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A Nonlinear Estimation of Aggregate Production Function: Implications on Growth Theories and Empirics

Tae Jeong Lee

To control for the structural difference, the Summers-Heston data is divided into four income groups: the top 16, the high income, the middle income, and the low income countries. It is found that the subsamples, which are likely to be more homogeneous than the whole sample, do not support the Solow's growth model. First, the Solow model do not explain the income variations within the subsamples, with an exception of the low income sample. Second, only the low income sample shows the convergence conditional on the variables relevant to the Solow's model. These findings point to the existence of multiple steady states. Though a convex-concave aggregate production technology can generate the multiple steady states in the Solow model, a nonlinear estimation of the aggregate production function suggests that such curvature is not pronouncing enough for multiplicity. Since the mechanics that shifts the production function remains as a possible source for the multiplicity, an endogenous growth model with multiple equilibria may be a promising way to follow in seeking an explanation for the widely different growth experiences across countries.

This paper provides a stronger test of the implications of the Solow's growth model using the Summers-Heston data.[1] The steady state income and the transitional dynamics of

Department of Economics, University of Chicago, Population Research Center, NORC. He thanks professor Nancy Stokey who inspired this research. He also thanks professor Jeremy Atack for the valuable comments. All errors are his own.

this model are determined solely by the savings rate, the population growth rate, the initial level of income, and possibly by the investment in human capital if the model is extended to incorporate the human capital as a factor of production. The simplicity and the sharpness of the Solow's model are bought at the cost of abstracting from the variations in the institutions as well as the production technology. If we confine our attention to the question of whether the developed economies can sustain the growth maintaining the full employment, this model provides an excellent guide on how to look at the problem. However, if we attempt to apply this model to the diverse growth experiences of the capitalist countries, letting alone the socialist economies, the role of widely different socio-economic institutions must be properly considered. Thus, if one intends to test the implications of the Solow's growth model against the Summers-Heston data which covers almost all the capitalist economies, he has to carefully control for the structural differences.

Among the recent empirical works on growth using the Summers and Heston's data, G. Mankiw, D. Romer, and D. Weil [21]s work stands out because their specification of the regression equations is most explicitly connected to the theoretical model of Solow and their conclusions have provoked many other related researches. Mankiw *et als.* found that if we assume that all the economies are in the steady state the variables suggested by the Solow model alone can explain 59 of the income variations across the non-oil countries. If the investment in human capital is added to the equation, the explanation power increases to 78%. They also found that if we assume that the economies are in a transitional phase the regression results indicate that the income of each economy converges to **its own** steady state level as the Solow model implies. They interpreted these findings as a strong supporting evidence for the Solow model and argued further that the endogenous growth models do not add much to the explanation power of the Solow's growth model. However, since they did not control for the structural difference, we should be careful in interpreting their results.

Their own regression results for the OECD sample provide a diagnostic indication that such an interpretation may not be valid. There is little doubt that OECD sample is more homogeneous than the non-oil sample which consists of 95 market economies. Mankiw *et als.* admit that "*[The OECD sample] has the advantages that the data appear to be uniformly of high quality and that the variation in omitted country specific factors is likely*

1) For the purpose of a direct comparison with the existing literature, I use the 1988 version of the World Table instead of the 1991 version.

to be small." Nevertheless, the regression results show that the Solow model provides virtually no explanation for the income variation among the OECD countries. They argue that the Solow model did not work for the OECD sample because "[*The OECD sample*] *has the disadvantages that it is small in size and that it discards much of the variation in the variables of interest.*" This is exactly the point that worries us. If it is the omitted country specific factors that drives the variation in the variables of interest, the findings of Mankiw *et als*. cannot be interpreted as a supporting evidence for the Solow model.

The Summers-Heston data contain the annual series of the per capita real GDP and some other aggregate variables for 121 market economies over the period of thirty five years from 1950 to 1985. Even a casual observation of this data reveals a very different growth patterns : the prosperous countries had been growing steadily, the many poor countries had been suffering from the prolonged poverty, and a few other countries had achieved an unusually successful growth over the same period of time.[2)]

It is refreshing to remind ourselves of the fact that the per capita real GDP of US in 1710, when US was a colonial agricultural economy, is estimated to be $550 in 1989 US prices (J. Atack and P. Passell [2]). Thus, the living standard of US in 1710 is somewhat comparable to the current living standard of Zaire, whose per capita GDP in 1985 is $210 in 1980 international prices. Just as it is hard to believe that the economic structure of US in 1710 is more or less the same as it is now, so is it to assume that the US and Zaire, currently, share the similar socio-economic institutions. The widely different growth experiences and living standards documented in the World Table must reflect the different economic structures as well as the different levels of the accumulated physical and the human capital.

There have been efforts to control for the structural difference in the cross-country growth regressions by including various proxy variables. For instance, Robert Barro [4] and Ross Levine and David Renelt [16] check the robustness of their regression results against the inclusion of various proxy variables for the regional peculiarity, the economic system, the degree of openness, the political stability, and the degree of government intervention. But we can easily think of the structural aspects that are unaccounted for by

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2) For instance, Zaire's per capita real GDP was $223 in 1950, it reached the peak of $404 in 1973 and since then it had decreased to $210 as of 1985. During the same period, the per capita real GDP of US had been growing steadily at the rate of 1.9% from $12362 to $18988. Meanwhile, Taiwan's per capita real GDP had increased almost tenfold from $ 378 to $ 3581 in the same period of 1950 through 1985.

those proxy variables but may make a serious influence on the growth performance of an economy, such as the income distribution, the maturity of industrialization, the market structure, the development of the financial intermediation, and so on. This consideration raises the suspicion that the introduction of such proxy variables may not be strong enough for the robustness of the growth regressions and that it may not be proper to treat the set of countries in the Summers-Heston data as one coherent sample in testing the implications of a growth theory that abstracts from the institutional evolution of the economy.

In this paper, I suggest that one way to control for at least some of the structural difference would be to segment the data into subsamples consisting of the countries with similar income levels. The literature of development economics in 1950's and 1960's witnesses that the economic institutions may evolve along with the quantitative expansion. For instance, Colin Clark [8] stresses the link between the growth and the maturity of industrial structure. Simon Kuznets [15] argues that the relation between the growth and the income inequality may be stylized by a reversed U-shaped curve. If their insights and finding are valid, we can control for at least some of the important structural differences by dividing the whole sample of the World Table according to the income levels. For that purpose, this paper divides the Summers-Heston data into four sub samples : the Top 16, the high income countries, the middle income countries, and the low income countries.

Indeed, it is found that the subsamples consisting of the countries with the similar living standard do not support the implications of the Solow model. First, the Solow model can explain virtually no variation of the income *within* a subsample, with an exception of the low income sample.[3] It is the variation *between* the subsamples that generated the strong correlation of the income level with the savings rate, population growth rate, and the human capital investments found by Mankiw *et als*. Second, *within* the high income and the middle income samples we cannot find a significant evidence for the conditional convergence. It is only the low income sample that shows a significant conditional convergence after controlled for the human capital. Again, it is evident that the conditional convergence for the whole sample found by Mankiw *et als*. was driven by the variation *between* the different income groups. Since the structural differences are likely to be more pronouncing between the subsamples than within a subsample, the findings of Mankiw *et als*. may not necessarily be a strong supporting evidence for the Solow model. Since the

3) The human capital is the only significant explanatory variable and the inclusion of the human capital increases the explanatory power from 12% to 42%.

more homogeneous subsamples reject the implications of the Solow model, however, the overall judgment leans towards the rejection of the 'prototype' Solow model.

