Implications of the New Growth Theory to Agricultural Trade Research and Trade Policy

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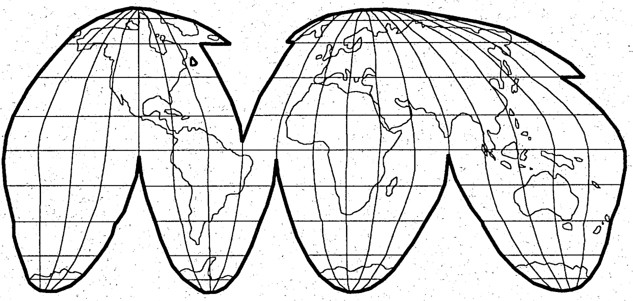

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R&D Spillovers, Economic Growth, Convergence and Divergence: A Time-Series Approach

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I. INTRODUCTION

Empirical research on the relation between R&D and economic growth has relied on cross-sectional or panel data. Most of the empirical research is based on the hypotheses generated by the predictions of the New Growth Theories (e.g, Romer, 1990) which focus on steady-state rate of economic growth. As such, cross-sectional tests are accurate *only* if the underlying growth rates are stationary (i.e., achieve steady-state) within country in the sample (Quah, 93; Jones, 95). But as Quah (93) and Jones (95) point out, the stationarity requirement is a very strong one and rarely borne out by the evidence. Moreover, unobserved country-specific factors always exist which make cross-sectional tests less reliable. These difficulties points to the need for time-series studies which has often been neglected in this literature.

Secondly, a natural (logical) relation exists between the R&D-growth hypothesis and the convergence-divergence debate. Specifically, because of the possibility of international R&D spillovers, the question of whether higher R&D promotes only domestic economic growth or the economic growth of other countries, is related to the question of whether differential rates of R&D investments result in differential growth rates of countries (divergence) or whether sufficient R&D spillovers exist to result in long-run convergence of the economies to a unique growth rate. The literature has not explicitly linked up these two hypotheses. Finally, tests of divergence or convergence have also typically relied on cross-sectional data. Thus they are subject to the same shortcoming as those discussed above.

This paper is an attempt to address these issues. Following a survey of the literature and a discussion of some theoretical issues, we then examine the convergence-divergence debate with the use of data over time. Here, we adopt a unique bi-country approach which allows us to view convergence or divergence between any given country and a reference country, as a temporal process. Next, we examine the R&D-growth hypothesis with and without international spillovers and compare the results with those from the convergence-divergence test.

The selected survey of the literature and discussion of theoretical issues are presented in Section II, the time series analysis is presented in Section III. Section IV makes concluding remarks.

II. A SELECTED SURVEY

Do Spillovers Exist?

A central theme of the new growth theories, and perhaps also a central point of contention, is that the current state of an economy, characterized by such variables as physical capital, human capital, or R&D capital, may influence the economy's path of subsequent growth for ever. Closely related to this "path-dependence" result, is the result that economic policies may have *permanent* long-run effects on the steady-state path of economic growth. Among the leading representative models of the new growth theories, one can point to the so called "AK" models, such as those by Romer (1986, 1987) and Rebelo (1991), and the R&D-based models of Romer (1990), Grossman and Helpman (1991a, 1991b). New growth theories which are also known as "endogenous growth theories" pose a challenge to the Solow models in which long-run growth is independent of current interventions or current stock of capital, as all economies converge to the same steady-state level of per capita income in the long-run. Although human capital often plays a key role in many of the varieties of the new growth theories, it is important to point out that the debate between the Solow growth models and the new growth theories is not about human capital. As such, the debate it is not resolved by incorporating human capital into the original Solow (1956) model, as the famous Augmented-Solow model by Mankiw, Romer and Weil (1992) demonstrates.

