sqrt{\zeta^2 + 4\left(\frac{1 - \alpha}{\theta}\right) \left(\rho + \theta x + \delta\right) \cdot \left[(\rho + \theta x + \delta)/\alpha - (x + n + \delta)\right]}^{1/2} \)

\( \beta \) is the speed of convergence.

The log-linearized solution for \( \log(\hat{k}) \) takes the form:

\[
\log[\hat{k}(t)] = \log(\hat{k}^*) + \psi_1 e^{\beta t} + \psi_2 e^{\beta t}
\]

(A18)

\( \varepsilon_1 > 0 \Rightarrow \psi_1 = 0 \)

\( \psi_2 = \log[\hat{k}(0)] - \log(\hat{k}^*) \)

Substitute \( \psi_1 = 0, \psi_2 = -\beta, \psi_2 = \log[\hat{k}(0)] - \log(\hat{k}^*) \) into (A18), we get

\[
\log[\hat{k}(t)] = (1 - e^{-\beta t}) \log(\hat{k}^*) + e^{-\beta t} \log[\hat{k}(0)]
\]

since \( \log[\hat{y}(t)] = \log(A) + \alpha \log[\hat{k}(t)] \)

\[
\Rightarrow \log[\hat{y}(t)] = (1 - e^{-\beta t}) \log(\hat{y}^*) + e^{-\beta t} \log[\hat{y}(0)]
\]
Minus $\log[\hat{y}(0)]$ and then divide $T$ on both sides, we get

$$\frac{1}{T} \cdot \log \left( \frac{\hat{y}(t)}{\hat{y}(0)} \right) = \left( \frac{1 - e^{-\beta T}}{T} \right) \cdot \log(\hat{y}^*) - \left( \frac{1 - e^{-\beta T}}{T} \right) \cdot \log[\hat{y}(0)]$$

which corresponds to the equation (Model 2).
Reference

Trade and International Convergence of Per Capita Income
(First Draft)

Lei Zhou
Economics Department, Utah State University
Tel: (435)797-6257
leizhou@cc.usu.edu

Basudeb Biswas
Economics Department, Utah State University
3530 Old Main Hill, Logan, UT 84322
Tel: (435)797-2304
biswas@b202.usu.edu
Abstract

Do countries that are more open achieve higher growth rates than countries which are less open? With the same degree of openness do poor countries tend to grow faster than rich countries? If they do, the poor countries will move toward equalizing the level of per capita income and there will be income convergence. The objective of this paper is to investigate empirically the role of trade in the process of convergence. International flows of goods and factors tend to result in convergence of factor prices among partner countries. Moreover, international trade serves as an important channel through which ideas and technology flow from one country to another country. Some empirical studies show that the countries trading intensively with each other tend to converge in per capita income. In this paper, we use the penn world data from 1950 to 1992 to study the role of trade in convergence. The average growth rate of real per capita gross domestic product (GDP) is regressed on the starting level of log real per capita GDP. This approach, is known as $\beta$ convergence, is used in the literature. If the growth rate of real per capita GDP is negatively related to the starting level of log real per capita GDP, it means that countries with lower per capita income grow faster and hence there will be movement toward equality in the level of per capita income. We estimate the coefficient by both linear and nonlinear least squares methods. The results show that convergence takes place among developed countries and trade helps in the process for the group of developed countries. As far as trade between developed and developing countries is concerned, there is no evidence of convergence.
I. Introduction

The purpose of this paper is to examine empirically the role of international trade in the cross-country convergence of per capita incomes. Today there exists in a world of great material prosperity tremendous difference in per capita income among countries. The per capita income of the wealthiest country is more than fifty times that of the poorest one. For example, in 1998, the per capita GDP of the United States was $29,605, while that of Sierra Leone was $458. Will the poorer countries ever catch up with the richer countries? Does trade help or hinder in this respect? To analyze convergence we need to focus at the first stage on the factors which determine the level of output per worker. The recent literature has identified physical capital, human capital, technology and infrastructure as the primary determinants of the level of per capita output. Therefore the difference in output per worker or per capita income can be attributed to cross-country differences in these determinants. The main objective of this paper is to examine whether international trade can serve as a contributing factor toward narrowing the differences in these factors. That is, could the existing difference in technology, knowledge and infrastructure be reduced through trade and hence will there be convergence by different countries to the same level of output per person?

There are two approaches in the empirical literature on cross-country convergence analysis. β convergence refers to the situation where poorer economies grow faster than richer economies, hence poorer economies can catch up with richer ones. σ convergence refers to the situation that the dispersion of income per capita across economies shrinks