The above regression results by subsamples point to the existence of multiple steady states and confirm the casual observations that the prolonged poverty and the sustained growth coexist and that some countries are unusually successful. Since a modified Solow model with a convex-concave production technology can bear multiple steady states, we need to assess this possibility. An estimating the 'global' aggregate production technology *a la* Solow [28] using the Summers-Heston data shows that though the convex-concave specification appears to fit the data very well it does not dominate the Cobb-Douglas function. More importantly, it turned out that the convex-concave curvature, if it really is the case, is not pronouncing enough to generate the multiple steady states. Therefore, the modified version of the Solow model with a convex-concave technology may not be a proper theoretical framework to explain the widely different growth experiences.

The multiplicity of equilibrium seems to be generated by a more subtle mechanism than the existence of the threshold level physical capital or human capital. As Lucas [17] points out, the answer may lie in the mechanism that shifts the production technology.

The section I explains how the data is divided into subsamples. In section II, we test whether the Solow model explains the income variation for the subsamples. Section III tests the robustness of the conditional convergence. In section IV, we estimate the '*global*' aggregate production function to check the plausibility of the modified version of the Solow model that can bear the multiple steady states. Section V concludes by discussing the implications of the findings of this paper.

I. Segmentation of the Data

The regressions in the following two sections are based on the same data that Mankiw *et als*. used, in order to facilitate a direct comparison. The output-labor ratio, y, is measured by the GDP per working-age population. The growth rate of labor, n, is represented by the growth rate of the working-age population. The savings rate, s_k , is computed as the average annual share of investment in real GDP over the period of 1960~1985. The fraction of the eligible population (aged 12 to 17) enrolled in secondary school multiplied by the fraction of the working age population that is of the school age (15 to 19) is used for the human capital investment rate, s_h.

Mankiw *et als.* consider three different samples taken from the Summers-Heston data: Non-oil, Intermediate, and OECD. The non-oil sample consists of 98 market economies whose major industry is not the production of petroleum. The intermediate sample comprises of 75 non-oil market economies, excluding from the non-oil sample 13 countries whose data quality is not reliable. The OECD sample includes 22 member countries as of 1985.[4)]

The inclusion of the various proxy variables may be inadequate to simply include the various proxy variables to control for the structural difference. The list of the proxy variables chosen by Barro [4] and Levine and Renelt [16] leaves out many important institutional aspects that cannot be captured by such proxy variables. For instance, there are the distribution of wealth and income, the maturity of industrialization, and the degree of development of the institutional financial markets. If those structural aspects are closely linked to the level of living standard of the economy as the development economics argues, the division of data according to the income level would reduce the harmful effect of the omitted variables. Thus, in order to control for the important structural differences we divide the non-oil sample into four subsamples according to their income level (measured by output-labor ratio): the top 16 richest countries (Top 16), the high income countries (HI), the middle income countries (MI), the low income countries (LI).

For the test of the steady state variation, we divide the data according to the 1985 level of income. For the convergence test, however, we divide the data according to the 1960 income, to avoid the Baumol's [5] selection bias criticized by De Long [9].

The Top 16 sample's contain the 16 richest countries. It is notable that the Top16 samples almost coincide with the Maddison's convergence club [19]; The 1960-Top 16 sample is the same as the convergence club except that it includes New Zealand, Trinidad Tobago, and Venezuela instead of Japan, Italy, and Austria; In the 1985-Top 16 sample there are Hong Kong and Singapore instead of Italy and Netherlands. The 1960-Top 16 sample and 1985-Top 16 sample are the same except that New Zealand, Netherlands, Trinidad Tobago, and Venezuela in the former sample are replaced by Austria, Hong Kong, Japan, and Singapore in the latter sample.

The 1985-HI and the 1960-HI samples contain the top twenty three rich countries in

4) Luxembourg and Iceland are not included because their population is less than one million.

1985 and 1960, respectively. In 1985, Norway has the highest output-labor ratio, \$19,723, and Ireland is the twenty third in output-labor ratio \$8,675. In 1985, the gap in the labor-output ratio between Ireland and Mexico, which are twenty third and the twenty fourth, respectively, is as much as about \$1,295. In 1960, the US has the highest output-labor ratio of \$12,362 and the twenty third is South Africa whose output-labor ratio which is \$4,768. In 1960, however, the gap in the output-labor ratio between the twenty third and the twenty fourth countries is not remarkable, which is only \$357. It is interesting to note that the size and the 1960-HI sample is very similar to De Long's Once-Rich Twenty-Two sample. De Long's sample includes East Germany, Ireland and Japan, instead of South Africa, Trinidad Tobago, and Venezuela in the 1960-HI sample.

The 1985-LI and the 1960-LI samples contain the 42 poorest countries in 1985 and 1960 respectively. The 42 countries in the 1985-LI sample have the output-labor ratio lower than 10% of that of the richest country in 1985. Meanwhile, 42 countries in the 1960-LI sample have the output-labor ratio less than 14% of that of the richest country in 1960.

The MI samples in 1985 and 1960 contain those countries that are not neither in the HI sample nor in the LI sample. There are 33 countries included in the MI samples. In the following two sections, we repeat the same regressions of Mankiw *et als.* for each subsample to check the robustness of their results.

II. Test of Cross-Country Income Variation

Under the premise that all the countries are in the steady state, Mankiw *et al.* derived the regression equations explicitly from two versions of the Solow model, which they refer to as the textbook version and the augmented version, respectively. In the augmented version, the human capital is included as an additional factor of production. The derived regression equations are as follows.

Textbook version : $\ln(y)=a+b\ln(s_k)+c\ln(n+g+\delta)+\varepsilon$ (1)

Augmented version : $\ln(y)=a+b\ln(s_k)+c\ln(n+g+\delta)+d\ln(s_h)+\mu$ (2)

where y is the output-labor ratio, s_k, is the savings rate, and s_h is the rate of investment in human capital. n is the growth rate of the working-age population (aged 15 top 64). g is the exogenous technological progress and δ is the rate of depreciation. It is assumed that

〈Table 1〉 Fit of Textbook Solow Model to the Cross-Country Variations in Income

Sample	Number of Obs.	Constant	Savings $\ln(s_k)$	Labor growth $\ln(n+g+\delta)$	$\bar{R}^2$
Non-oil	98	5.48**	1.42**	−1.98**	0.59
		(4.25)	(9.95)	(−3.35)	
Intermediate	75	0.50**	1.31**	−2.01**	0.59
		(3.45)	(7.71)	(−3.77)	
OECD	22	9.14**	0.50	−0.74	0.01
		(4.25)	(0.43)	(−0.84)	
Top 16 in 1985	16	9.77**	−0.04	−0.02	−0.15
		(13.17)	(−0.20)	(−0.06)	
High Income in 1985	23	9.32**	0.21	−0.26	−0.03
		(9.76)	(0.95)	(−0.74)	
Middle Income in 1985	33	8.20**	0.27	−0.30	0.03
		(6.54)	(1.46)	(−0.60)	
Low Income in 1985	42	4.34**	0.33*	0.93	0.12
		(2.68)	(2.27)	(1.12)	
Low & High Income in 1985	65	10.62**	1.42**	−3.36**	0.69
		(6.20)	(8.20)	(−4.45)	

1. Numbers in the parantheses are t-statistics.
2. ** : significant at 1% level.
 * : significant at 5% level.

all the countries share the same values for g and δ: specifically, it is assumed that $g+\delta=0.05$.