Recently much of the interesting theoretical and empirical work in endogenous growth has focused on the role of R&D. The common theoretical thread is the hypothesis that there are significant *spillover* effects in research and development related activities. Since R&D spillovers lead to *increasing returns* in production, competition cannot exist in this sector. Hence, imperfectly competitive characterization of the market is needed *if* private proprietorship of R&D returns is assumed such as in patents (Romer, 1990). An empirical survey of the R&D and its spillover effects in agriculture and in industry by Griliches (1992) shows that (a) R&D spillover effects do exist (b), their magnitude may be large and (c), social return to R&D exceeds its private return. These conclusions support the case of increasing returns to R&D, and suggest that such increasing returns are more likely found at the *macro* level, because at this level inter-firms spillovers are already incorporated. To capture this effect, the social return to R&D is often calculated and compared with its private return. The macro level studies of spillovers or increasing returns can be found at the industry level, country level, or internationally. Some of the earliest and most sophisticated studies of R&D occurred within the agricultural sector (see Griliches, 1992 for a survey) and found a rather high "social rate of return" to R&D (some of which were public R&D) in agriculture. In the case of industrial sector, one example of spillovers is the study by Bresnahan (1986) who shows large spillovers from the computer industry to the financial sector. As for inter-sectoral spillovers that involve agriculture one example in a recent study by Gopinath and Roe (1996) which uses time-series data for 1961-90 and a cost function approach to find large spillovers from agricultural R&D (mostly public) to food processing sector and somewhat smaller (but significant) R&D spillovers from food processing sector to agriculture. These examples all point to the existence of substantial intra and inter-sectoral spillovers effects.

Implications for Growth, Divergence and Convergence:

If research and development activities spillover from firm to firm, then in fact higher aggregate growth rates should result in the long run. In the endogenous growth theory, this means the existence of "scale effects", i.e., effects in which larger current size of the R&D puts the economy at a higher steady-state growth path. Naturally, this issue has significant policy implications. It is also important for the international comparison of the growth record of countries. For, to the extent that R&D-produced knowledge spills over to other firms within but not across nations, countries with large R&D sector should growth faster and this should lead to the *divergence* of productivity across countries, a dramatic departure from Solow. However, the existence of international spillovers should produce a counter-tendency. If this latter effect dominates, productivities *converge* across countries as their knowledge base--the country specific scale effect in Romer (1990)--becomes unified. Thus the nature and the extent of R&D spillovers is very much related to the well known divergence-convergence debate (Baumol, 1986; Baumol and Wolf, 1988; De Long, 1988).

What does the evidence say about all this? Focusing on the role of R&D *within national borders* evidence points to a statistically significant positive effect on aggregate growth. For example, Litchenberg's (1993) production function approach in an expanded "augmented Solow" form that includes R&D capital, shows large and significant effect of R&D investment on both the level and the rate of growth of productivity. Taking his sample for 74 countries for the 1960-85 period, Litchenberg finds a social rate of return to R&D nearly 7 times the private return. Similar finding is reported in an earlier study by Fagerberg (1988), but the latter is confined only to 22 OECD countries. However, neither study tests for the existence of international R&D spillovers. In fact Litchenberg (1993) believes such international effects to be limited and slow. If so, then economies with more R&D investment should grow more rapidly and since international diffusion of knowledge is not enough, according to Litchenberg, productivity levels across countries should diverge in the long-run.

Yet, *international* R&D spillovers do seem to exist, or so at least for the OECD countries. For example, a panel study of OECD countries for the 1970-87 period by Park (1995) points to significant positive effects of (a) domestic R&D on growth, (b) foreign R&D on domestic output, and (c) foreign R&D on domestic R&D in a sample that includes the US (but not so when US is excluded). The existence of international R&D spillovers among OECD is further supported by the cross-sectional study of Gittleman and Wolf (1995) for the 1960-88 period (but especially for 1960-70 period), and also by Coe and Helpman (1993) for the 1970-90 period who use pooled cointegration regressions and find a significant role of foreign R&D spillovers on total factor domestic productivity. The evidence with respect to R&D spillovers to the developing countries is somewhat weaker and more mixed. For example, the Gittleman and Wolf (1995) study also covers a larger sample that includes low-income countries, but fails to find evidence of R&D spillovers in this larger sample. By contrast, a study of R&D spillovers from "North" to "South," by Coe and Helpman (1995) finds some evidence in support of such spillovers.

The unambiguous evidence in support of R&D international spillovers among the OECD countries points to the possibility of productivity *convergence* among this group. But the mixed evidence with respect to R&D spillovers to low-income countries, suggests whether this group's incomes or productivities converge towards the OECD group or diverges away from them may only be settled empirically.

