CROSS-COUNTRY R&D AND GROWTH: VARIATIONS ON A THEME OF MANKIW-ROMER-WEIL

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INTRODUCTION

Why have rich countries gotten richer and poor countries poorer? This is a subject of debate in the literature on international economic divergence. The present paper extends the literature by focusing on the effects of R&D investments in the divergence and convergence process.

In previous work, *endogenous* growth models [Lucas, 1988; Romer 1989] challenge the assumption of "diminishing returns" in the *neoclassical* Solow growth models. Under diminishing returns, international economic convergence should have taken place or be taking place. Poorer economies should have a higher marginal productivity of reproducible resources (such as physical capital) and hence a higher growth rate than richer economies, eventually enabling the lagging economies to catch up. Therefore, in the long run, all nations will "converge" in levels of development. However, the data do not support the convergence prediction.

Recently, though, Mankiw, Romer and Weil [1992] shows that it is not necessary to abandon the assumption of diminishing returns to explain international economic divergence. The strategy of Mankiw et al. is to introduce human capital as a factor of production, and show thereby that once international differences in human capital are accounted for, there exists *conditional* convergence—conditional in the sense that if all nations had the same level of human capital, they would converge in the long run. This strategy for explaining global divergence is referred to here as the "factor differences" approach.

The results of Mankiw et al., however, do not rule out increasing returns, especially since their study does not include knowledge-intensive inputs.[1] As Romer [1994] argues, *these* are the sources of increasing returns (given the nonrival and indivisible character of knowledge). This helps explain why existing empirical work which focuses on traditional inputs (such as physical capital and labor) fails to find evidence of aggregate increasing returns [Caballero and Lyons, 1990]. The new growth literature emphasizes knowledge-intensive inputs and international knowledge spillovers as important sources of growth, and refers particularly to the kind of knowledge capital associated with research and development (R&D) [Griliches, 1992; Grossman-Helpman, 1994]. By employing world R&D data, a proximate test can be provided of whether increasing returns exist once domestic and foreign knowledge inputs are accounted for. Of course, research capital is only a rough proxy for knowledge. Absent direct measures of knowledge, cumulative investments in knowledge (such as research and development) are used to measure the stock of knowledge.[2]

By introducing R&D, this paper bridges the two approaches to explaining international economic divergence. On the one hand, R&D is shown to be an important factor that differs across countries. On the other hand, R&D knowledge, as an international public good, is shown to be a source of increasing returns.

However, R&D's role as a source of international factor differences or scale economies is not straightforwardly linked with either international divergence or convergence. Consider first R&D's role as a factor input: on the one hand, increased investments in research enable a country to grow faster. To the extent that they are undertaken by leader countries, the result will be greater international economic divergence. On the other hand, research generates spillovers benefitting foreign countries. To the extent that follower countries receive these benefits, the result will be greater international economic convergence. Secondly, consider R&D's role as a source of global scale economies. As world research spillovers increase, the result will be greater convergence among countries that share this world pool of knowledge but greater divergence between those countries that have access to this pool and those that do not.

Thus some combination of factor differences and scale effects is at work in the process of international economic convergence or divergence. Through these various channels, research activities can be both a source of cross-country divergence as well as a force behind the catching-up process.

Few studies address international R&D spillovers. Coe and Helpman [1995] and Park [1995] focus on spillovers within the OECD group, but do not address the issue of international economic divergence. In a related paper, Lichtenberg [1992] studies divergence issues, but does not directly estimate the impact of international spillovers on growth rates since no explicit measure of spillovers was created, as in this paper.

The remainder of this paper describes the empirical specification and results, and provides some concluding thoughts.

EMPIRICAL SPECIFICATION

R&D and other factors of production can affect the *level* and *growth rate* of output per worker. Hence, in this section, we derive two regression models: one for the level of output per worker and the other for the growth rate of output per worker.

The R&D augmented production function is

$$Y = K^{\alpha} H^{\beta} R^{\gamma} (A(S)L)^{1-\alpha-\beta-\gamma} \tag{1}$$

where Y denotes output, K physical capital, H human capital, R R&D capital, L labor, and A the technical efficiency index. The latter in turn is assumed to be a function of the stock of foreign research spillovers, S.