The upper panels of the 〈Table 1〉 and 〈Table 2〉 show Mankiw *et als*' regression results for the non-oil, the intermediate, and the OECD samples. Both the textbook version and the augmented version can explain a significant part of the cross-country income variation for the non-oil and the intermediate samples. The textbook version explains 59% of the cross-country income variation for the both samples only by the savings rate and the population growth rate. The augmented version which includes the investment in human capital as an additional explanatory variable explains as much as 78% and 77% of the cross-country income variation for the non-oil and the intermediate samples, respectively.

But when it comes to the OECD sample, the textbook version explains only 1% and the augmented version explains only 24% of the income variation. This result is disturbing. If

〈Table 2〉 Fit of Augmented Solow Model to the Cross-Country Variations in Income

Sample	Number of Obs.	Constant	Savings $\ln(s_k)$	Labor Growth $\ln(n+g+\delta)$	Investment in Human Capital $\ln(s_h)$	$\bar{R}^2$
Non-oil	98	8.66**	0.70**	−1.75**	0.65**	0.78
		(9.16)	(5.25)	(−4.20)	(8.99)	
Intermediate	75	8.11**	0.70**	−1.50**	0.73**	0.77
		(8.32)	(4.66)	(−3.72)	(7.66)	
OECD	22	8.78**	0.28	−1.08	0.77**	0.24
		(4.66)	(0.71)	(−1.42)	(2.62)	
Top 16	16	9.56**	−0.06	−0.03	0.14	
in 1985		(12.06)	(−0.31)	(−0.10)	(0.84)	
High Income	23	9.27**	0.21	−0.27	0.03	−0.08
in 1985		(9.10)	(0.90)	(−0.73)	(0.15)	
Middle Income in	33	8.04**	0.25	−0.31	0.12	0.03
1985		(6.36)	(1.36)	(−0.61)	(1.03)	
Low Income	42	5.49**	0.20	0.41	0.32**	0.42
in 1985		(4.09)	(1.67)	(0.61)	(4.58)	
Low & High	65	9.93**	0.71**	−2.43**	0.66**	0.83
Income in 1985		(7.91)	(4.47)	(−4.28)	(7.43)	

1. Numbers in the parantheses are t-statistics.
2. ** : significant at 1% level.
 * : significant at 5% level.

the Solow model is truly in effect it should provide a better explanation for the OECD sample, because this model is originally constructed to explain the developed economies and the OECD sample is unarguably more homogeneous than the whole sample. Thus, we are left to suspect that the seemingly high explanatory power of the Solow model for the non-oil and the intermediate samples may be driven by the country-specific omitted variables that ought to have been included in the regressions to control for the structural difference.

Our suspicion is confirmed by the regression results for the subsamples shown in the upper panels of 〈Table 1〉 and 〈Table 2〉. The textbook version provides virtually no explanation for the Top 16, the HI, and the MI samples. Only for the LI sample, the textbook version can explain the 12% of the income variation. On the other hand, if we combine the HI sample and the LI sample, the textbook version can explain 69% of the income variation. Thus, it is obvious that the high explanatory power of the Solow model for the non-oil and the intermediate sample was driven by the variation between the different income groups that are unlikely to be structurally homogeneous.

Likewise, the augmented version can't explain any significant part of the income variation for the Top 16, the HI, and the MI samples. For these samples, the inclusion of the investment in human capital does not improve the explanatory power of the Solow model at all. For the LI sample, however, the augmented model explains 42% of the income variation. It is notable that the investment in human capital is the only significant variable in this regression, and that it and by itself provides the additional 30% explanatory power. It is also very impressive that the augmented model explains 83% of the income variation for the Tail sample which merges the HI and the LI samples. Again, this proves that the regression results for the non-oil and the intermediate samples were driven by the variation between the different income groups.

In sum, neither the textbook version nor the augmented version of the Solow model cannot explain any significant part of the income variation ***within*** the same income groups, with an exception of the augmented model for the LI sample. Even in the exceptional case, the most of the explained variation has to do with the investment in the human capital, not with the savings rate nor the population growth rate. On the contrary, the Solow model explains a large part of the income variation ***between*** the HI and the LI samples. Evidently, the high explanatory power of the Solow model for the non-oil and the intermediate samples must have come from the relationship of the variables across different income groups, not within the same income groups. Since there are significant institutional differences across different income groups, however, it is not clear whether the high explanatory power for the non-oil and the intermediate samples can indeed be interpreted as an evidence for the validity of the Solow model. Considering that it fails to explain the income variation within more homogeneous samples, the regression results in ⟨Table 1⟩ and ⟨Table 2⟩ as a whole would have to be interpreted as against the Solow model.

The rejection of the regression equations (1) and (2) may mean two different things. First, the Solow model is still in effect but the countries are not in the steady state. Second, the Solow model is not a proper framework for the analysis of the cross-country income variation. In the following section we are going to see how well the Solow model fits the data under the assumption that the countries are in a transitional phase.

III. Test of Convergence

There have been many empirical studies on the convergence of the income level. Baumol [5] found that the sixteen rich countries in Maddison's data show a strong unconditional convergence. That is, for this sample the long-run growth rate has a significant negative correlation with the income in the initial year. But De Long [9] criticized that the convergence among the well-to-do nations in the Maddison's sample may merely be a reflection of the selection bias and that showed that a slightly extended sample (Once-Rich Twenty-Two) strongly rejects the unconditional convergence.

Since the Summers and Heston data became available, the discussion of the convergence hypothesis has become dominantly based on this data. Romer [24] argued that a simple scatter diagram of the long-run growth rate during the period of 1960 through 1985 and the level of income in 1960 clearly shows the lack of convergence among the 121 market economies. He argued that this casual observation is consistent with the income divergence implied by the endogenous growth models of Romer [23] and Lucas [18]. Indeed, 〈Table 3〉 shows that for the non-oil and the intermediate samples, the long-run growth rate do not have a significant correlation with the initial level of income. Though the OECD sample appears to show a strong convergence, it has the same selection bias problem as does the Maddison's convergence club. 〈Table 3〉 also shows that there is no significant indication of unconditional convergence within any income groups, except for the Top 16 sample. For the 1960-HI sample, the sign of the coefficient of the initial income is negative but insignificant. For the MI and LI samples, the sign of coefficients points at the unconditional divergence, though not significant.

Mankiw *et als.* [21], Barro [4], and Levine and Renelt [16] along with many others found that the Summers-Heston data supports the convergence of the income if we control properly for the difference in the steady state level income and/or the other country-specific factors. In particular, Mankiw *et als.* argued that the Solow model provides an excellent guide on how to control for the difference in the steady state level of income in testing the convergence hypothesis. From the Solow model, they derive the following regression equations to test the conditional convergence.