Direct evidence in fact points to *divergence* of incomes and productivities for an overall sample of both developed and industrialized countries but convergence among the industrialized countries. For example an elegant non-parametric study of 118 countries for the 1962-84 period by Quah (1993) focuses on transition probabilities from one "income-group" to another in an ergodic state and finds strong evidence of increasing divergence of incomes, between the poor and the rich countries. Overall, divergence was also documented for the much smaller historical sample of De Long (1988) in his original work. On the other hand, convergence seems to be the rule when focusing on the high income groups, as found in Baumol and Wolf's (1988) reply to De Long (1988). Moreover, Dowrick (1992) study of 113 countries for the 1960-88 period finds evidence of "conditional convergence" among the high income countries, "conditional divergence" among the low income countries, and neither convergence nor divergence among the mid income countries. In short, while convergence on top of the income scale appears to be the case, divergence of incomes between the poor and the rich tends to dominate, leading to overall divergence of incomes in the larger samples.

Returning to the question of spillovers, one remaining question is this: If international spillover effects are important and may even dominate domestic R&D effects, as Park (1995) has shown for the OECD group (when considering private R&D only), then what is the incentive for private firms to engage in private R&D activity? The answer lies in the fact that although for OECD, aggregate productivity effects are larger from foreign private R&D, this is a form *social* return to R&D. Thus the possibility of a higher private return from domestic R&D remains. In fact this is the case: Park's estimates that domestic private R&D has a higher return than does foreign private R&D (0.44 versus 0.047).

Some Theoretical Considerations:

An important recent paper by Jones (1995) has posed a challenge to the endogenous growth theory's main thesis, i.e., the existence of increasing returns to R&D. While Jones' main focus is on the "AK" models, rejecting these models based on time series evidence, Jones suggests that time-series evidence also points to the lack of a relation between R&D and growth, though he does not provide any formal test of this claim. Jones's theoretical focus is on one of the central equations linking R&D activities to growth in which R&D is represented by the size of the skilled labor force employed in the R&D sector. Adopted from Romer (1990), this equation is:

$$\dot{A} = \delta L_A A \tag{1}$$

where L_A is the R&D skilled labor force, A is the present state of knowledge (stock of R&D) and δ is constant. With $\dot{A}/A$ measured by the rate of growth of total factor productivity (TFP), data on selected OECD countries suggests an *exponential* rate of growth of engineers and scientists in the R&D sector, but a distinct absence of a trend in productivity growth. Jones provides an alternative formulation of Romer's central R&D equation, above, in which the growth of knowledge $\dot{A}$ shows *deceasing*, instead of constant returns to A. This equation is:

$$\dot{A} = \delta L_A A^{\phi} \tag{2}$$

with $\phi<1$. Dividing by A we have, $\dot{A}/A = \delta(L_A/A^{1-\phi})$. In steady-state output and A grow at the *same* constant rate. For this to hold we must have $\dot{L}_A/L_A = (1-\phi)\dot{A}/A$. But, $\dot{L}_A/L_A$ in steady state grows at the rate of growth of population, say n. As a result, economy and technology growth at the common steady state rate of:

$$g_y = g_A = n/(1-\phi). \tag{3}$$

Equation (3) implies that long run growth is *pre-determined* as in the Solow family, thus refuting both the scale effects and the importance of policies in influencing long-run growth. Since R&D manpower constitutes a small and evidently increasing fraction of total population, it need not grow at the rate of population growth over exceedingly long time horizons. Thus, lengthy transitional dynamics to are implied. Jones own criterion with respect to his AK model is that long-run processes exceed 8 to 10 years. Such criterion may be valid here as well.

An Alternative Formulation:

To the extent that Jones measures human capital by the ***number*** scientist and engineers, rather than some measure of their "effective labor input", a unique characteristic of human capital, that of learning by doing, may be overlooked (Arrow, 1962). As such, the growth rate in the number of scientist and engineers may not be meaningful.