The technical efficiency function is parameterized as

$$A(S) = ES^{\phi}, \tag{2}$$

where E is the exogenous component of technical efficiency. Let g be the (exogenous) growth rate of E and σ the endogenously-determined growth rate of S. The growth rate of technical efficiency is then $g + \phi\sigma$. The output elasticity of spillovers, S, is $\phi(1-\alpha-\beta-\gamma)$, obtained by substituting equation (2) into (1).

In the specification above, international knowledge spillovers have the characteristics of a global public good insofar as their use is non-rivalrous. Furthermore, each country takes $A(S)$ as given; that is, the effects of spillovers are treated as external. The formulation above is compatible with the original Arrow-Romer external economies formulation as well as with an underlying innovation model driven by market power [Rivera-Batiz and Romer, 1991].

Let $y = Y/(A(S)L)$, $k = K/(A(S)L)$, $h = H/(A(S)L)$, and $r = R/(A(S)L)$. The various capital accumulation rates are then (in per worker efficiency units):

$$\dot{k} = s_k y - (n + \delta + g + \phi\sigma)k; \tag{3a}$$

$$\dot{h} = s_h y - (n + \delta + g + \phi\sigma)h; \tag{3b}$$

$$\dot{r} = s_r y - (n + \delta + g + \phi\sigma)r; \tag{3c}$$

where s_k, s_h, s_r are the fractions of output invested in the reproducible stocks, n is the growth rate of labor, and δ is the depreciation rate (assumed to be the same for all stocks).

The *level* equation is then derived by solving the model in steady-state:

$$\begin{aligned} \ln(Y/L) = {} & c + \phi \ln S + (\alpha/1-\alpha-\beta-\gamma)\ln s_k + (\beta/1-\alpha-\beta-\gamma)\ln s_h \\ & + (\gamma/1-\alpha-\beta-\gamma)\ln s_r - (\alpha+\beta+\gamma/1-\alpha-\beta-\gamma)\ln(n+\delta+g+\phi\sigma) + \epsilon \end{aligned} \tag{4}$$

where c denotes the constant.[3] Equation (4) is estimated in the empirical section. The steady-state stock of spillovers, S, is $I_s/(\delta+\sigma)$, where I_s is the gross investment in foreign R&D.[4]

Compared to the augmented Solow model in Mankiw et al. (where only physical and human capital are considered), the output elasticities of physical and human capital should be lower to the extent that R&D matters—that is, to the extent that γ is significantly positive. Also, the higher the growth rate of S, given by σ, the faster the growth of labor in efficiency units, and the more investments in physical, human, and research capital needed to maintain constant steady-state stocks of physical, human, and research capital.

The growth rate equation is derived by linearizing the model around the steady-state:

$$\Delta \ln y = \Omega(\ln y^* - \ln y_0), \tag{5}$$

where $\Omega = (1 - e^{-\lambda t}) > 0$ and $\lambda = (1-\alpha-\beta-\gamma)(n + \delta + g + \phi\sigma) > 0$ are convergence parameters. The intuition in equation (5) is that the growth rate of output depends on the gap between its long-run level of output ($\ln y^*$) and its initial ($\ln y_0$). Output grows if initial output is below its long-run level, and vice versa. Moreover, the economy's growth rate slows down as initial output approaches its long-run level (from below). Thus, leading economies slow down and lagging economies catch up. But if there were increasing returns to all *domestic* reproducible inputs ($\alpha + \beta + \gamma > 1$), then Ω is negative (for $t > 0$), and the opposite prediction arises: leading economies grow faster than the lagging economies, and divergence is the norm. Alternatively, divergence occurs if countries have different long-run levels of output (i.e. different $\ln y^*$'s) owing to international differences in factors accumulated (see equation (4)).

The convergence parameter λ reveals the dual role of research activities. On the one hand, as domestic R&D is more important (that is, the larger γ is), the value of λ and Ω is lower, and thus the catch-up process is slower. On the other hand, as the growth of research spillovers is greater (a higher σ), the value of λ and Ω is higher, and the catch-up process is faster. Thus, as argued earlier, own domestic R&D has a divergence effect while spillovers have a convergence effect. Of course, the convergence effect of spillovers applies only to countries that are actually *able* to benefit from foreign research (more on this later).