〈Table 3〉 Tests for Unconditional Convergence

[redacted]

Sample	Number of Obs.	Constant	Income in 1960 $\ln(y_0)$	$\bar{R}^2$
Non-oil	98	−0.27 (−0.70)	0.09* (1.90)	0.03
Intermediate	75	0.59 (1.36)	−0.004 (−0.08)	−0.01
OECD	22	3.69** (5.38)	−0.34** (−4.34)	0.46
Top 16 in 1960	16	10.41** (2.89)	−1.09* (−2.75)	0.34
High Income in 1960	23	1.97 (0.90)	−0.17 (−0.68)	−0.03
Middle Income in 1960	33	−2.63 (−1.31)	0.42 (1.62)	0.05
Low Income in 1960	42	−0.21 (−0.23)	0.10 (0.86)	−0.01
Low & High Income in 1985	65	−0.13 (−0.34)	0.07 (1.33)	0.01

1. Numbers in the parantheses are t-statistics.
2. ** : significant at 1% level.
 * : significant at 5% level.

Textbook version :

$$\ln(y_t)-\ln(y_0)=a\ln(y_0)+b\ln(s_k)+d\ln(n+g+\delta)+\varepsilon_t \qquad (3)$$

Augmented version :

$$\ln(y_t)-(y_0)=a\ln(y_0)+b\ln(s_k)+c\ln(s_h)+d\ln(n+g+\delta)+\mu_t \qquad (4)$$

The lower panels of 〈Table 4〉 and 〈Table 5〉 show that the regression results for the non-oil, the intermediate, and the OECD samples support the conditional convergence. Especially, the augmented version appears to generate not only the right sign but also the proper magnitude of the coefficients. However, as shown in the previous section, within the subsamples the savings rate, the population growth rate, and the investment in human capital control for the difference in the steady state level of income, with an exception of the LI sample. Therefore, the conditional convergence for the non-oil and the intermediate samples may have been driven by the country-specific omitted variables. If this is the case, 〈Table 4〉 Tests for Conditional Convergence : The Textbook Version

Sample	Number of Obs.	Constant	Income in 1960 $\ln(y_0)$	Savings Rate $\ln(s_k)$	Labor Growth $\ln(n+g+\delta)$	Investment in Human Capital $\ln(s_h)$	$\bar{R}^2$
Non-oil	98	0.33	−0.14**	0.65**	−0.30	—	0.38
		(0.41)	(−2.71)	(7.47)	(−0.99)		
Intermediate	75	1.38	−0.23**	0.65**	−0.46	—	0.35
		(1.58)	(−3.98)	(6.22)	(−1.49)		
OECD	22	4.03**	−0.37**	0.55**	−1.05**	—	0.79
		(4.25)	(−5.54)	(3.53)	(−3.35)		
Top 16	16	2.40	−0.13	0.53**	−1.31**	—	0.81
in 1960		(1.01)	(−0.51)	(3.11)	(−3.49)		
High Income	25	1.23	−0.06	0.63**	−1.20**	—	0.61
in 1960		(0.76)	(−0.39)	(3.86)	(−3.73)		
Middle Income	27	−1.62	−0.03	0.86**	−0.01	—	0.54
in 1960		(−0.87)	(−0.14)	(5.60)	(−0.02)		
Low Income	27	0.77	−0.08	0.54**	−0.55	—	0.30
in 1960		(0.61)	(−0.70)	(4.33)	(−1.00)		
Low & High	48	1.69*	−0.17**	0.55**	−0.80**	—	0.34
Income in 1960		(1.68)	(−2.87)	(5.53)	(−2.05)		

1. Numbers in the parantheses are t-statistics.
2. ** : significant at 1% level.
 * : significant at 5% level.

the credit can't be given to the Solow model. Again, a stronger test would be the regression using more homogeneous subsamples.

The lower panels of 〈Table 4〉 and 〈Table 5〉 show the results of the conditional convergence tests for the subsamples. It is only the 1960 LI sample that shows a significant convergence conditional on the savings rate, the population growth rate, and the investment in human capital. These results are consistent with the findings of the previous section : the chosen control variables explain the steady state level of income only of the LI sample. For the Top 16, the HI, and the MI samples, however, the coefficient of the initial income is highly insignificant. This insignificance is not likely to be an artifact of the measurement error, since the simple least square estimation assumes that the variances of measurement errors in 1960 income and 1985 income are the same, which favors the convergence

〈Table 5〉 Tests for Conditional Convergence : The Augmented Version

Sample	Number of Obs.	Constant	Income in 1960 $\ln(y_0)$	Savings Rate $\ln(s_k)$	Labor Growth $\ln(n+g+\delta)$	Investment in Human Capital $\ln(s_h)$	$\overline{R}^2$
Non-oil	98	1.87**	−0.29**	0.52**	−0.51*	0.23**	0.46
		(2.21)	(−4.68)	(6.03)	(−1.75)	(3.88)	
Intermediate	75	2.49**	−0.378**	0.54**	−0.55*	0.27**	0.43
		(2.82)	(−5.42)	(5.26)	(−1.89)	(3.36)	
OECD	22	4.33**	−0.42**	0.45**	−1.11**	0.27*	0.81
		(4.25)	(−6.01)	(2.87)	(−3.72)	(1.81)	
Top 16	16	1.53	−0.07	0.47**	−1.43**	0.31*	0.85
in 1960		(0.72)	(−0.28)	(3.05)	(−4.27)	(2.10)	
High Income	25	1.86	−0.18	0.58**	−1.14**	0.21	0.63
in 1960		(1.13)	(−1.03)	(3.52)	(−3.57)	(1.39)	
Middle Income	27	−1.87	−0.001	0.90**	0.01	−0.05	0.53
in 1960		(−0.94)	(−0.005)	(4.86)	(0.03)	(−0.38)	
Low Income	27	2.31*	−0.35**	0.44**	−0.40	0.28**	0.40
in 1960		(1.77)	(−2.43)	(3.68)	(−0.79)	(2.71)	
Low & High	48	2.93**	−0.31**	0.46**	−0.90**	0.23**	0.44
Income in 1960		(2.92)	(−4.52)	(4.69)	(−2.46)	(3.38)	

1. Numbers in the parantheses are t-statistics.
2. ** : significant at 1% level.
 * : significant at 5% level.

results. Hence, the regression results in 〈Table 4〉 and 〈Table 5〉 are a strong evidence ***against*** the conditional convergence within the subsamples. Furthermore, the omission of the initial level of technology is not likely to be a driving force of the regression results, because its difference within the same income groups would be much smaller than between the different income groups. Hence, the rejection of the convergence within the income groups are not the result of mistreatment of the initial technological level, either.

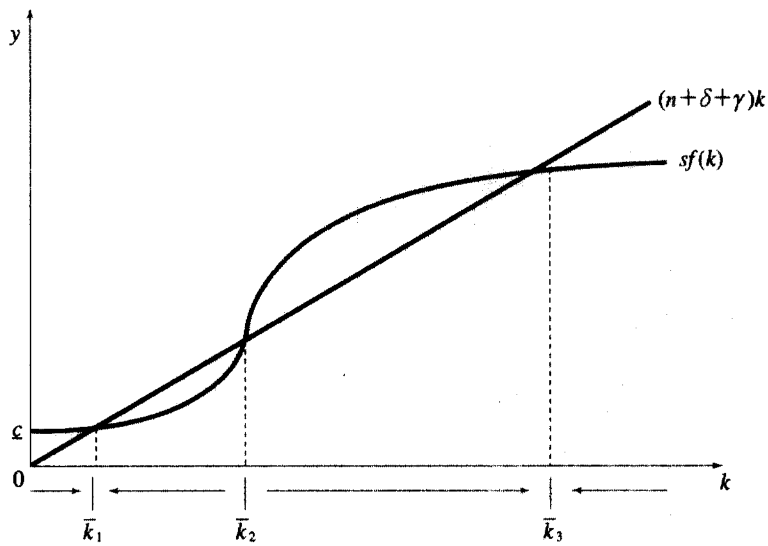
It should also be noted that the HI & LI sample shows a highly significant conditional convergence. This suggests that the conditional convergence for the non-oil and the intermediate samples is driven by the variation between the different income groups, while there is no strong conditional convergence within the same income groups. Because the countries with widely different income levels may have very different institutional conditions which cannot are not accounted for, it is hard to accept the conditional convergence for the non-oil and the intermediate samples as a supporting evidence for the Solow model.