With respect to the first point, I incorporate learning by doing in a Jones' formulation such that (a) the final result preserves the scale dependence of the Romer-like models, and (b) provides the basis for an alternative empirical specification of the relation between human capital and total factor productivity. The model, which is presented in the Appendix, shows that the growth rate is proportion to the size of current "stock" of R&D labor force as a fraction of a weighted stock of *past* R&D labor. To the extent that current human capital is involved, this formulation restores the "scales" effects or "path-dependence". However, incorporation of the successive past values of R&D labor tends to *moderate* the exponential measure of R&D human capital growth, observed in Jones (1995). In this formulation, knowledge spillovers are attributed to the accumulation in the *learning* process, somewhat akin to Lucas (1988). Since knowledge spillovers are purely external, Romer's monopolistic competitive firms may be replaced with perfectly competitive ones, engaged in R&D activities that are fully excludable (as in patents), but "spillover" to other firms only via the movement of experienced R&D agents (scientists and engineers) across firms which firms cannot internalize. Agents need not divulge "trade-secrets" from their former firms, but their embodied knowledge and experience is their useful human capital. These agents accumulate knowledge (i.e. learn) and propagate knowledge by moving from one firms to the next.

III. A TIME-SERIES APPROACH

The macroeconomic studies of the role of R&D in growth cited so far, have all used cross-country evidence. One time-series approach cited earlier (Gopinath and Roe, 1996) addressed intersectoral rather than macroeconomic questions. The other (Jones, 1995), uses time-series to test the "AK" variety of growth models, not the R&D models. Owing to important structural differences among countries, and the steady-state requirements of cross-sectional data, discussed earlier, time series evidence may yield more reliable evidence of the R&D-growth models as well. Surprisingly, however, such studies have not been carried out. Here, we present two time-series analyses, one on convergence-divergence hypothesis, and the other on the relation between R&D and growth. We will then make an attempt to relate the two studies.

With respect to the first task, we focus on the process of convergence or divergence as a "bi-lateral" process, examining the difference of per capital income of each country from a reference country (say US) over time. This is a novel approach and differs from the traditional literature's view of convergence or divergence as a single aggregate cross-sectional process. Thus, the regression equations are carried out *separately* for each country i, as follows:

$$(Y_{US}-Y_i)_t = \alpha + \beta.t + \varepsilon_t \qquad \text{(i=country index)}$$

in which $(Y_{US}-Y_i)_t$ is the difference in real per capita income of the US and each of the other countries in the sample. The data cover 42 years (1950-1992) for a subset of the countries in the Summers and Heston (1995) dataset. This includes the countries originally covered by DeLong (1988), plus a number of other countries. Because the Summers and Heston's data uses purchasing price parity to calculate national incomes, the US per capita income turns out to excceed that of other countries so that $(Y_{US}-Y_i)_t$ is non-negative for all t. Then, a positive β coefficient should indicate divergence and a negative coefficient, convergence. Stationarity of the error term is established by correcting for AR(1) process, though higher order corrections improve the results even more.[1]

Results are reported in Table I. As the table shows, convergence is indicated for most of the OECD countries while divergence for others. Thus, time-series results are consistent with the results of the cross-sectional analysis. The next question is to what extent is economic growth associated with R&D expenditures and how is this related

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[1] It is conceivable that the linearity in time of the long-run per capital income series may be violated, should they not be in steady-state. This is a complicated issue which is not addressed here, but in a separate paper by Datta and Mohtadi (1996) by means of a non-linear Kalman Filter mechanism.

to some of the convergence-divergence results from Table I.

First, we examine the role of "own" R&D expenditures on growth rate via the following *time series* regression:

$$(Y_i)_t = \alpha + \beta(R\&D_i)_t + \varepsilon_t$$

Data are from 1971 to 1990. The per capita data are from Summers and Heston, while the R&D data are based on Coe and Helpman (1993).[2] The time-series R&D data are available only for the OECD group which is a subset of the countries in Table I. Results are reported in Table II. Since the variables in the regression are "level" variables, growing in time, the possibility of spurious association must be ruled out. To do this the table corrects for first and second order autoregressive processes in the error term, yielding values of DW statistics that in most of the cases are near to 2. Results indicate that while own R&D is important to higher per capita income in many instances, in five of the countries, Finland, Greece, Norway, Portugal, Spain, it is not significantly associated with higher per capita income. (In three other case, Belgium, Denmark and Germany, iterations for AR calculations did not converge.) Interestingly, all the five countries are those which in Table I either diverged from the US per capita income (Greece, Spain, Portugal), or showed statistically insignificant (convergence) results. The next question is whether any convergence in Table I may be due to *international R&D spillovers*, and any divergence due to a *lack* of such spillovers, as