Substituting equation (4) into (5) yields the *growth rate* equation estimated in the empirical section:

$$\begin{aligned}(6)\quad \Delta\ln(Y/L) = {} & c - \Omega\ln(Y/L)_0 + \Omega\phi\ln S + (\Omega\alpha/1-\alpha-\beta-\gamma)\ln s_k + (\Omega\beta/1-\alpha-\beta-\gamma)\ln s_h \\ & + (\Omega\gamma/1-\alpha-\beta-\gamma)\ln s_r - \Omega(\alpha+\beta+\gamma/1-\alpha-\beta-\gamma)\ln(n+\delta+g+\phi\sigma) + \epsilon\end{aligned}$$

EMPIRICAL RESULTS

First, a few remarks about the data sources and measurement of spillovers. A sample of 59 countries that conduct R&D has been selected.[5] The sample period is 1960-85. Data on output, investment, and labor are from the *Penn World Tables*, research data are from the *Statistical Yearbook* of UNESCO, and human capital data are from Mankiw et al. The human capital investment rate, s_h, is proxied by the percentage of the working age population in secondary school.

Spillover research data for each country are derived by a weighted aggregate of the rest of the world's R&D investments. Simply summing the gross investments in

TABLE 1
Steady-State Equation
Dependent Variable: Log GDP per Worker (1985)

	Full Sample	Full Sample Excluding U.S.	OECD Countries Excluding the U.S.	Non-OECD Countries
C	-3.986	-16.533	-53.914	-20.630
	(7.42)	(9.345)	(19.021)	(11.61)
ϕ	0.611	1.191	2.950	1.348
	(0.349)	(0.434)	(0.877)	(0.533)
α	0.218	0.255	0.102	0.182
	(0.079)	(0.081)	(0.121)	(0.140)
β	0.184	0.132	0.190	0.162
	(0.063)	(0.067)	(0.095)	(0.104)
γ	0.124	0.114	0.152	0.027
	(0.028)	(0.028)	(0.044)	(0.061)
Adjusted R^2	0.718	0.735	0.729	0.532
S.E.R.	0.459	0.442	0.195	0.504
N	59	58	22	36

S.E.R. is the standard error of regression. Standard errors are in parentheses. Estimation is by non-linear least squares.

R&D by the rest of the world is not appropriate, as this would imply that research stocks of different countries are perfect substitutes. The research stocks of different countries are more likely to substitute for one another if those countries have similar underlying technological structures. Thus, for each country, spillover R&D investment is given by $I_s = \Sigma\Theta_i s_{ri} Y_i$. Only a fraction, Θ_i, of the ith foreign nation's R&D investment spills into the domestic economy. This fraction depends on the technological similarity between those two countries. The Appendix discusses the derivation of the spillover metrics, Θ.

The empirical results are shown in Tables 1 and 2. Table 1 presents estimates of equation (4) and Table 2 presents those of equation (6).

In column 1 of Table 1, the model explains about 72 percent of the cross-country variation in output per worker. As predicted, once R&D is accounted for, the output elasticities of physical and human capital (α and β respectively) are smaller than the estimates of 0.3 for each obtained by Mankiw et al. The stock of spillovers is significant at about the 8 percent level of significance and its estimated output elasticity is $0.3 = (0.61(1-0.51))$, which is greater than that of domestic R&D (estimated to be 0.124). Holding spillovers constant, there are constant returns to all domestic inputs (k, h, and r), but aggregate increasing returns to all inputs, including the foreign

TABLE 2
Growth Rate Equation
Dependent Variable: Log Difference GDP per Worker (1985)

	Full Sample	Full Sample Excluding U.S.	OECD Countries Excluding the U.S.	Non-OECD Countries
C	-6.661	-12.701	-7.661	-15.163
	(4.958)	(6.407)	(17.783)	(8.408)
Ω	0.314	0.343	0.522	0.340
	(0.082)	(0.082)	(0.131)	(0.119)
φ	1.436	2.161	1.127	2.478
	(0.806)	(0.934)	(1.490)	(1.278)
α	0.588	0.612	0.296	0.643
	(0.142)	(0.142)	(0.148)	(0.234)
β	-0.011	-0.058	0.197	-0.105
	(0.108)	(0.115)	(0.111)	(0.190
γ	0.092	0.081	0.071	0.028
	(0.041)	(0.041)	(0.058)	(0.089)
Adjusted R^2	0.416	0.445	0.606	0.351
S.E.R.	0.306	0.301	.0150	.0362
N	59	58	22	36

S.E.R. is the standard error of regression. Standard errors are in parentheses. Estimation is by non-linear least squares.

input S. However, since the effects of foreign knowledge spillovers are external to a country and since it is the global economy that experiences internal increasing returns, the domestic factors of production can be paid their marginal products.