In sum, the above regression results for the subsamples are consistent with the findings of Danny Quah [22], who showed that the low income group shows a stable egordicity, while the other income groups do not. These results imply that we may have to look for a model that can explain the sustained poverty as well as the sustained prosperity. In the context of the Solow model, there might be multiple steady state equilibria if the production technology is convex-concave and its curvature is pronouncing enough. In the following section, I estimate the aggregate production function to assess this possibility.

IV. Nonlinear Estimation of the Aggregate Production Technology

In the context of the Solow model, there can be multiple steady states if the output-labor ratio is a convex-concave function of the capital-labor ratio with a positive intercept, and the function has an enough curvature. With such a production function, if the savings rate is exogenous there may be three steady states, $\bar{k}_1<\bar{k}_2<\bar{k}_3$, as shown in ⟨Figure 1⟩. Among

⟨Figure 1⟩ Transitory Dynamics with Exogenous Technological Change and Exogenous Savings



the three steady states, $\bar{k}_1$ and $\bar{k}_3$ are stable and $\bar{k}_2$ is unstable. It can be easily shown that $\bar{k}_1$ and $\bar{k}_3$ are increasing in the savings rate, s, and decreasing in the population growth rate, n, the depreciation rate, δ, and the rate of Harrod-neutral technological progress, g. On the contrary, $\bar{k}_2$ is decreasing in s and increasing in n, δ, and g. The steady state level of capital-labor ratio in the middle, $\bar{k}_2$, is the *threshold* level. If the initial capital-labor ratio is less than $\bar{k}_2$, then the economy converges to $\bar{k}_1$. But if the initial capital-labor ratio is greater than $\bar{k}_2$, then the economy converges to $\bar{k}_3$. If the production function is convex-concave with a positive intercept and if the savings rate is exogenous, the equilibrium growth path is unique and the global economy would eventually be separated into two groups, the rich and the poor, depending on the initial stock of capital. Though this model can explain the coexistence of the sustained poverty and the sustained growth, it cannot explain the widely different growth experiences of once-similar economies.

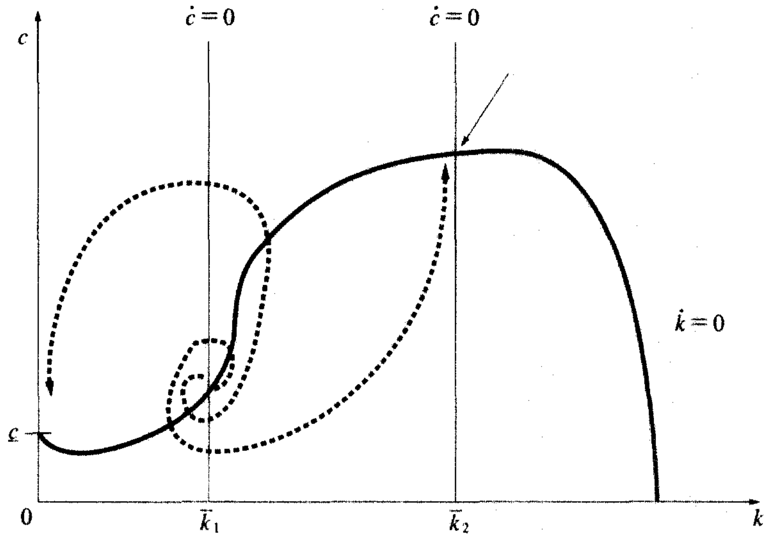
However, if the savings rate is determined endogenously as in the Cass's model [7], there can be two steady state capital-labor ratios, $\bar{k}_1 < \bar{k}_2$, as shown in 〈Figure 2〉. $\bar{k}_2$ is a stable saddle point. But $\bar{k}_1$ may be a knot or a focus, depending on the curvature of the production function and the values of the time preference rate, ρ, the elasticity of intertemporal substitution, σ, and the depreciation rate, δ.[5)] If $\bar{k}_1$ is a knot, $\bar{k}_1$ is a threshold level of capital-labor ratio. If the initial capital-labor ratio exceeds $\bar{k}_1$ the economy converges to $\bar{k}_2$. Otherwise, it degenerates to the primitive economy without any physical capital. But when $\bar{k}_1$ is a focus, as A. Skiba [26] showed, there exist multiple equilibria. In this case, initially similar economies may end up with a completely different situation, depending on which trajectory an economy follows. Therefore, at least potentially, this model can explain not only the coexistence of the sustained poverty and the sustained growth but also the widely different growth experiences of once-similar economies.

A prioi, the convex-concave production with a positive intercept can be justified for two reasons. First, the convex-concave production function implies that the corresponding average cost curve has a U-shape. Since the conventional measure of physical capital includes only the reproducible capital, it does not reflect the values of land and the other natural resources including the environments. If we treat these left-out factors as a fixed cost, then the average cost curve should have a U-shape. Second, the positive intercept

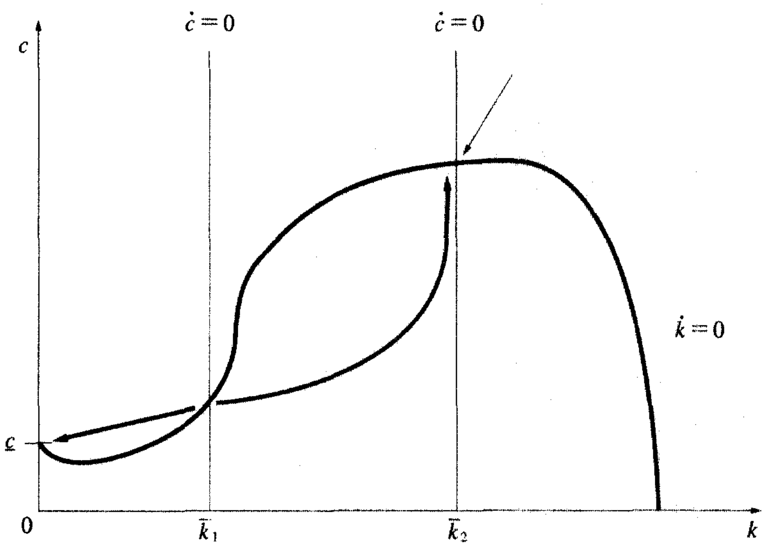
5) The eigenvalues are $\lambda = \rho/2 \pm \sqrt{\frac{\rho^2}{4} - \frac{1}{\sigma} f'(f' - \delta)(f - \delta k)^{(1-\sigma)}}$, in the vicinity of a steady state. λ's are either positive or complex numbers at $\bar{k}_1$. If λ's are positive, $\bar{k}_1$ is a knot, and otherwise, $\bar{k}_1$ is a focus.

〈Figure 2〉 Transitory Dynamics with Exogenous Technological Change and Endogenous Savings

Case 1 : Trajectories when $\bar{k}_1$ is a focus.



Case 2 : Trajectories when $\bar{k}_1$ is a knot.



implies that only with the crude stones and sticks the human beings were able to subsist. That is, as the capital per unit labor approaches zero the output per unit labor remains positive.

It must be a matter of empirical judgment whether such logical possibility is the reality. In the following section, we assess how well a convex-concave functional form with a positive intercept fits the Summers-Heston data.