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[2] Since the R&D data in Coe and Helpman were based on an index value in which a specific year (1985) was used as a base-year, pooling data for the OECD group was not directly possible, as then base year values would all be identical across countries. Dr. Coe kindly provided us with the actual (unindexed) R&D data which allowed then us to pool for the OECD group.

the discussion of the previous section suggested. For this reason, we run a second test in which US R&D expenditures is included as an indicator of the international R&D spillovers, *along with* domestic R&D expenditure levels. These regressions are represented by,

$$(Y_i)_t = \alpha + \beta(R\&D_i)_t + \gamma(R\&D_{US})_t + \varepsilon_t$$

The choice of US R&D as an indicator of international R&D spillovers is made because the convergence-divergence results of Table I were also made with reference to the US Results are reported in Table III. The table shows evidence of international R&D spillovers on growth (via US R&D) in most instances *including* the group of countries in Table II that showed no significant own R&D effect. (Recall from Table I that there was no evidence of convergence for this subgroup.) The only exception is Norway which did not show significant effect of own R&D before and still does not show a significant effect of international R&D. (Again, Germany is dropped because the iterations for AR calculations did not converge.) Thus, for the most part, evidence of international R&D spillover is consistent with evidence of convergence, though one cannot claim any causality between R&D international R&D spillovers and convergence *a priori*.

Finally, there is one remaining puzzle in Table III, i.e., the drop in the importance of *own* R&D in explaining per capital income when the US R&D variable is included. This must imply existence of significant collinearity between own R&D and US R&D, a finding that was also documented in the cross-country analysis of Park (1995). To test this hypothesis, we run regressions of the following form,

$$(R\&D_i)_t = \alpha + \beta(R\&D_{US})_t + \varepsilon_t$$

Results are reported in Table IV. With the exception of Spain, US R&D seems to spillover to domestic R&D as indicated by the significant coefficient of the US R&D in the Table. But Spain is a country that *diverges* from the US per capita income, according to Table I, and so the existence of little spillover from the US R&D to its own is consistent with Table I. However, countries such as Greece and New Zealand also diverge in Table I and yet indicate positive sign of US R&D spillover in Table III. Moreover, Table III indicated a significant role of US R&D in their per capita incomes. Despite these exception and anomalies, one can conclude that in a majority of cases, time-series evidence points to (a) the importance of *own* R&D in growth, (b) the role of international R&D spillovers as a factor influencing domestic growth and convergence, (c) the possibility of international spillovers to domestic R&D, in addition to output growth.

IV. CONCLUSION

Cross-country evidence suggests that R&D spillover effects exist, within sectors, between sectors and across countries. Such effects would tend to imply increasing returns to scale and thus make a positive contribution to aggregate growth. To the extent that spillovers cross national borders they must imply convergence of incomes and productivities across countries. Evidence for international spillovers *and* economic convergence are consistent with respect to OECD group. On the other hand, spillovers to the poor countries appear more limited, consistent with the divergence of this group's per capital incomes and productivities.

Owing to methodological limitations of cross-country data, a pure time-series approach is presented. Results show convergence for many OECD countries and divergence for other. For OECD, they also show positive role of *own* R&D in aggregate growth, in those cases where convergence is observed. International R&D spillovers, via the US R&D, are also observed both in contributing to output and in contributing to *own* R&D, consistent with cross-country studies (e.g., Park, 1995), but this spillover seems to not only occur for countries that converge to the US per capita income, but for a few that diverge from it. Thus, while some relation between international R&D spillovers and convergence seems to exist, this relation is not entirely deterministic. A simple theoretical model is also provided consistent with R&D human capital data and growth.

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Table I: Time Series Results on Convergence