Column II contains results without the United States in the sample. The U.S. can be considered an outlier. Since the United States accounts for 50 percent of the world's R&D, its stock of spillovers is rather small compared to that of others in the sample, even when foreign R&D is weighted. Eliminating the United States from the sample raises the statistical significance of the stock of spillovers and its output elasticity to $\psi = 0.6 = (1.19(1-0.49))$.

Next, the sample of countries considered in column 2 is separated into OECD and non-OECD groups. Column 3 contains the results for the OECD and column 4 for the non-OECD. Within each group, the traditional variables like physical and human capital are not statistically important (except in the case of human capital for the OECD). The reason is that each group consists of economies with fairly similar investment ratios s_k, s_h. The rates of R&D investments, s_r, vary little also in the case of the non-OECD countries. Thus, the driving force behind the explanatory power of the domestic rates of investment in the earlier regressions (shown in columns 1 and 2) is their "between-group" variability (that is, between the rich OECD and poorer non-OECD). However, spillovers do have explanatory power *within* each of these groups. The estimated output elasticity of spillover research is 1.5 for the OECD and 0.88 for the non-OECD. These numbers are rather large, a consequence perhaps of the fact that the other variables are not important determinants of output per worker. The spillover variable could be proxying for the relevant omitted within-group explanatory variables.

Table 2 shows estimates of the *growth rate* equation. The model explains about 35-60 percent of the cross-country differences in growth rates. Again in the full sample, the spillover variable is significant at about the 8 percent level of significance. Output elasticity of spillover research in the growth eqation is 0.47. Without the U.S., the output elasticity of spillovers is 1.4. The output elasticity of domestic research is in the range of 0.081-0.092. Differences in estimates between Tables 1 and 2 arise because a good deal of the cross-country variation in output per worker represents deviations from steady-state. The results in Table 1 are valid only if countries are in the neighborhood of steady-state. If not, the various factor inputs have not had a chance to complete their full effects on productivity.

That domestic and spillover research are not statistically significant (column 3) suggests that for the OECD, research activities influence primarily the levels of output per worker and not their growth rates. The reason is that within-group convergence is strong, as can be seen from the large estimate of the convergence parameter Ω (or λ). The initial level of output per worker has the most explanatory power. Within the OECD, the stocks of physical, human, and research capital may have been accumulated in such large amounts that strong diminishing returns to domestic reproducible inputs have set in, accounting for the dominance of the convergence effect.

As before, the spillover variable strongly explains growth in the non-OECD. The strong impact of spillovers on non-OECD growth rates and the weak impact of spillovers and domestic research on OECD growth rates suggest that increased spillovers (or increased world research) will lead to greater economic convergence between the two regions. Greater convergence is also predicted because the sample correlation between the growth rate of spillovers (given by σ) and the level of development (given by output per worker) is negative. That is, smaller economies experience a faster growth in research spillovers. This is favorable in the long run to their catching up with the rest of the world.

Finally, the human capital variable is not a statistically significant determinant of growth rates for this 59 country sample due to the low variability of human capital investment rates in this sample. Low variability is attributable to the educational requirements of scientific research. Since scientific research requires a fairly high level of education, in regions that conduct research, secondary school completion rates are rather high. What drives human capital to explain divergence in previous studies (which use a much broader sample), must largely be the differences in human capital between the very rich and the very poor.[6] For the sample of R&D nations, however, human capital *cannot* account for divergence!

CONCLUSION

The empirical findings support the idea that both increasing returns and cross-country differences in factor accumulation matter for aggregate economic growth. The results, in particular, show that differences in domestic research help explain international economic divergence. Moreover, were it not for international research spillovers, this divergence would have been greater. The results also show economies of scale in the presence of spillovers. These scale effects cause increases in spillovers to *raise* the growth rates of countries that benefit from spillovers. This has two effects: on the one hand, it expedites convergence by raising the growth rate of followers (who are the dominant beneficiaries of spillover research). On the other hand, it creates greater divergence between those countries that derive spillover benefits and those that do not.