1. Functional Forms for the Aggregate Production Technology

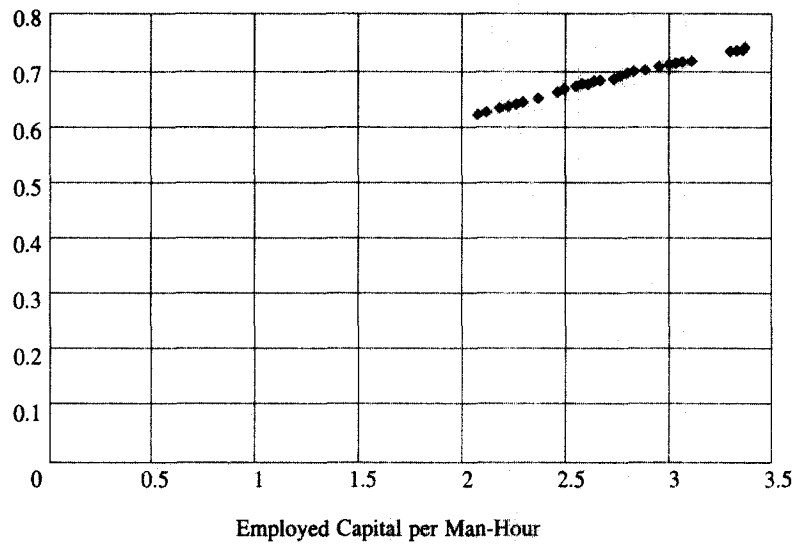
An aggregate production function, if it exists at all, represents a persistent relationship, between the aggregate inputs and the aggregate output. Although F. Fisher [11] showed that the existence of the aggregate production function is justified only under very strong conditions, the aggregate production function has been a major element for the macroeconomic analysis. In fact, it is the development of the theory of economic growth that contributed significantly to the wide acceptance of the notion of the aggregate production function. Following the convention, I would presume that the conditions for the existence of the aggregate production function are met. In the following, a special attention is paid to checking whether a convex-concave functional form can fit the data well and, if so, whether the curvature is pronouncing enough to generate multiple equilibria in the context of the Solow model.

It was Solow [28] who first showed how to estimate the aggregate production function, using the data on the non-agricultural sector of the US over the period of 1909 to 1949. After separating the shifters of the production function, referred to as Solow residuals, he checked which functional form fits the data well. He tried five functional forms that are consistent with constant returns to scale and have a linear representation in parameters : linear, semi-logarithmic, hyperbolic, Cobb-Douglas, and logistic functions.

Linear :	$q = \alpha + \beta \cdot k$	(5)
Semi-Logarithmic :	$q = \alpha + \beta \cdot \log k$	(6)
Hyperbolic :	$q = \alpha - \beta \cdot k$	(7)
Cobb-Douglas :	$\log q = \alpha + \beta \cdot \log k$	(8)
Logistic :	$\log q = \alpha - \beta / k$	(9)

where q is the output-labor ratio and k is the capital-labor ratio.

〈Figure 3〉 Aggrgate Production Technology U.S. 1909~1942(Solow's Data(1957))



He found that all the five functional forms fit extremely well the US data during the period of 1909 to 1949. His finding, however, may be a consequence of the limited observations over a short period of time only after the US economy became fully industrialized. As shown in 〈Figure 3〉, Solow's data appears like a small segment of a whole curve. Since this segment shows a slightly concave curvature, any locally concave functional form should fit the data very well as well as the globally concave functional forms that Solow tried.

While the constant return to scale is an essential assumption in Solow's estimation procedure, the linearity is an assumption taken for the sake of convenience. If we allow nonlinear specification, there must be a wider variety of functional forms that still exhibit constant returns to scale. One such example is a logistic function with a positive intercept (LFP) :

$$\text{Logistic with a positive intercept} : q = \gamma + \alpha \exp(-\beta / k) \qquad (10)$$

The regression equation (10) is a slight modification of the regression equation (9). The equation (9) is a logistic function which has an S-shape starting from the origin in the (q, k)-space. If the logistic function starts from the origin, it has a linear representation in parameters. But this functional form does not allow the multiplicity of the 'non-trivial'

〈Table 6〉 Aggregate Production Function : The US Non-Agricultural Sector, 1909~1942

Linear	0.438(167.4)	0.091(92.3)	–	0.996
Semi-Log	0.221(−29.1)	0.239(187.8)	–	0.999
Hyperbolic	0.916(252.6)	0.618(66.3)	–	0.992
Cobb-Douglas	−0.730(−419.3)	0.354(197.3)	–	0.999
Logistic	−0.037(−9.3)	0.914(89.9)	–	0.996
Logistic with a positive intercept	0.668(73.6)	3.159(16.8)	0.448(40.9)	0.999

* Numbers in the parentheses are t-statistics.

stable steady states. This problem can be solved by letting the logistic function have a positive vertical intercept, although it does not have a linear representation in parameters.

The estimation results in 〈Table 6〉 show that the LFP fits the Solow data at least as well as the other linear specifications. This finding is hardly surprising because of the limitation of the Solow's data mentioned above. To discriminate effectively the performance of different functional forms, however, we need to fill out the blanks of Solow's data. There are two ways to fill out the blanks ; i) we can retrieve the long enough backward series of a particular country ; or we can use the cross-section data that covers the developing countries as well as the developed countries. Because of the data availability, I take the second alternative, using the Summers-Heston data and other supplementary data published by UN subsidiaries.

2. The Data

The Solow's procedure of estimation requires the data for the output-labor ratio, the capital-labor ratio, and the share of property income. First, the real output data are obtained from the Summers-Heston data by simply multiplying the GDP per capita by the population.

Second, the cross section capital data is constructed by the perpetual inventory method. The real investment series for each country are taken from the SH data. Following King and Levine [14], the estimated steady state capital stock is used as the initial level of capital. If the *ith* economy is in a steady state, its capital-output ratio is a constant, $\kappa_i = i_i/(\delta + g_i)$, where κ_i, i_i, and g_i are steady state values of the capital-output ratio, the investment, and the growth rate. δ is the depreciation rate, which is assumed to be 0.07 for all the countries, following King and Levine. We use the average investment rate and the average growth rate in 1950's for the values of i_i and γ_i . Plugging all these numbers, we have the estimate of steady state capital-output ratio, κ_i. Then the initial level of capital stock is obtained by $K_0 = \kappa_i Y_0$, where Y_0 is the real output in the initial year. Based on this estimated initial capital stock, we can build a capital series according to the following law of motion for capital :

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

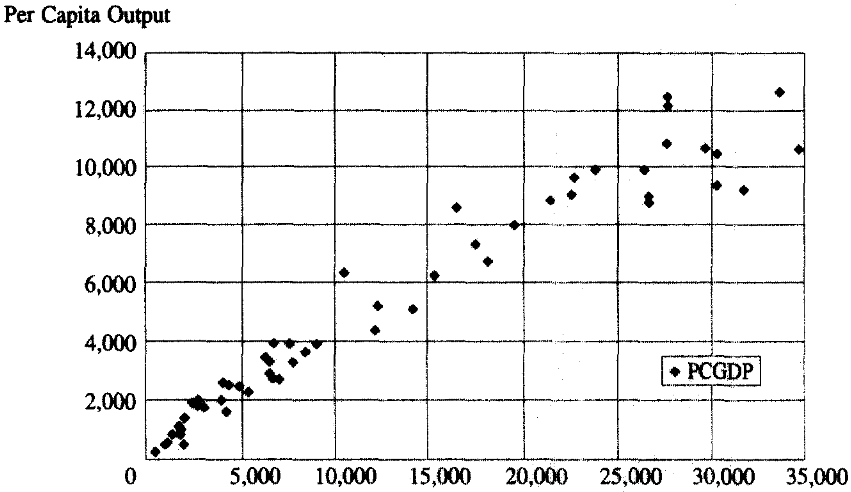
It should be reminded that when the depreciation rate, δ, is 0.07, only less than twelve per cent of the initial capital stock is retained in the capital thirty years later. Among the 121 market economies in the World Table, 72 countries have time series longer than thirty years. We are going to confine the attention to these 72 countries.