Country	Regression Coefficients Constant	Time	R^2
Africa			
Egypt	7603.72 (24.74)	199.81 (16.90)	0.98
Ethiopia	11081.00 (4.81)	14.75 (0.17)	0.55
Ghana	3533.45 (3.19)	353.15 (8.49)	0.90
Kenya	7486.94 (27.43)	225.21 (21.36)	0.98
Morocco	7479.16 (27.18)	194.99 (18.30)	0.98
Nigeria	7772.34 (20.58)	212.84 (14.73)	0.98
S. Africa	6103.83 (18.89)	195.05 (15.70)	0.98
Uganda	7536.58 (27.01)	233.97 (21.76)	0.99
Zambia	4933.87 (3.5)	270.15 (5.09)	0.54
Zimbabawe	4471.12 (5.36)	313.90 (9.94)	0.88
North America			
Canada*	2994.14 (6.3)	-40.73 (-2.31)	0.91
Mexico	6214.03 (13.68)	129.86 (7.52)	0.95
South America			
Argentina**	4313.58 (8.57)	158.73 (7.78)	0.59
Brazil	7023.61 (19.30)	154.56 (11.09)	0.97
Chile**	5600.18(17.73)	187.88 (15.47)	0.98
Colombia	6850.23 (24.59)	184.05 (17.13)	0.98
Uruguay	4368.53 (13.49)	206.65 (16.46)	0.97

Country	Regression Coefficients Constant	Time	R^2
Venezuela	4145.67 (6.39)	161.43 (6.68)	0.96
Asia			
China	1796.25 (0.95)	395.94 (5.83)	0.91
Hongkong	3694.84 (1.65)	53.39 (0.67)	0.79
India	7601.91 (24.42)	217.16 (18.13)	0.98
Indonesia	1890.57 (0.97)	382.38 (5.44)	0.91
Iran	2592.85 (2.47)	292.86 (7.44)	0.88
Japan*	8062.10 (32.01)	-106.33 (-10.87)	0.94
S. Korea	7449.19 (5.57)	104.22 (2.03)	0.40
Malaysia	5168.64 (5.20)	214.07 (5.70)	0.77
Pakistan	7588.64 (28.67)	212.95 (20.80)	0.98
Philippines	7232.15 (22.30)	209.03 (16.77)	0.98
Sri Lanka	7257.36 (20.75)	205.04 (15.33)	0.98
Taiwan	8168.63 (8.9)	59.56 (1.63)	0.15
Thailand	7848.34 (26.87)	163.59 (14.52)	0.97
Europe			
Austria*	5704.61 (21.43)	-18.17 (-1.76)	0.56
Belgium*	4522 (18.61)	-1.95 (-0.21)	0.41
Denmark*	3422.81 (12.34)	3.30(0.31)	0.45
Finland*	5223.39 (18.80)	-18.11 (-1.67)	0.48
France*	4492.51 (18.22)	-21.40 (-2.25)	0.65

Country	Regression Coefficients Constant	Time	R^2
W. Germany*	4796.20 (14.17)	-44.94 (-3.48)	0.79
Greece	7692.44 (14.35)	47.41(2.23)	0.12
Ireland**	6299.64 (23.43)	69.67 (6.78)	0.92
Italy*	5930.91(29.22)	-17.07 (-2.15)	0.47
Netherlands*	4026.28 (11.76)	13.88 (1.06)	0.64
Norway*	4644.37 (8.20)	-9.53 (-0.45)	0.74
Portugal**	7978.27 (12.54)	55.23 (2.14)	0.18
Spain**	6568.60 (21.77)	37.63 (3.23)	0.78
Sweden*	2271.21 (7.56)	15.16 (1.30)	0.53
Switzerland*	1546.02 (3.72)	-13.45 (-0.85)	0.63
Turkey	7045.97 (27.86)	171.18 (17.45)	0.98
U.K.*	3299.30 (10.92)	48.26 (4.19)	0.88
U.S.S.R.	4193 (1.98)	107.44 (1.36)	0.62
Oceania			
Australia*	2050 (12.93)	23.29 (3.78)	0.51
New Zealand**	1565.05 (3.83)	96.12(6.13)	0.91

Source: Summers, Robert and Alan Heston, The Penn World Tables (Mark 5.6), 1994.

Note: (i) Results are corrected for first order serial correlation.
(ii) Numbers in parentheses represent the t statistics
(iii) * denotes country included both in Baumol's 16 and DeLong's 22..
(iv) ** denotes country included in DeLong's 22 but not in Baumol's 16.