Will the *convergence* or *divergence* effects of research prevail as world research activities increase? An unambiguous answer cannot be given in the case where a single country expands its research, for it depends on the country and on where its research knowledge goes. But if all countries proportionally increase their stocks of research capital, the results of this paper predict greater convergence for three reasons:

1. The measured impact (or output elasticity) of spillovers is larger than the impact of domestic research. To the extent that convergence is associated with spillovers and divergence with domestic research, the result favors net convergence.

2. Spillovers are more important to non-OECD growth rates.

3. Because of increasing returns, countries with a larger stock of spillovers grow faster. Yet it is precisely the lagging economies that have the larger stock of spillovers.

No doubt the discussion above excludes from consideration countries that might not derive any spillover benefits. Increases in world research would widen the gulf between those countries that do not benefit from foreign research and those that do. The issue is how many countries do not benefit. In order for countries to derive no spillover benefits whatsoever, they must have no technological similarity to *any* of the R&D nations (and thus have spillover metrics of zero), which seems exceptional.[7] Thus, an extension for future research is to include non-R&D nations and examine whether they receive any international knowledge spillovers. Another extension is to improve the empirical modelling of the OECD and non-OECD sub-samples. The estimates of the scale of increasing returns are rather large for these within-group samples. One possible reason is that, aside from the spillover variable, the other explanatory variables do not exhibit much variation. Thus, one way to introduce more variation in the data is to include other factors that might affect within-group differences in growth (such as laws, infrastructure, or government policies). Another way is to incorporate time-series data, as in a panel data set. More plausible scale estimates are likely to be obtained from these extensions.

APPENDIX

The technological likeness between any two countries is measured by comparing their GDP composition by kind of activity.[8] The extent of overlap should reflect the degree of similarity. From an input-output perspective, using this procedure can be justified on the basis that it reveals the underlying mix of technologies.

The spillover weights are thus constructed as follows. Let $Y = (Y_1,\ldots,Y_J)$ and $Y^* = (Y_1^*,\ldots,Y_J^*)$ be the percentage composition of GDP in the home and foreign country respectively, where J is the number of sectors. The technological similarity between these two countries can be defined by the angle between the two vectors Y and Y*; that is, $\theta = (Y \cdot Y^*)/(|Y|\ |Y^*|)$, where $\cdot$ denotes the dot product and $|\ |$ the length of the vector. Note that θ varies from 0 to 1. If it is one, the two countries are perfectly similar technologically; if zero, they are completely dissimilar.[9]

NOTES

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1. Human capital may be regarded as a knowledge-related input, but it measures knowledge acquired from general education rather than from specialized production and innovation activities.
2. Essentially, this is the strategy used to measure human capital, namely to measure expenditures on education.
3. The constant and error terms appear because it is assumed that the exogenous log level of technical efficiency of all countries is randomly distributed around a constant; that is $\ln E = c + \epsilon$.
4. This is from the fact that $\dot{S} = I_s - \delta S$ out of steady-state.
5. A data appendix is available from the authors upon request.
6. Mankew et al. and Benhabib-Siegel [1994] also find that human capital is statistically weak in explaining growth among the OECD countries.
7. Even a modest degree of technological similarity enables a country to grow at the same long-run rate as its technological neighbors if it invests in reproducible stocks at the same rate as they. Its long-run level of development, however, will differ depending on how much of these factors it has accumulated relative to its neighbors.
8. Data on the economic composition of GDP are taken from the United Nation's *National Accounts Statistics*, 1965-1985.
9. As an example, consider four universities. The flow of research spillovers from one university to another depends on the composition of each university by department. If one university is 50 percent Humanities, 40 percent Theology, and 10 percent Science, while another is 95 percent Science, 4 percent Theology, and 1 percent Humanities, the two schools are not likely to generate much cross-campus research spillovers. In contrast, a university that is 95 percent Economics, 5 percent Art, and another that is 93 percent Economics, 7 percent Music, would exchange much economics research spillovers.

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