The share of property income is taken from *National Accounts Statistics* : *Main Aggregates and Detailed Tables*, [37] from UN. Among the 72 countries for which we have constructed the capital series, only 55 countries have a comparable measure of the property income share.

Although a more desirable measure of labor input may be the hours of work, such a measure is available only for the developed countries. If we use the sample of developed countries, the data would have the same problem as in the Solows original work. That is, the data represent only a small fraction of the whole curve. We can think of three alternative measures of labor input : population, labor force, and employment. The most crude measure of labor input is the population. The population data are taken from the SH data. The other alternatives, the labor force and the employment data, are taken from *Year Book of Labor Statistics* [35] from ILO. Although the employment may be the better measure of labor input, when we use it we will have to lose thirteen additional observation points and are left with only 42 countries. All three measures are used to check the sensitivity of the estimation result. The panel A of the 〈Figure 4〉, 〈Figure 5〉, and 〈Figure 6〉 are the plot of the output-labor ratio and the capital-labor ratio, corresponding to different measures of labor input.

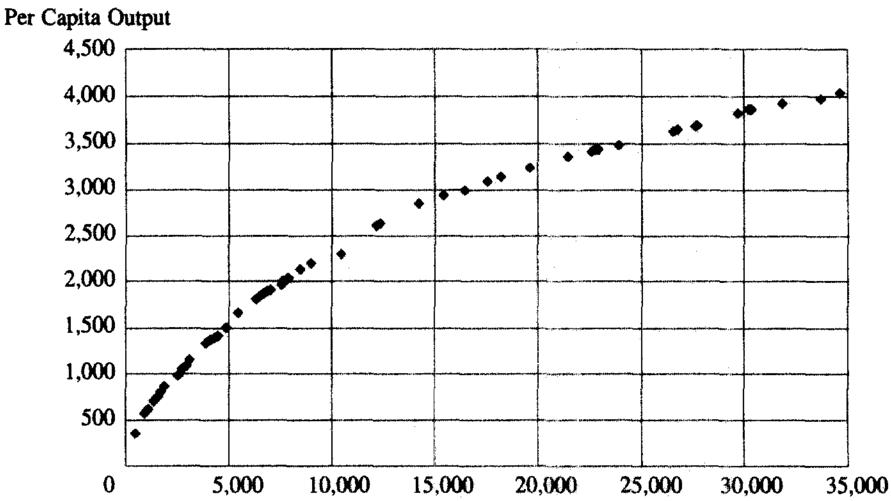
〈Figure 4〉

Global Aggregate Technology (Labor Input = Population)



Per Capita Capital

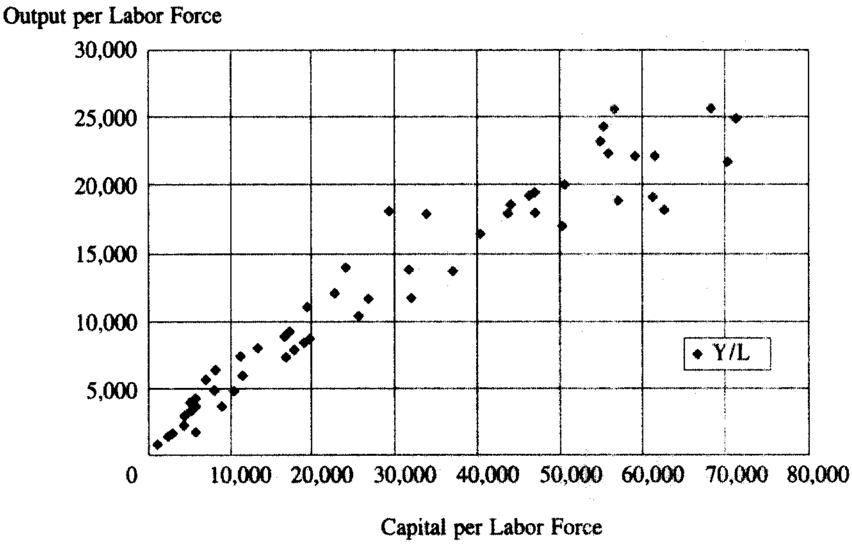
Global Aggregate Production Technology after Adjusted by Solow Residual
(Labor Input = Population)



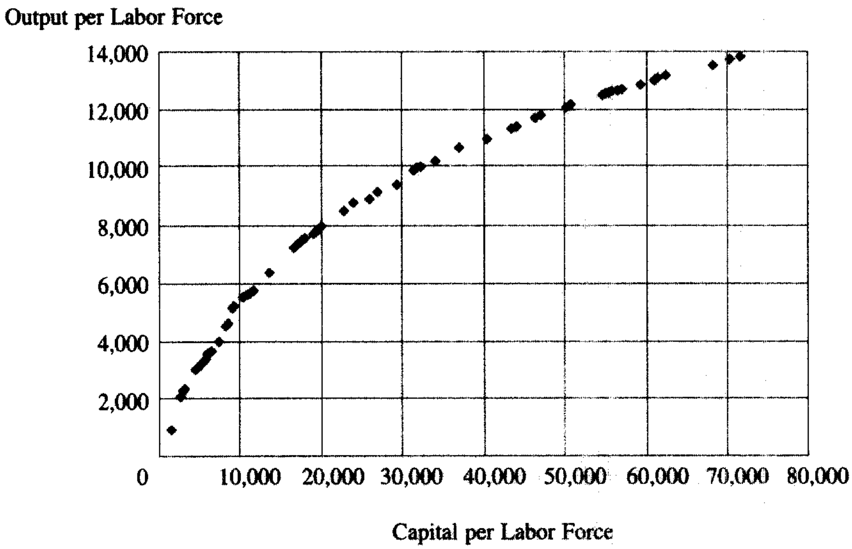
Per Capita Capital

〈Figure 5〉

Output per Labor Force vs. Capital per Labor Force Cross-Section 1985



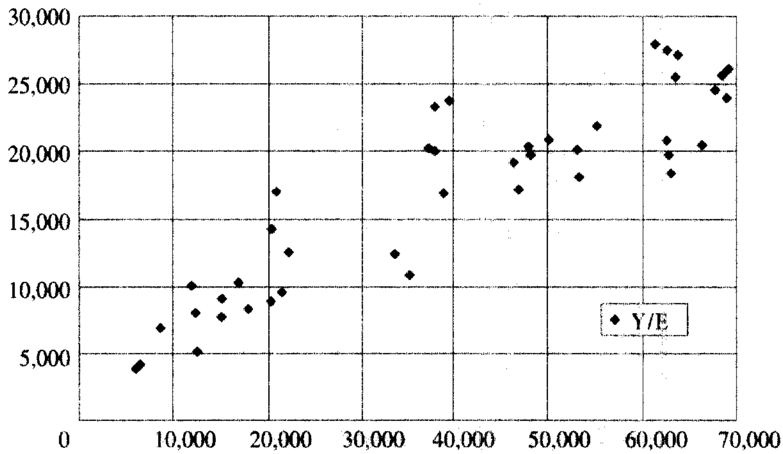
Global Aggregate Production Technology after Adjusted by Solow Residual
(Labor Input = Labor Force)