Table II
R&D and Growth

Per Capita GDP	Constant	R&D Country	R-Sq	Durbin-Watson
Canada	5133.899 (6.09)	0.015 (11.44)	0.96	1.95
Japan	806.295 (1.00)	0.025 (12.56)	0.97	1.76
Austria	6291.196 (12.24)	0.036 (9.46)	0.97	1.92
Belgium*				
Denmark*				
Finland	6607.880 (7.39)	0.004 (0.48)	0.96	1.61
France	6607.880 (7.39)	0.038 (6.298)	0.95	1.96
Germany*				
Greece	9043.288 (3.10)	-0.006 (-1.37)	0.93	2.19
Ireland	4139.949 (5.69)	0.014 (4.40)	0.95	2.22
Italy	-1764.67 (-1.64)	0.082 (11.11)	0.93	1.86
Netherlands	7609.621 (11.40)	0.024 (5.68)	0.93	1.74
Norway	23141.29 (2.04)	-0.011 (-1.28)	0.98	1.38
Portugal	4389.611 (7.50)	-0.0006 (-0.31)	0.93	1.87
Spain	6615.100 (2.62)	-0.0029 (-1.37)	0.96	2.12
Sweden	8216.062 (17.63)	0.034 (10.10)	0.96	1.71
Switzerland	10156.02 (10.67)	0.031 (4.55)	0.87	2.11
U.K.	9869.166 (12.90)	0.030 (6.01)	0.90	2.26
Australia	7883.907 (25.00)	0.017 (15.64)	0.86	2.04
New Zealand	9309.228 (16.87)	0.007 (3.12)	0.75	2.11

Source: Summers and Heston (1994) and Coe and Helpman (1993) and communications with Coe (IMF)

Notes: (i) Results are correction for serial correlation

(ii) Numbers in ( ) are t statistics

(iii) * Convergence not achieved after correcting for serial correlation.

Table III
R&D and Growth : Own and Spillover Effects

Per Capita GDP	Constant	R&D Country	R&D US	R-Sq	Durbin Watso
Canada	7743.398 (2.89)	0.007 (0.89)	0.032 (1.05)	0.96	1.86
Japan	5299.760 (5.18)	0.001 (0.39)	0.061 (5.12)	0.99	1.39
Austria	6953.742 (7.95)	0.019 (1.14)	0.017 (1.04)	0.97	1.93
Belgium	8843.124 (4.25)	-0.004 (-0.20)	0.037 (3.00)	0.95	2.01
Denmark	8624.129 (14.82)	-0.0006 (-0.06)	0.044 (4.88)	0.96	2.12
Finland	6159.261 (23.79)	0.013 (2.79)	0.044 (8.62)	0.98	2.32
France	9303.862 (8.21)	0.0004 (0.04)	0.009 (3.58)	0.97	1.86
Germany*					
Greece	5636.011 (9.03)	-0.007 (-1.38)	0.016 (4.55)	0.94	2.03
Ireland	4081.436 (8.03)	0.001 (0.25)	1.463 (3.03)	0.97	1.91
Italy	7694.050 (4.12)	-0.004 (-0.30)	0.042 (5.65)	0.97	2.01
Netherlands	8602.346 (10.50)	0.008 (0.90)	0.018 (1.86)	0.95	1.89
Norway	40789.84 (0.52)	-0.011 (-1.27)	-0.018 (-0.45)	0.98	1.38
Portugal	2935.238 (4.16)	-0.0008 (-0.28)	0.031 (3.25)	0.94	1.88
Spain	6327.214 (10.15)	-0.003 (-1.37)	0.027 (5.40)	0.97	2.41
Sweden	9909.261 (28.61)	-0.001 (-0.21)	0.040 (6.31)	0.98	2.11
Switzerland	12401.90 (13.54)	-0.012 (-0.90)	0.048 (3.50)	0.93	1.94
U.K.	11499.61 (10.83)	0.001 (0.12)	0.034 (2.16)	0.92	2.01
Australia	10157.79 (33.87)	-0.004 (-1.70)	0.050 (8.52)	0.97	1.88
New Zealand	9627.479 (14.62)	0.002 (0.24)	0.012 (0.78)	0.76	2.01

Source: Summers and Heston (1994) and Coe and Helpman (1993) and communications with Coe (IMF)

Notes: (i) Results are correction for serial correlation

(ii) Numbers in ( ) are t statistics

(iii) * Convergence not achieved after correcting for serial correlation.

Table IV
Spillover Effects on Own R&D

R&D Own	Constant	R&D US	R-Sq	Durbin-Watson
Canada*				
Japan	204251.7 (9.89)	2.486 (9.94)	0.97	2.02
Austria	38144.02 (6.44)	1.035 (14.75)	0.98	1.87
Belgium	88000.71 (5.06)	0.522 (2.94)	0.95	2.26
Denmark	54113.33 (9.43)	0.848 (11.69)	0.93	1.79
Finland	49755.04 (3.64)	0.969 (6.05)	0.93	2.11
France	72606.28 (11.92)	0.840 (11.37)	0.97	1.81
Germany	64476.85 (16.64)	0.683 (13.56)	0.95	1.99
Greece	96532.31 (13.96)	0.333 (4.04)	0.75	2.30
Ireland	41534.30 (4.55)	2.004 (17.75)	0.98	2.14
Italy	106627.2 (18.40)	0.509 (7.12)	0.92	2.00
Netherlands	76175.16 (7.71)	0.993 (8.01)	0.96	1.86
Norway	55437.29 (4.83)	0.899 (6.27)	0.94	2.40
Portugal*				
Spain	211671.3 (4.34)	0.117 (0.22)	0.76	2.01
Sweden	54224.54 (6.89)	1.019 (10.68)	0.97	2.04
Switzerland	60713.49 (7.46)	0.969 (9.50)	0.95	2.24
U.K.	67050.52 (9.65)	1.100 (12.66)	0.96	2.00
Australia	109386.9 (10.91)	2.314 (18.18)	0.92	2.06
New Zealand	67585.96 (4.70)	1.876 (11.04)	0.96	2.18

Source: Summers and Heston (1994) and Coe and Helpman (1993) and communications with Coe (IMF)

Notes: (i) Results are correction for serial correlation

(ii) Numbers in ( ) are t statistics

(iii) * Convergence not achieved after correcting for serial correlation.

Appendix: A Model of R&D Spillovers via Human Capital

Replace L_A (number of R&D workers) in equation (1) with effective human capital, say H_A:

$$\dot{A} = \delta H_A A^{\phi} \tag{1A}$$

Then, $\dot{A}/A = \delta(H_A/A^{1-\phi})$ and steady state implies that $\dot{A}/A = (\dot{H}_A/H_A)/(1-\phi)$. However, H_A now represents effective human capital level which *need not* grow at the rate of the labor force. To illustrate the point, suppose human capital involves leaning by doing, so that $\dot{H}_A$ increases in with the size of the R&D labor force,

$$\dot{H}_A = \nu L_A. \tag{2A}$$

Assume H_A is subject to *obsolescence*. Then, the current stock of human capital is,

$$H_A = \int_{t-T}^{t} w(\tau)L_A(\tau)d\tau \qquad \text{with } w' < 0. \tag{3A}$$

The length T indicates maximum "useful R&D labor life", and $w(\tau)$ indicates the weight of past labor in the present stock of effective human capital which decreases with R&D labor from more distant past. Then steady state growth of the economy becomes:

$$g_y = g_A = \frac{1}{1-\phi}(\dot{H}_A/H_A)_t = \frac{1}{1-\phi}\cdot\frac{\nu L_{A,t}}{\int_{t-T}^{t} w(\tau)L_A(\tau)d\tau} \tag{4A}$$

In this formulation, growth rises in proportion to the size of current R&D labor force as a fraction of total past labor force in R&D sector. To the extent that *current* human capital is involved, this formulation restores some of the "path-dependence" results inherent in Romer (1990). However, incorporation of the successive past values of R&D labor in the denominator of (4A), tends to *moderate* the exponential measure of R&D human capital growth, observed in Jones (1995). Depending on the the weight function $w(\tau)$ and the length of useful R&D labor, τ, one may obtain correlation between growth and human capital. In this formulation, knowledge spillovers are attributed to the accumulation in the *learning* process, somewhat akin to Lucas (1988). Since the latter are purely external, Romer's monopolistic competitive firms may be replaced with perfectly competitive ones, engaged in R&D activities that are fully excludable (as in patents). Then "spillovers" to other firms occur only via the movement of experienced R&D agents (scientists and engineers) across firms. Agents need not divulge "trade-secrets" from the former firms, but their embodied knowledge and experience is their useful human capital. These agents accumulate knowledge (i.e. learn) and propagate knowledge by moving from one firms to the next. Freedom of workers to move across firms is a purely external effect, that firms cannot internalize.