〈Figure 6〉

Output per Employment vs. Capital per Employment: Cross-Section 1985

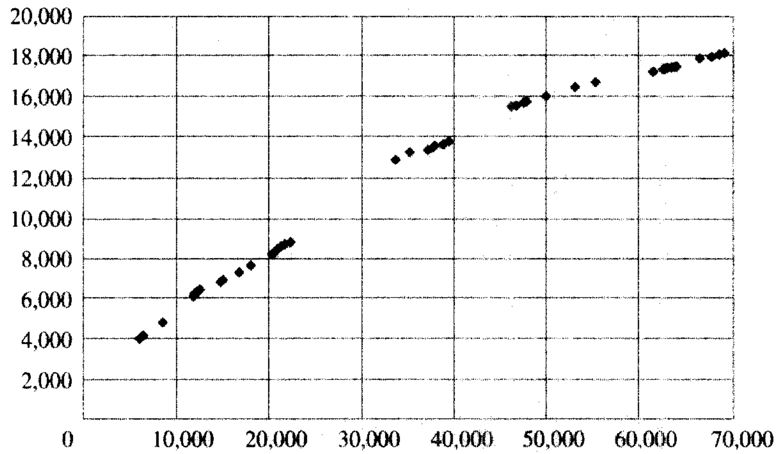
Output per Employment



Capital per Employment

Global Aggregate Production Technology after Adjusted by Solow Residual
(Labor Input = Employment)

Output per Employment



Capital per Employment

3. Estimation

Before estimating the production function, we need to separate the shifting factors from the persistent relationship between the output-labor ratio and the capital-labor ratio. Under the assumptions of constant returns to scale and the perfect competition, the rate of change in shifting factor, $\dot{G}/G$, is computed by

$$\dot{G}/G = \dot{y}/y - \pi_k \cdot \dot{k}/k, \tag{11}$$

where y is the output-labor ratio, k is the capital-labor ratio, and π_k is the property income share. Unlike the time series data, the array of the cross-country data is not dictated by the time dimension. But if there exists a stable relationship between the output-labor ratio and the capital-labor ratio at the global level, one natural array of the data would be the one in the ascending order of the capital-labor ratio. Given the array of the observations in the order of capital-labor ratio, the rate of change in residuals is computed according to the formula, (11). By normalizing the technology level of the country with the lowest capital-labor ratio to be one, $G_0 = 1$, we can construct the technological level of all the other countries from the estimated rate of change in technology. With this series, we construct the output-labor ratio controlled for the technological gaps, by dividing the output-labor ratio by the estimated technological level. The Panel B of ⟨Figure 4⟩, ⟨Figure 5⟩, and ⟨Figure 6⟩ shows the plots of the adjusted output-labor ratio against the capital-labor ratio. The shapes of the plotting show a remarkably smooth concavity. They also show a positive vertical intercept.

⟨Table 7⟩ Regression Results with Population Dependent Variable : Real GDP per Capita Adjusted by Solow Residual

Linear	933.027(15.5)	0.104(28.8)	–	0.94
Semi-Log	−6521.490(−24.8)	981.955(33.7)	–	0.95
Hyperbolic	2786.200(20.1)	1973842.500(6.8)	–	0.46
Cobb-Douglas	2.642(20.1)	0.549(103.8)	–	0.99
Logistic	7.905(137.8)	1319.138(11.1)	–	0.69
Logistic with a positive intercept	3966.464(66.7)	8444.624(26.8)	745.377(21.6)	0.99

* Numbers in parentheses are t-statistics.

〈Table 7〉 Regression Results with Labor Force Dependent Variable : Real GDP Adjusted by Solow Residual

Linear	3286.369 (13.8)	0.172 (26.2)	–	0.925770
Semi-Log	−25848.221 (−29.1)	3471.709 (38.6)	–	0.964391
Hyperbolic	9979.31 (22.7)	155550240.730 (7.5)	–	0.498899
Cobb-Douglas	3.051 (27.6)	0.590 (52.7)	–	0.980694
Logistic	9.214 (190.4)	3271.918 (14.3)	–	0.786658
Logistic with a positive intercept	13608.808 (58.8)	16834.379 (21.4)	3289.827 (15.4)	0.986907

* Numbers in parentheses are t-statistics.

〈Table 9〉 Regression Results with Employment Dependent Variable : Real GDP Adjusted by Solow Residual

Linear	3894.728 (13.6)	0.224 (34.4)	–	0.966368
Semi-Log	−56222.355 (−28.0)	6635.366 (34.3)	–	0.966231
Hyperbolic	17208.5 (30.4)	112471444.4 (10.9)	–	0.742653
Cobb-Douglas	2.658 (28.1)	0.646 (70.9)	–	0.991916
Logistic	9.831 (252.5)	1651.991 (16.5)	–	0.868036
Logistic with a positive intercept	22631.206 (77.4)	34288.244 (32.8)	4382.252 (27.9)	0.996404

* Numbers in parentheses are t-statistics.

〈Table 7〉 to 〈Table 9〉 show the regression results. Among the six functional forms, Cobb-Douglas function (8) and LFP (10) fit the data better than the other functional forms. Though LFP performs slightly better than Cobb-Douglas function, we have to be careful in interpreting these results. First, the regression equation (10) has three parameters whereas all the other equations (5) to (9) have two parameters. Nevertheless, the fitting by equation (10) does not dominate the fitting of equation (8). Second, the slightly better performance of equation (10) comes from the inclusion of the positive vertical intercept, rather than the convex-concave curvature of the production function. The same logistic function without the vertical intercept, equation (9), fits only 70 to 87% of the data. But the logistic function with a positive intercept fits the data as much as 99%. The results suggest that the convex-concave production technology may not be used as a legitimate\source of the multiple steady states in the Solow model.

V. Conclusion

The findings in the above sections indicate that neither the prototype nor the modified version of the Solow model is an adequate framework for explaining the data contained in the World Table.[6].One possible extension of the Solow model is to relax the assumption that the growth is determined by the exogenous technological progress, as is done in the recent endogenous growth models.

The promising direction of the theoretical development seems to be the endogenous mechanism of technological progress that can generates multiple steady states. There are already some models in that direction. For instance, Azariadis and Drazen [1] investigates the role of threshold level of human capital. Benerjee and Newman [3] pays attention to the income distribution and the occupational choice under the incomplete financial market. Benhabib and Gali [6] emphasizes the effect of the imperfect market structure. Stokey [29] captures the role of the product diversification when the development of a new product is risky and costly. In the context of an open economy, Stokey [29] and Young [34] provides a mechanism that generates coexistence of the poverty trap and the sustained growth based on the learning by doing and the knowledge spillover. To judge the relevance of all these theoretical models, we need to test their implications against observations.

6) R. Easterlin [10] pays attention to the fact that so many countries are not developed until now, and suggests that the modern education may be a key to the way out. R. Lucas [17] underlines the widely different growth experiences of the initially similar economies, such as Philippines and Korea, and argues that we need to understand the endogenous mechanism for the technological progress to explain such phenomenon.

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